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TOF Method Measurements of Neutron Cross Sections in 299 Energy Intervals of the ABBN-93 Group Constants

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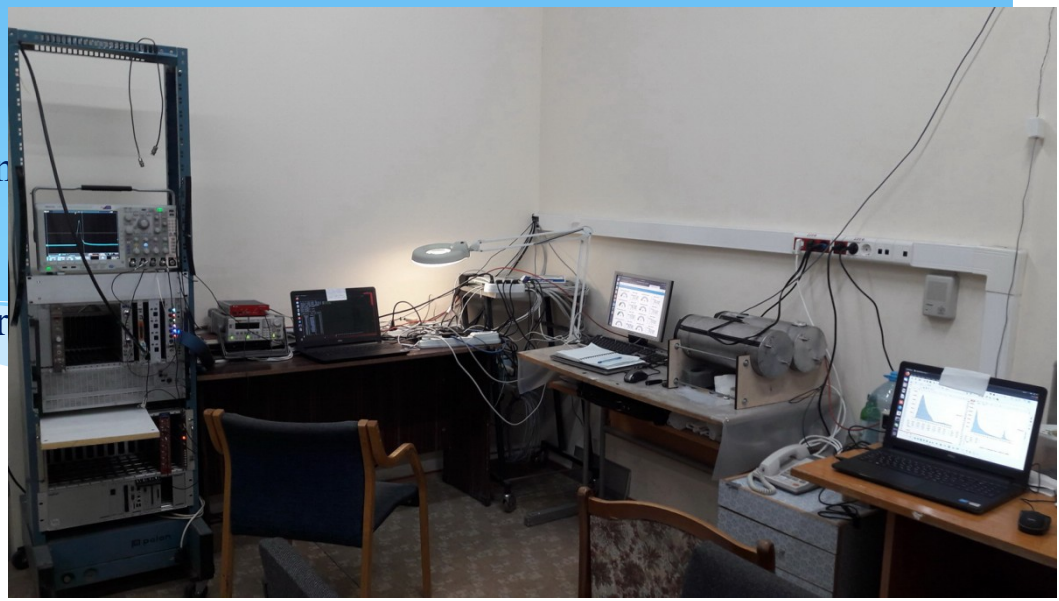
Abstract

Numerical Monte-Carlo codes, designed for calculation of fast breeder reactors and their radiation shields, in order to achieve high accuracy are currently being transformed to the use of 299-group ABBN-93 constants, instead of classical 28-group ABBN-78 system. The new system, having a smaller step of lethargy, puts forward increased requirements on performance of nuclear physics facilities. On which, in order to provide calculation codes with initial data, experimental measurements of the cross sections for interaction of neutrons with nuclei of fissile, raw and structural materials are carried out.

In this paper we review the possibility of measurements of the 299-group constants at the existing 50 meter, and at projected 500-meter, flight bases of the INES TOF spectrometer of a pulsed spallation neutron source RADEX, installed on the beam of the INR RAS linear proton accelerator.

Results of numerical calculations for the diffusion time of neutron spectrums from tungsten targets of various thicknesses are also presented, within the framework of the analysis for possibility to reduce the duration of neutron flashes.



Review: what the ‘group cross sections’ are, how the group constants are used, and how many groups are necessary

Neutron group cross sections are used for calculation of the cores of nuclear reactors and their radiation shields. Neutron cross section of partial processes, such as capture, fission, elastic and inelastic scattering, are measured in barns, and being multiplied to concentration of nucleus define mean free path of neutron in substance:

$\tilde{\lambda} = \left(\frac{1}{sn}\right) = \left(\frac{1}{\Sigma}\right); \quad n = \left(\frac{pN_A}{A}\right);$

$\tilde{\lambda}$ – mean free path of neutron in substance, cm.

s – microscopic cross section measured in barns.

Σ – macroscopic cross section measured in cm^{-1}.

In some practically important tasks, when all neutrons are fast or all neutrons are thermal, it’s possible to describe all the neutron spectrum by averaged cross section.

Neutron balance is being described as number of events per unit of volume per second, physical issue of which are born, capture and leakage of neutrons from unit of volume:

$$\Phi\Sigma_f\nu_f - \Phi\Sigma_a + D\Delta\Phi = 0 \qquad \text{if } K_{\text{eff}} = 1;\ \Phi = \Phi(r);$$

$$\Phi\Sigma_f\nu_f - \Phi\Sigma_a + D\Delta\Phi = \left(\frac{dn}{dt}\right)_{\text{Volume=1}} \qquad \text{if } K_{\text{eff}} \neq 1;\ \Phi = \Phi(r,t);$$

$$\left(\frac{\Phi\Sigma_f\nu_f}{K_{\text{eff}}}\right) - \Phi\Sigma_a + D\Delta\Phi = 0 \qquad \text{if } K_{\text{eff}} \neq 1;\ \Phi = \Phi(r); \qquad (*)$$

Equation (*) can be written as:

$$\Delta\Phi(r) + \left(\frac{\Sigma_a}{D}\right)\left(\frac{\nu_f\Sigma_f}{K_{\text{eff}}\Sigma_a} - 1\right)\Phi = 0; \qquad (**)$$

From the view of mathematics, this is type of differential equation where so called ‘material parameter’

$$\Delta\Phi(r) + B_m^2\Phi = 0;$$

$$B_m^2 = \left(\frac{\Sigma_a}{D}\right)\left(\frac{\nu_f\Sigma_f}{K_{eff}\Sigma_a} - 1\right); \quad D = \left(\frac{\lambda_{transport}}{3}\right) = \left(\frac{1}{3\Sigma_{tr}}\right) = \left(\frac{\lambda_{scattering}}{3(1-\cos\varphi)}\right)$$

Laplasian operator is:

$$\Delta_{sph} = \left(\frac{d^2}{dr^2}\right) + \left(\frac{2}{r}\frac{d}{dr}\right) \quad \text{for spherical geometry}$$

$$\Delta_{cyl} = \left(\frac{\partial^2}{\partial r^2}\right) + \left(\frac{1}{r}\frac{\partial}{\partial r}\right) + \left(\frac{\partial^2}{\partial r^2}\right) \quad \text{for cylinder}$$

$$\Delta_{par} = \left(\frac{\partial^2}{\partial x^2}\right) + \left(\frac{\partial^2}{\partial y^2}\right) + \left(\frac{\partial^2}{\partial z^2}\right) \quad \text{for parallelepiped}$$

Solution of differential equation is function Φ(r). It’s physical issue is distribution of neutron flux density between center and external surface of the sphere.

Solution of the function is a number: value of radius, on which flux Φ(r) equals to zero. Physically it is a critical radius of the sphere. For criticality of spherical reactor’s core, material parameter defined by Laplasian must be equal to this geometry parameter:

$$B_g^2 = \left(\frac{\pi}{R}\right)^2 \quad \text{for sphere}$$

Making equal material parameter with geometry parameter, we can find useful correlations for critical radius and for neutron multiplication coefficient:

$$R_{crit} = \left(\frac{\pi}{\sqrt{3(\eta-1)\Sigma_a\Sigma_{tr}}}\right) - 0.71\lambda_{tr};$$

$$K_{eff} = \left(\frac{K_\infty}{1+B_g^2L^2}\right) = \left(\frac{\nu_f\Sigma_f}{\Sigma_a + DB_g^2}\right) = \left(\frac{\eta}{1+\left(\frac{DB_g^2}{\Sigma_a}\right)}\right)$$

Combination DB_g^2 has dimension ‘1/cm’ the same as macroscopic cross section.

This combination defines leakage of neutrons from the core.

Thus, we introduced correlations when cross sections of partial processes – fission, capture, inelastic and elastic scattering – can be expressed as average for all spectrum. These are one-group equations.

In many practical important cases it's not possible to describe neutron spectrum by only one averaged cross section, because the spectrum significantly changes during propagation and diffusion of neutrons in reactor or in radiation shield: exist simultaneously neutrons of all energies. One of such important technological applications is the case of fast breeder reactors.

Historically, systems of neutron constants with different number of groups were used. Most famous became ABBN-78 [3]. It has 28 groups, so as 14 Mev neutron from DT reaction must have, averaged, 28 scatterings to reduce energy from 14 MeV to thermal 0,0253 eV in practically most important cases of scattering on deuterium in LiD and in D2O:

$$N = \left(\frac{1}{\xi}\right)\ln\left(\frac{E_{\max}}{E_{\min}}\right) = \left(\frac{1}{\xi}\right)\ln\left(\frac{14*10^6}{0.0253}\right); \quad \left(\frac{1}{\xi}\right) \approx \frac{A}{2} + \frac{1}{3} + \frac{A}{18}; \quad N \approx 28$$

Also this quantity of groups is enough for detailed description of neutron flux moderation in hydrogen substances such as water H2O.

Equation marked above as '*' for multi-group case involve also the matrix of inelastic transition of neutron between groups, existing in upper energy groups and determined mainly by inelastic scattering. Also appears coefficients χ_i which describe share of prompt fission neutrons which were born in described group.

The 28-group equations are:

$$-D_1\Delta\Phi_1+\Sigma_{ув1}\Phi_1=\chi_1 Q;$$

$$-D_2\Delta\Phi_2+\Sigma_{ув2}\Phi_2=\chi_2 Q+\Phi_1\left(\Sigma_{m1}+\Sigma_{in}^{k\to 2}\right);$$

(…….)

$$-D_{11}\Delta\Phi_{11}+\Sigma_{ув11}\Phi_{11}=\chi_{11}Q+\Phi_{10}\Sigma_{m10}+\sum_{k=1}^{10}\Phi_k\Sigma_{in}^{k\to 11};$$

$$-D_{12}\Delta\Phi_{12}+\Sigma_{ув12}\Phi_{12}=\Phi_{11}\Sigma_{m11};$$

(……..)

$$-D_{27}\Delta\Phi_{27}+\Sigma_{ув27}\Phi_{27}=\Phi_{26}\Sigma_{m26};$$

$$-D_{th}\Delta\Phi_{th}+\Sigma_{a\_th}\Phi_{th}=\Phi_{27}\Sigma_{m27};$$

Here numbers of the groups, also as on pictures below, are marked as 1...28 instead of classical ABBN-78 sequence as №"-1",№ "0", №"1"…..№26.

Thus, prompt fissile neutrons exist above 12th group. So as 28-group allow to calculate in detail nuclear reactors with such substances of the cores, like lithium deuteride LiD, like water H2O and like pure fissile materials, it satisfies majority of requirements for military and civil applications.

However, in modern times grew importance of detailed predictions for fast breeder reactor's breeding ratio, and for effects in light compact radiation shields of transport small modular reactors. More detailed description of neutron's moderation process became necessary.

Thus, in year 1993 by the same group of authors leaded by professor Nikolaev M.N. who created ABBN-93, was created new, the 299-group system of neutron cross sections ABBN-93. It allows to describe in detail moderation of neutrons in sodium Na23, which is used as cooler in fast spectrum sodium breeders.

As we can see for isotope Na23: $\left(\frac{1}{\xi}\right)\approx\left(\frac{23}{2}\right)+\left(\frac{1}{3}\right)+\left(\frac{23}{18}\right)=13{,}111;$

$$N(Na^{23})=\left(\frac{1}{\xi}\right)\ln\left(\frac{14*10^{6}}{0{,}0253}\right)=\left(\frac{1}{\xi}\right)(20{,}13)\approx 13{,}111*20{,}13=263;$$

Were added also low energy groups. Lethargy step is not constant for some reasons, partly to combine some energy borders with the thresholds of reactions in some practically important isotopes.

Analogically to the case of 28-group equations, 299-group neutron cross sections of capture, fission, inelastic and elastic scattering, are used during group flux calculations as coefficients in differential equations. Necessary precision of neutron cross sections is defined by the share of delayed neutrons in fission reaction.

Reactivity $\rho=\left(\frac{K_{eff}-1}{K_{eff}}\right)$ must be calculated with the same or higher precision. Share of delayed neutrons during fission of the U235 is 0,65%. Fission of Pu239 gives 0,2% of delayed neutrons. Considering contribution of U238 fission above the threshold, the BN-1200 reactor on plutonium fuel has 0,42% of delayed neutrons.

This value defines high requirements for accumulation of statistics in TOF measurements, considering that group precision has order of $\left(\frac{\delta\sigma}{\sigma}\right)\approx\left(\frac{1}{\sqrt{N}}\right)$ where N is number of neutrons per one energy group.
To provide statistical error component several times smaller then share of delayed neutrons, we must accumulate around one million useful counts to each of 299 groups.

As a result of this neutron theory review, we can make strict conclusions.

1). Group neutron cross sections constants are coefficients for differential equations, describing transfer of neutrons in reactor's core and radiation shield. With required precision, at least 0,4% these coefficients can be taken only from experiment measurements. Theory predicts only approximately values, which can not be implemented in numerical calculations.

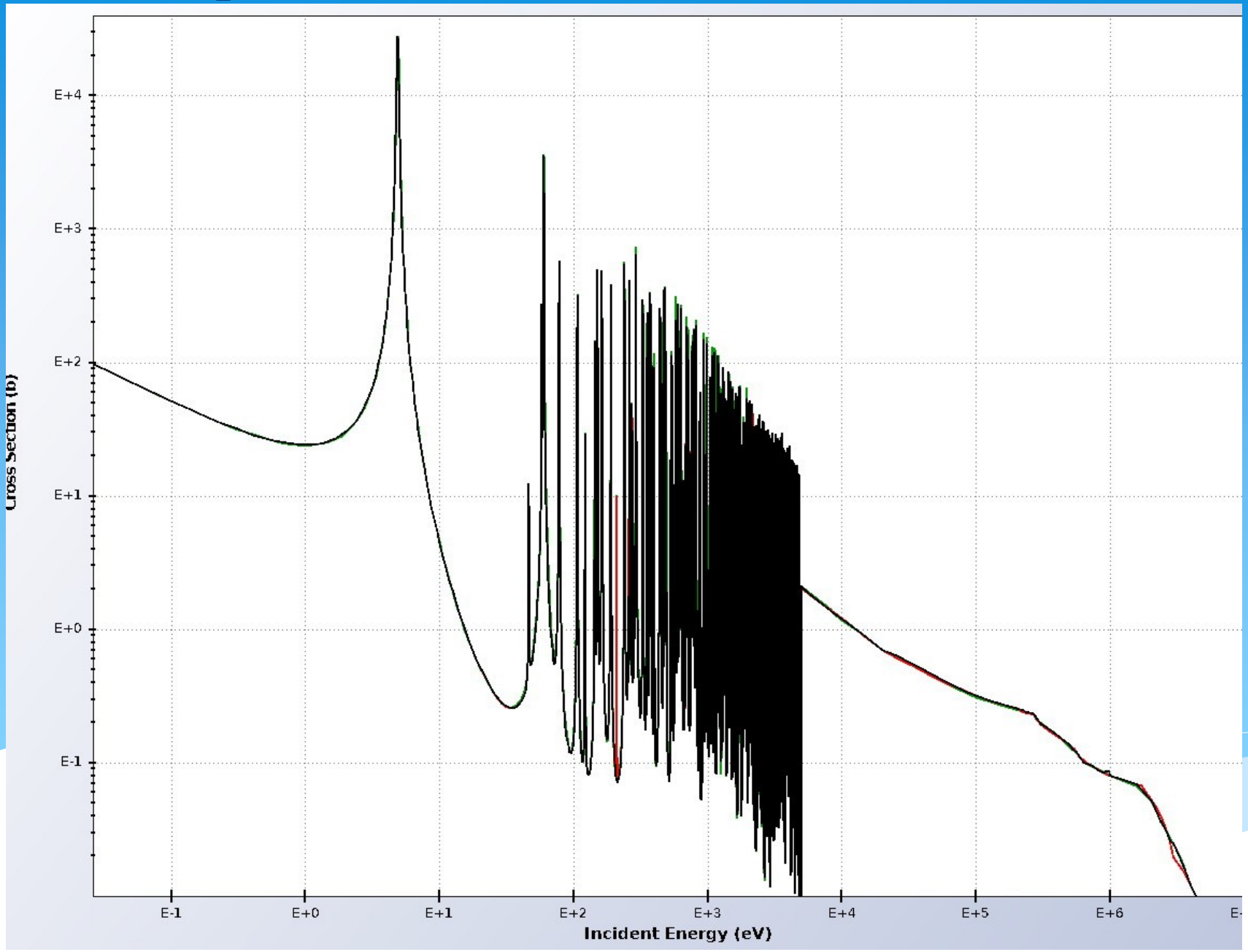
2). TOF measurements are straightly useful for applied nuclear engineering tasks, only if they satisfy three requirements.

First of them is ability to have energy resolution, (tau/L) factor measured in nanoseconds per meter, high enough to have (delta E)/E better then in lethargy partition of actual group energy system. Energy error of the spectrometer, even in high energy groups, must be several times smaller then width of the group. For 299 group it is more difficult than for 28 group system.

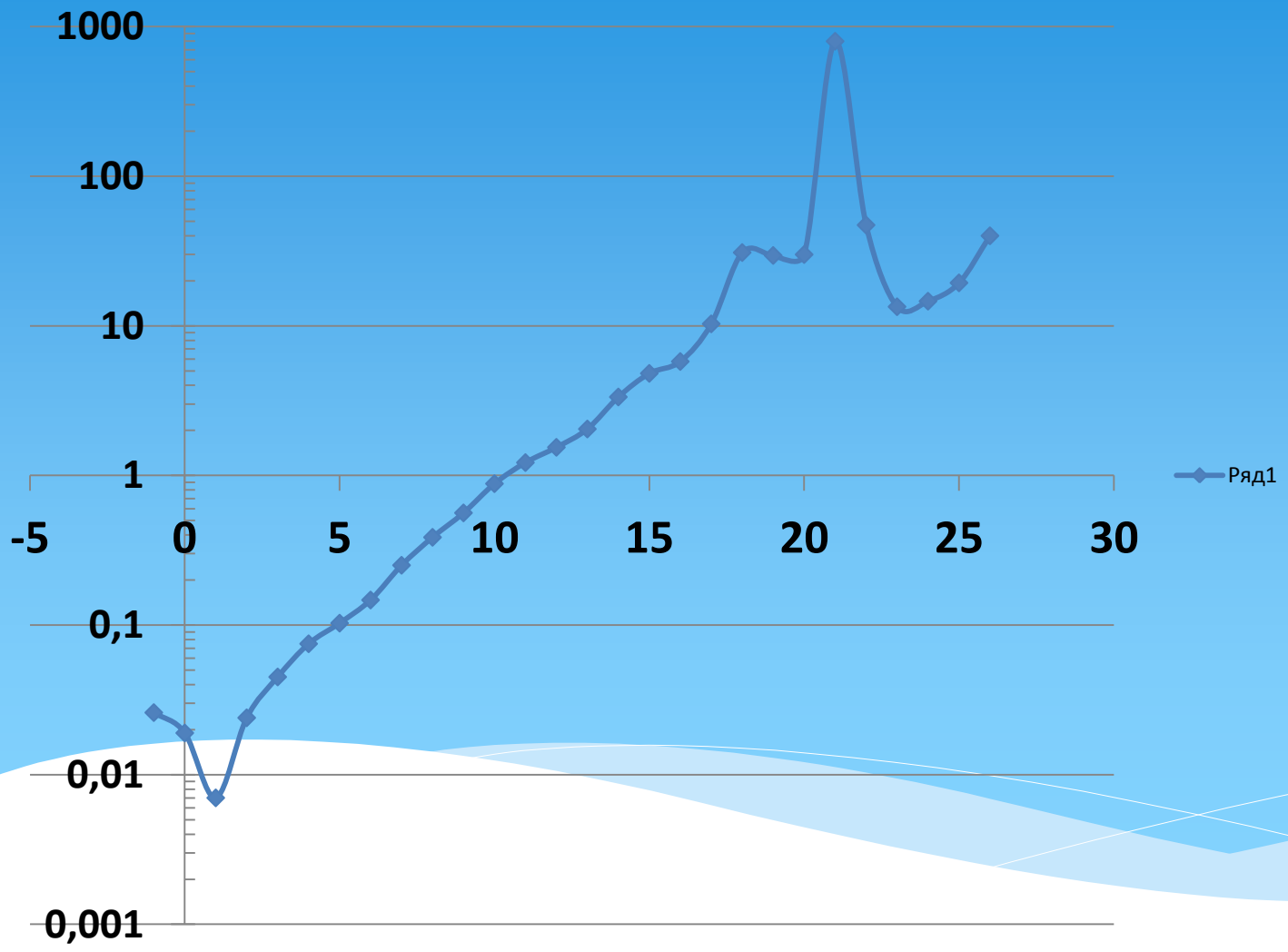
Second requirement is ability to accumulate statistics for each group, considering $\left(\frac{\delta\sigma}{\sigma}\right)\approx\left(\frac{1}{\sqrt{N}}\right)$ Necessary value is physically related with the delayed neutrons share of the one or another fissile nuclide, on which nuclear reactor works.

Third requirement is methodological: when experimental histogram is obtained, it's necessary to delete the background layer with precision, enough for two previous requirements. This can be done by several different physical methods. In many cases, precision of background's deletion defines precision of all the experimental result.

Au197 capture cross section, barns, ENDF/B-VII.1 [4]

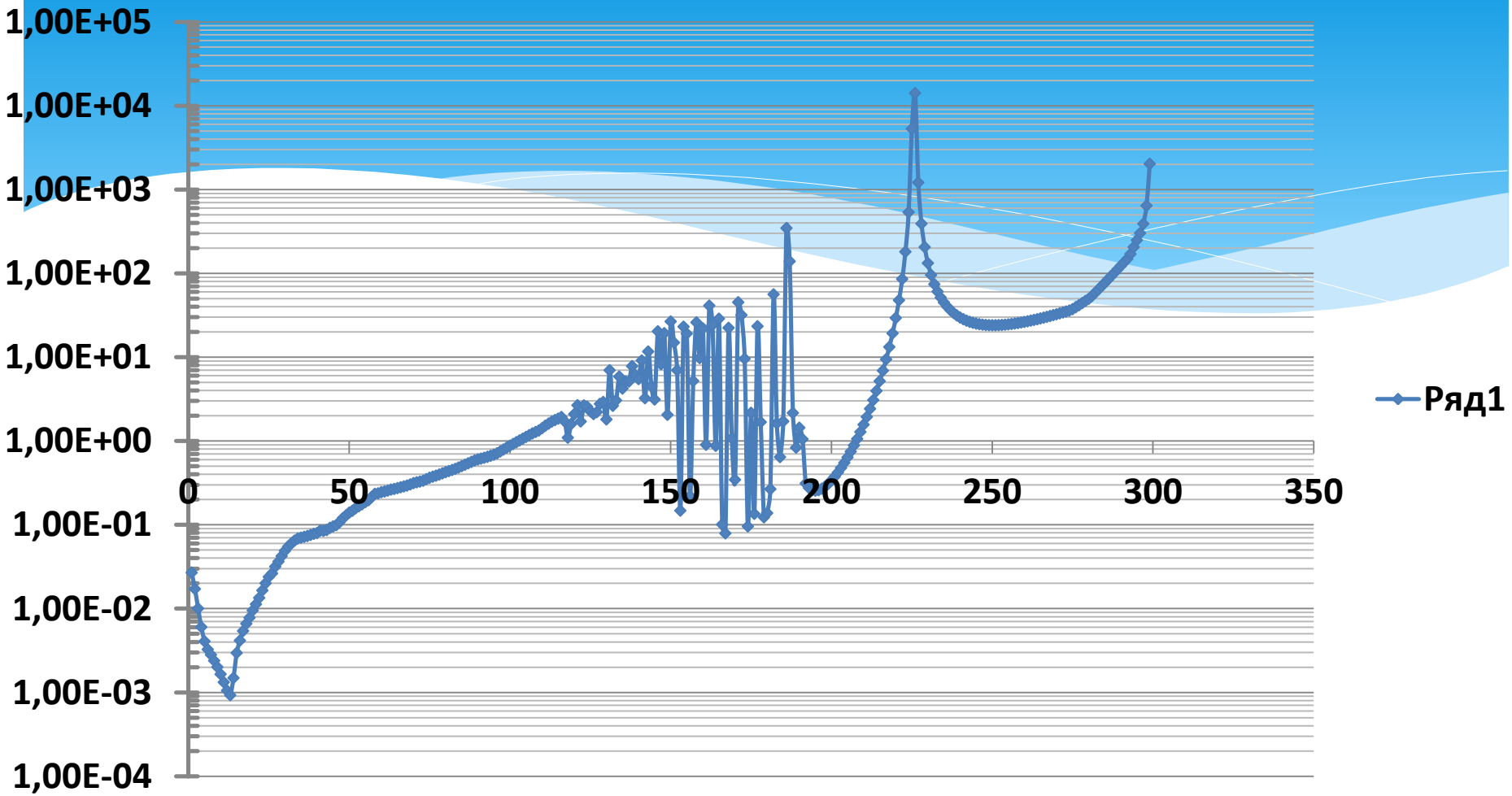


Au197 capture cross sections, barns, ABBN-78
Group number on horizontal axis ABBN-93, BNL



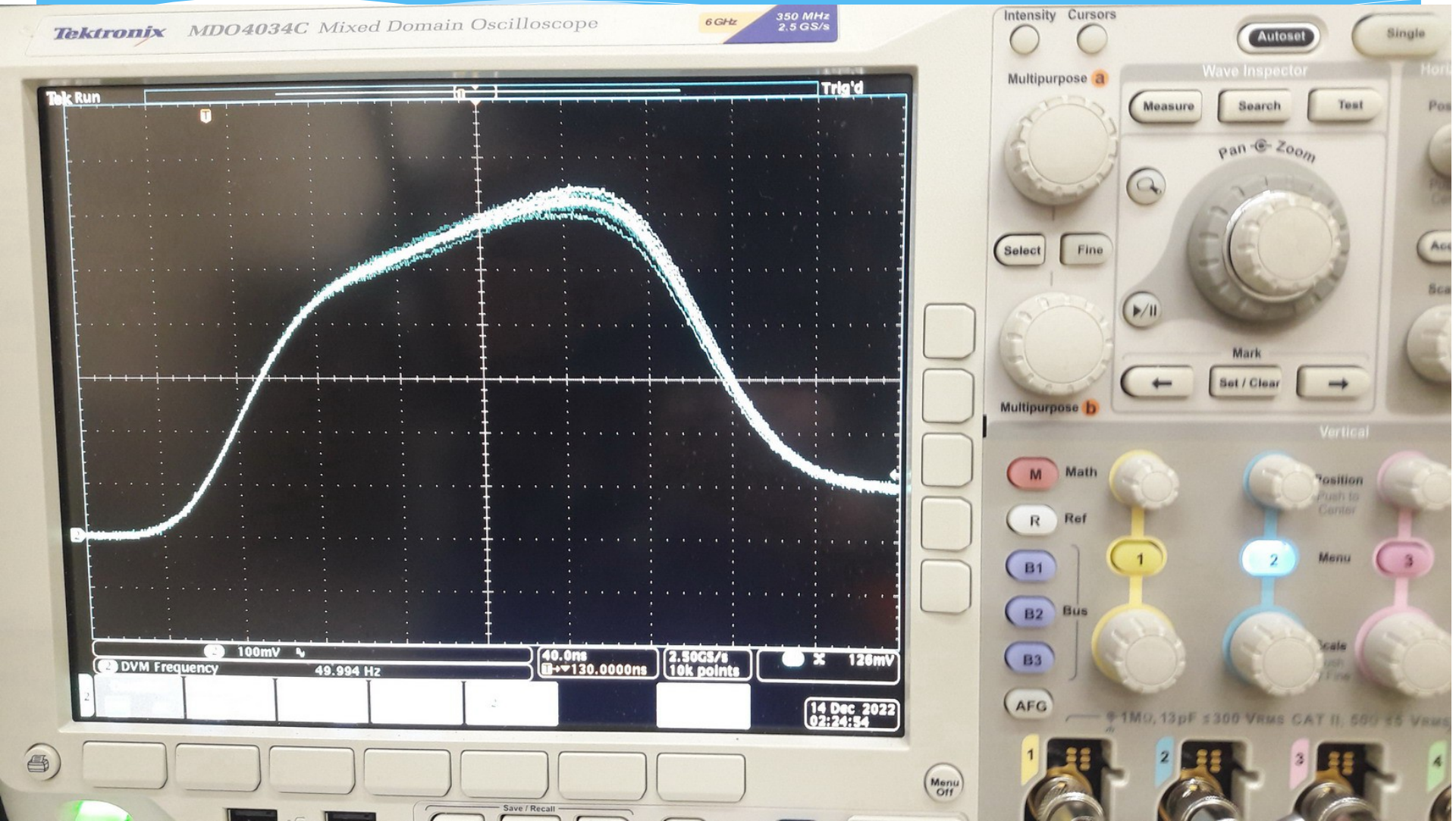
N	б(с)
-1	0,026
0	0,019
1	0,007
2	0,024
3	0,045
4	0,075
5	0,103
6	0,147
7	0,251
8	0,386
9	0,562
10	0,881
11	1,219
12	1,542
13	2,044
14	3,346
15	4,811
16	5,775
17	10,305
18	30,898
19	29,532
20	29,964
21	798,106
22	47,146
23	13,417
24	14,61
25	19,375
26	39,979

Au197 capture cross section in ABBN-93 system.



Vertical axis is Au197 capture cross section in barns.
Horizontal axis is group number: 299 groups
with neutron energies between 20 MeV and 0.00001 eV.

Proton beam during accelerator's turning:
tau = 230 nanoseconds on half-altitude.
Grid of the screen of the oscilloscope is 40 nanoseconds per division.



Group № on pictures	Group ABBN 78	Upper energy border	Low energy border	Tau of neutron mksec	Channel № at low border	Channels per group	ΔE, eV	(ΔE)/ E(Low)	ΔE/ (Group Width)
1	-1	14,5 MeV	14 MeV	0,955	10	0,17	8795812	0,628	17,6
2	0	14 MeV	10,5 MeV	1,10	11	1,5	5727272	0,545	1,63
3	1	10,5 MeV	6,5 MeV	1,40	14	3	2785714	0,428	0,696
4	2	6,5 MeV	4 MeV	1,787	18	4	1343033	0,335	0,537
5	3	4 MeV	2,5 MeV	2,26	23	5	663716	0,265	0,442
6	4	2,5 MeV	1,4 MeV	3,02	30	7	280000	0,20	0,25
7	5	1,4 MeV	0,8 MeV	3,99	40	10	120000	0,15	0,2
8	6	0,8 MeV	0,4 MeV	5,65	56	16	42477	0,106	0,106
9	7	0,4 MeV	0,2 MeV	7,99	80	24	15000	0,0075	0,075
10	8	0,2 MeV	0,1 MeV	11,3	113	33	5309	0,053	0,053
11	9	0,1 MeV	46,5 keV	16,58	166	53	1682	0,036	0,031
12	10	46,5 keV	21,5 keV	24,4	244	78	528	0,024	0,021
13	11	21,5 keV	10 keV	35,75	357	113	167	0,0167	0,0145
14	12	10 keV	4,65 keV	52,4	524	167	53,2	0,0114	0,0099
15	13	4,65 keV	2,15 keV	77,1	771	247	16,7	0,00776	0,00668
16	14	2,15 keV	1 keV	113	1130	359	5,3	0,0053	0,0046
17	15	1 keV	465 eV	165,8	1658	528	1,68	0,0036	0,00314
18	16	465 eV	215 eV	243,8	2438	780	0,529	0,00246	0,00212
19	17	215 eV	100 eV	357,5	3575	1137	0,167	0,00167	0,00145
20	18	100 eV	46,5 eV	524,2	5242	1667	0,53	0,00114	0,00099
21	19	46,5 eV	21,5 eV	771	7710	2468	0,0167	0,000716	0,000668
22	20	21,5 eV	10 eV	1130,5	11305	3595	0,0053	0,00053	0,00046
23	21	10 eV	4,65 eV	1657,8	16578	5273	0,00168	0,00036	0,000314
24	22	4,65 eV	2,15 eV	2438,1	24381	7803	0,00053	0,000246	0,000212
25	23	2,15 eV	1 eV	3575	35750	11369	0,000167	0,000167	0,000145
26	24	1 eV	0,465 eV	5242,6	52426	16676	0,000053	0,000114	0,000099
27	25	0,465 eV	0,215 eV	7710	77100	24674	0,0000167	0,0000776	0,0000668
28	T	0,0253 eV	0,0253 eV	22476	200000	122900	-------	---------	----------

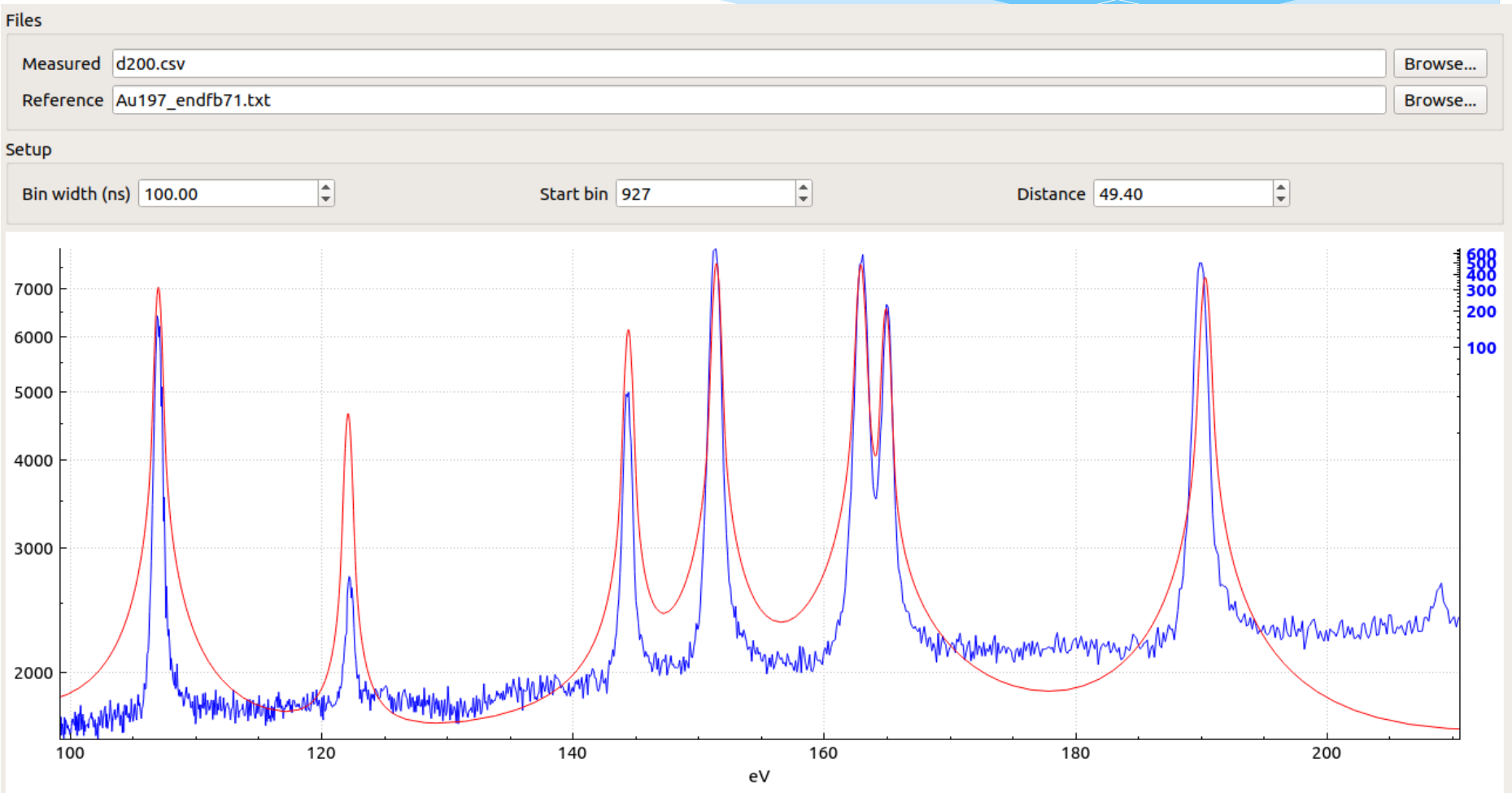
Performance of group cross sections measurements on existing TOF base:
L = 50 meters,
tau = 300 nanoseconds.
Energy resolution
6 nanoseconds/meter,
histogram channel width
100 nanoseconds.

Au197 capture cross section ABBN-78 group №17, energy interval 100 – 215 eV

Energy resolution factor 6 nsec/meter

Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX

Red line: ENDF/B-VII.1 BNL Au197 capture cross section data [4]

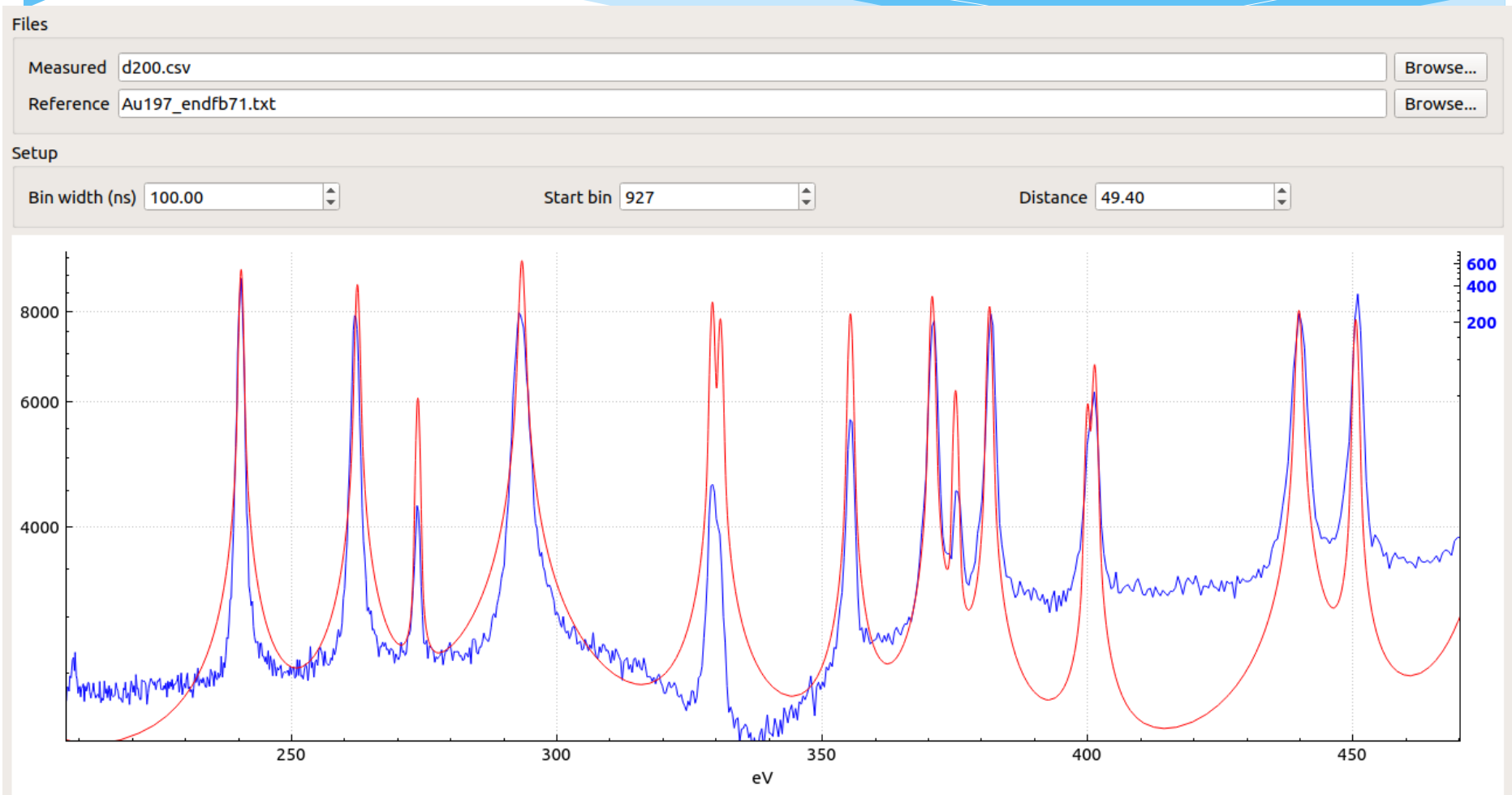


Au197 capture cross section ABBN-78 group №16, energy interval 215 – 465 eV

Energy resolution factor 6 nsec/meter

Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX

Red line: ENDF/B-VII.1 BNL Au197 capture cross section data [4]

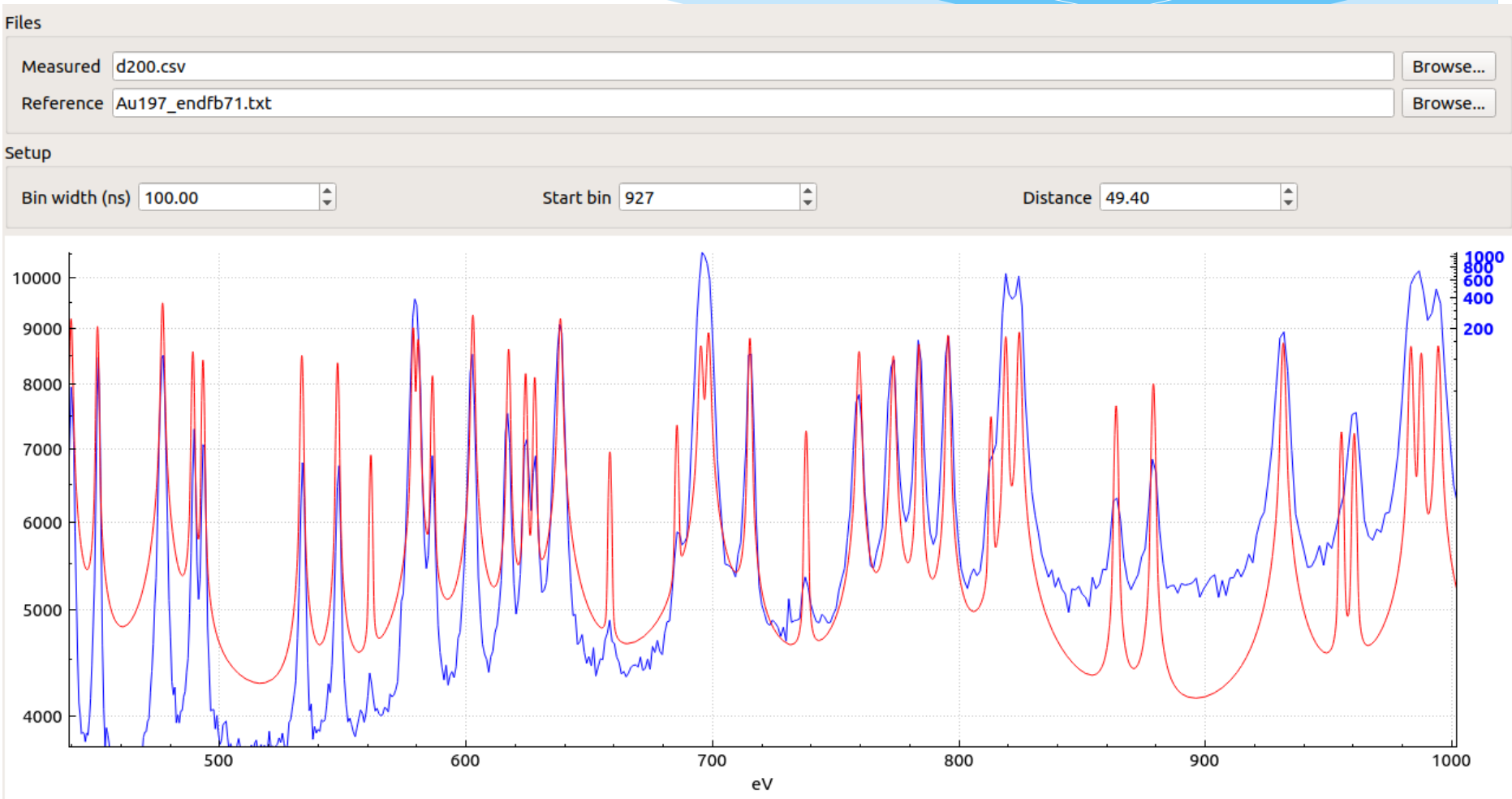


Au197 capture cross section ABBN-78 group №15, energy interval 465 – 1000 eV

Energy resolution factor 6 nsec/meter

Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX

Red line: ENDF/B-VII.1 BNL Au197 capture cross section data [4]

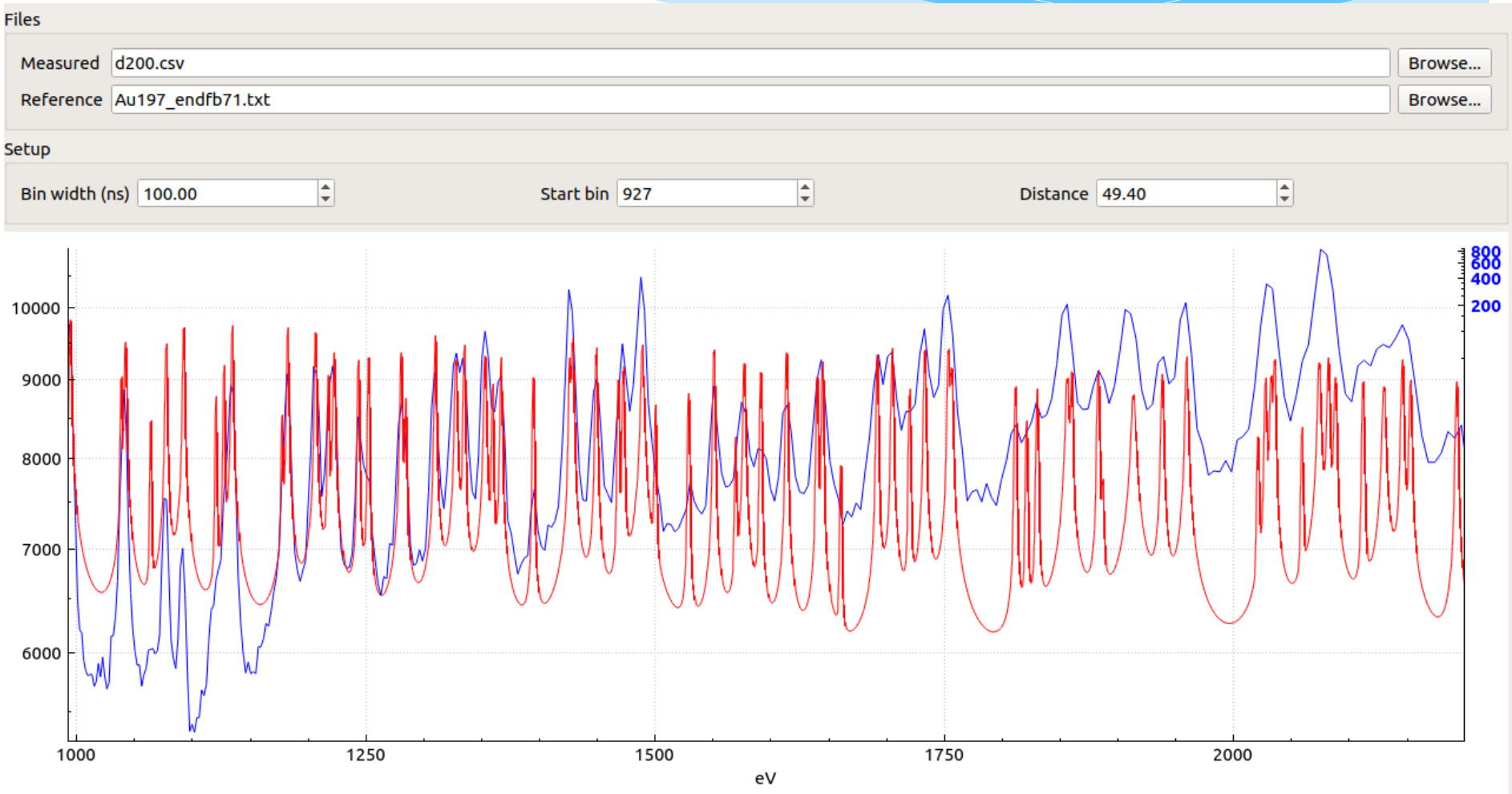


Au197 capture cross section ABBN-78 group №14, energy interval 1.0 – 2.15 keV

Energy resolution factor 6 nsec/meter

Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX

Red line: ENDF/B-VII.1 BNL Au197 capture cross section data [4]

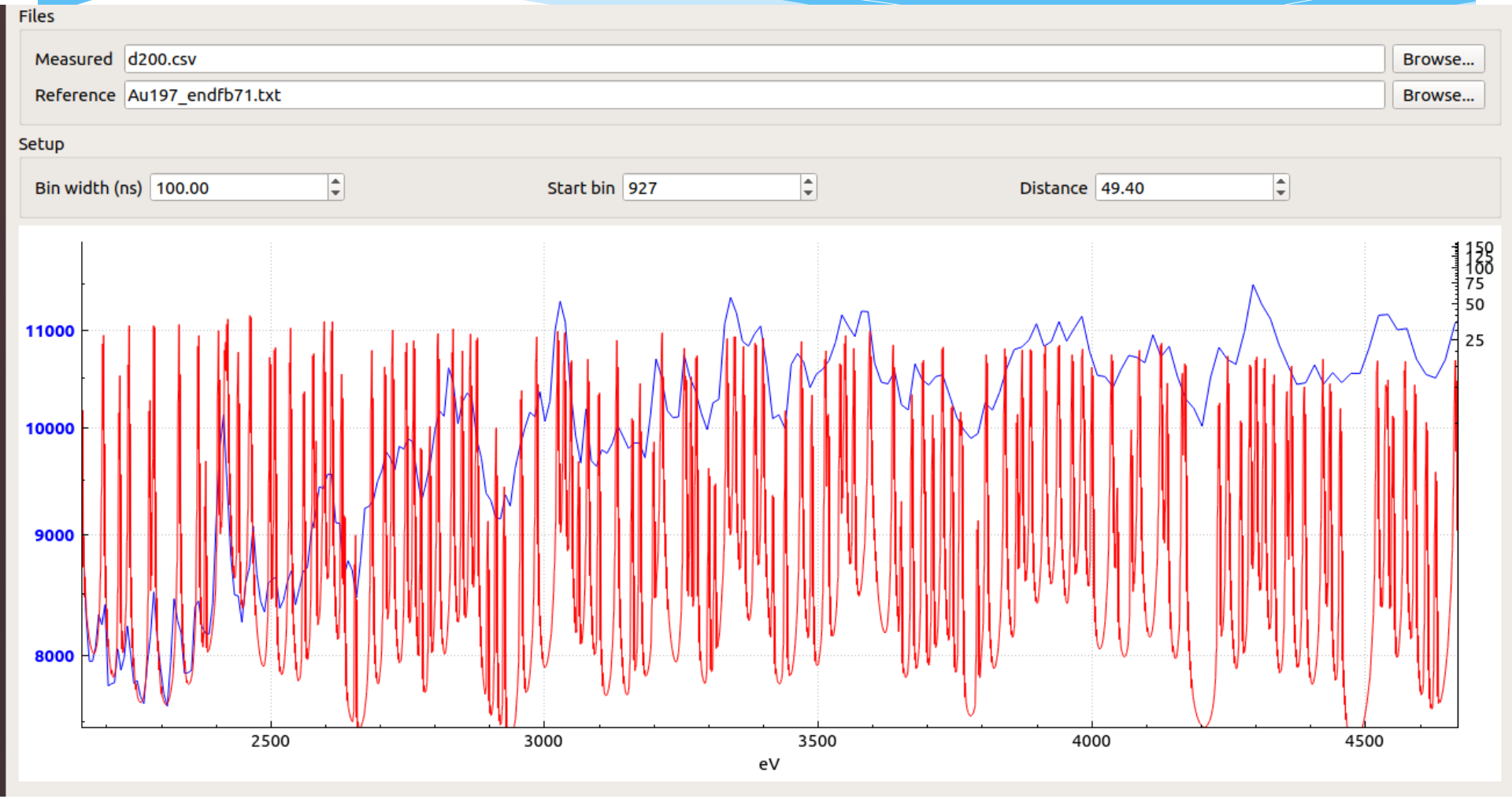


Au197 capture cross section ABBN-78 group №13, energy interval 2.15 – 4.65 keV

Energy resolution factor 6 nsec/meter

Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX

Red line: ENDF/B-VII.1 BNL Au197 capture cross section data [4]



Important idea:
Value delta(E) is in proportion E^(3/2)
while in the case of group cross sections, width of each group grows with increasing of neutron energy.
Value delta(E)/E is in proportion E^(1/2)
Thus, using one and the same TOF spectrometer, we can measure group cross sections much higher than we observe resonance structure.

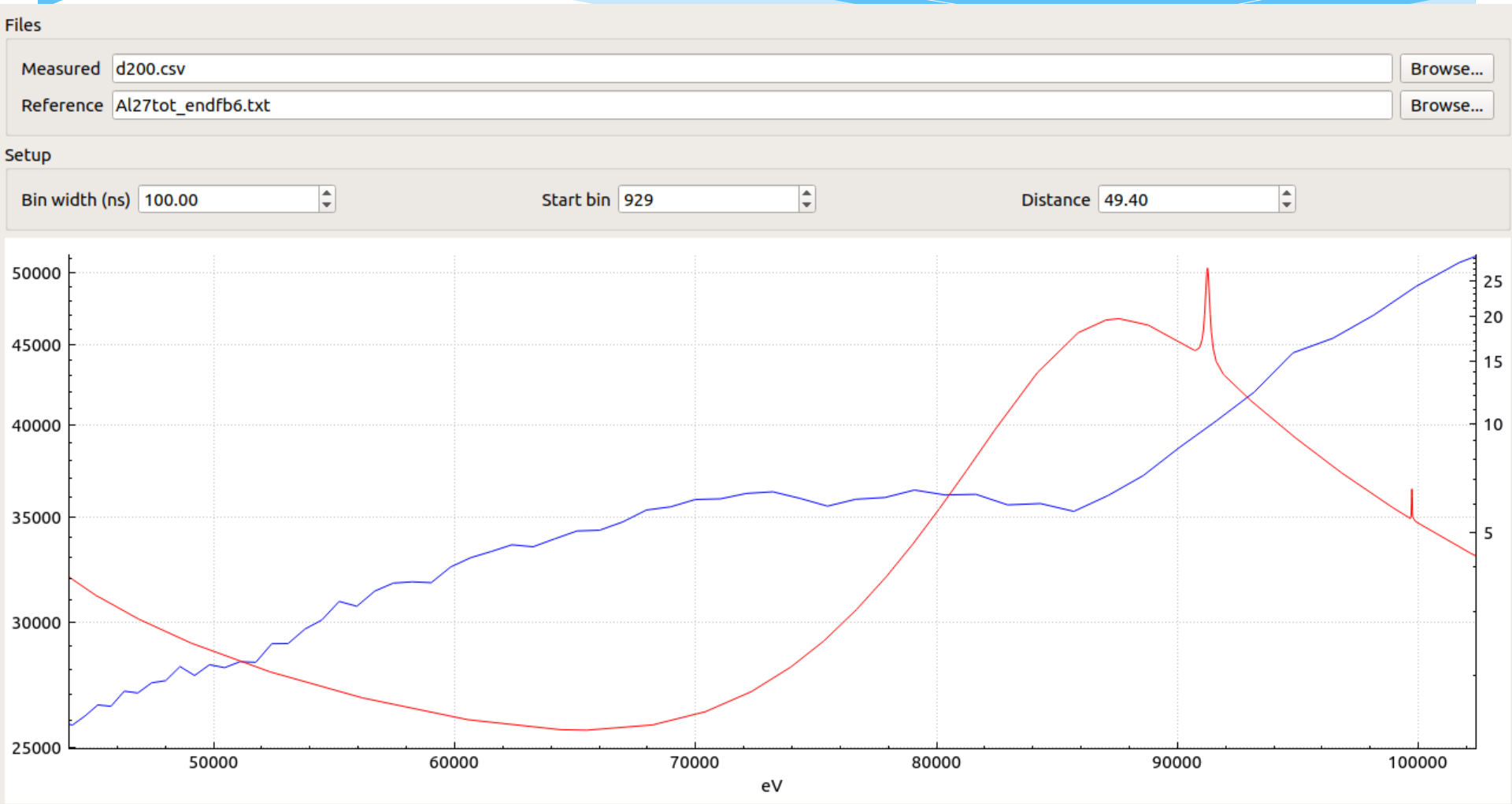
Au197 capture cross section ABBN-78 group №12, energy interval 4.65 – 10 keV

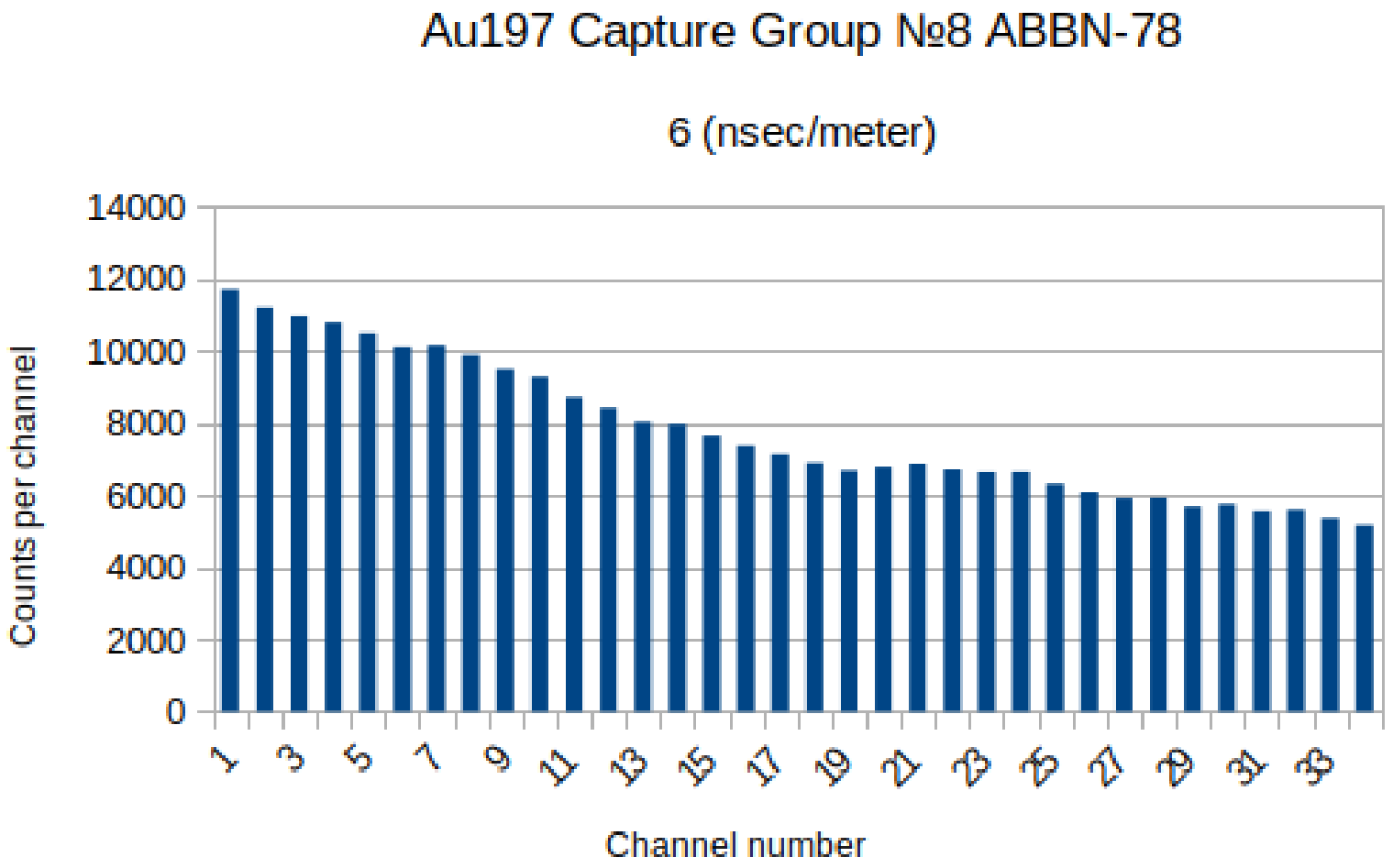
Energy resolution factor 6 nsec/meter

Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX

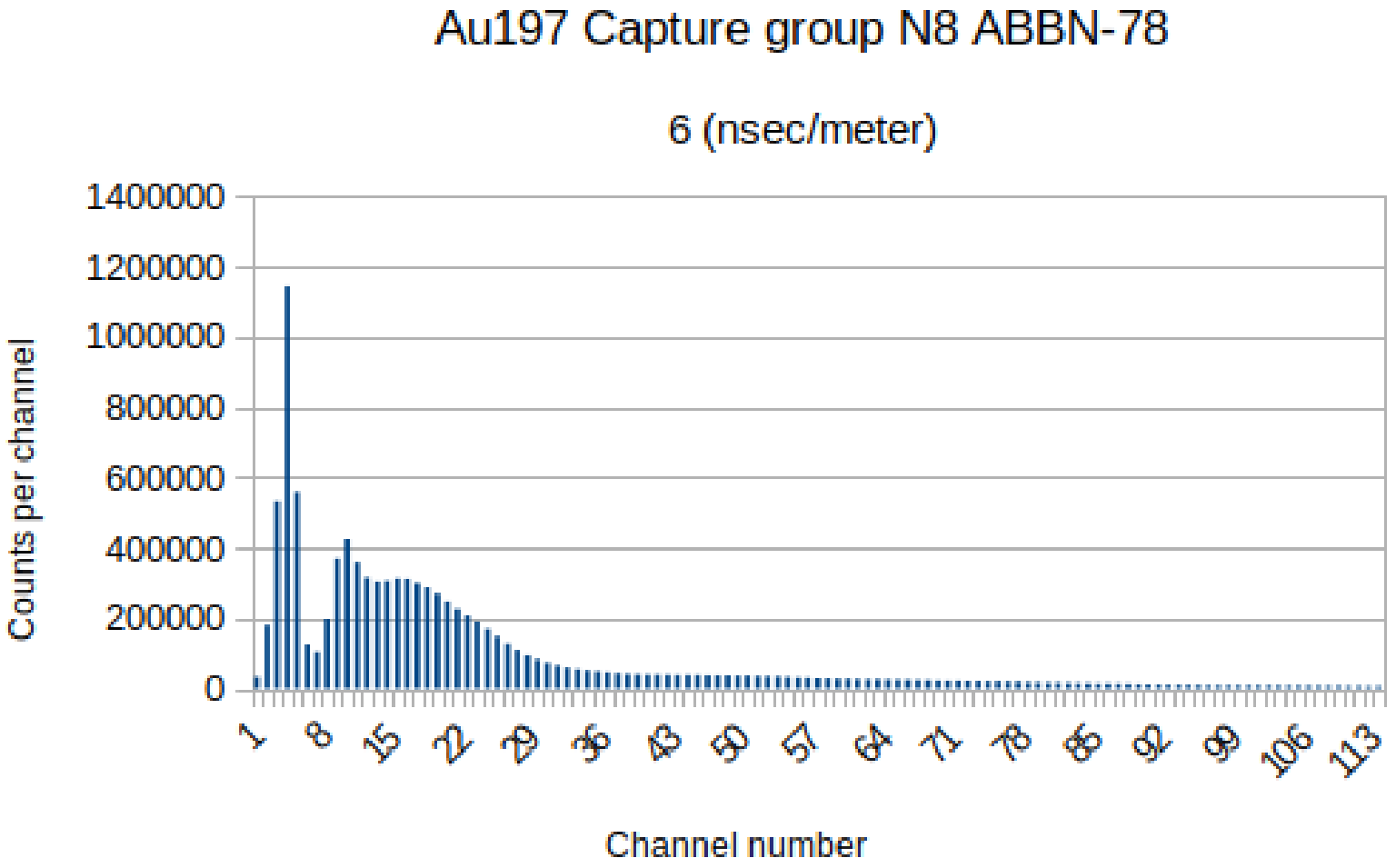
Red line: ENDF/B-VII.1 BNL Au197 capture cross section data [4]

Au197 capture cross section, in the area of unresolved resonances, ABBN-78 group №9, energy interval 46.5 – 100 keV. Energy resolution factor 6 nsec/meter.
Blue line: measured at 50 meter TOF base, installation INES of pulsed spallation neutron source RADEX. Red line: ENDF/B-VII.1 BNL Al27 total cross section data [4].
Neutron beam filter's (Al27) total cross section resonance at 0.087 Mev is observed.





Beam filter's, Al27 total cross section, resonance at 140 keV is observed in the histogram channel number 19. Ability to observe it allows to delete the background in the Au197 capture cross section measurement, even in the high energy ABBN-78 groups where Au197 resonances are not resolved or even physically interferers due to Doppler effect.



Number of the ABBN-78 group	'-1'	'0'	'1'	'2'	'3'	'4'	'5'	'6'	'7'	'8'
Numbers of channels on histogram	10	11	12, 13, 14	15,16 17,18	19,20 21,22 23	№24 - №30	№31 - №40	№41 - №56	№57 - №80	№81 - №113

Projected 500 meter TOF base for the experimental facility INES of the INR RAS spallation neutron source RADEX

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Group № on pictures	Group ABBN 78	Upper energy border	Low energy border	Tau of neutron mksec	Channel № at low border	Channels per group	ΔE, eV	(ΔE)/ E(Low)	ΔE/ (Group Width)
1	-1	14,5 MeV	14 MeV	9,55	191,09	3,32	366682	0,02616	0,773
2	0	14 MeV	10,5 MeV	11,03	220,65	29,56	238167	0,02265	0,1047
3	1	10,5 MeV	6,5 MeV	14,02	280,44	59,79	116002	0,01782	0,0595
4	2	6,5 MeV	4 MeV	17,87	357,50	77,05	56000	0,01398	0,0464
5	3	4 MeV	2,5 MeV	22,61	452,2	94,70	27669	0,01105	0,0373
6	4	2,5 MeV	1,4 MeV	30,21	604,28	152,0	11595	0,008274	0,0251
7	5	1,4 MeV	0,8 MeV	39,96	799,39	195,1	5008	0,006254	0,0193
8	6	0,8 MeV	0,4 MeV	56,52	1130,5	331,1	1770	0,004422	0,0125
9	7	0,4 MeV	0,2 MeV	79,94	1598,7	468,2	626	0,00312	0,000885
10	8	0,2 MeV	0,1 MeV	113,05	2261,0	662,2	221	0,00221	0,00626
11	9	0,1 MeV	46,5 keV	165,78	3315,7	1054	70	0,00150	0,00413
12	10	46,5 keV	21,5 keV	243,81	4876,2	1560	22	0,00102	0,0028
13	11	21,5 keV	10 keV	357,50	7150,0	2273	7,0	0,000699	0,0019
14	12	10 keV	4,65 keV	524,26	10485,2	3335	2,2	0,00047	0,0013
15	13	4,65 keV	2,15 keV	771,0	15420	4934	0,69	0,000324	0,00088
16	14	2,15 keV	1 keV	1130,5	22610	7190	0,2213	0,000221	0,00060
17	15	1 keV	465 eV	1657,8	33157	10547	0,0701	0,000150	0,00041
18	16	465 eV	215 eV	2438,1	48762	15605	0,0220	0,000102	0,00028
19	17	215 eV	100 eV	3575,0	71500	22737	0,0070	0,0000699	0,00019
20	18	100 eV	46,5 eV	5242,6	104852	33352	0,00221	0,0000476	0,00013
21	19	46,5 eV	21,5 eV	7710,0	154200	49348	0,00069	0,0000324	0,000088
22	20	21,5 eV	10 eV	11305,1	226102	71901	0,000221	0,0000221	0,000060
23	21	10 eV	4,65 eV	16578,6	331573	105470	0,000070	0,0000150	0,0000413
24	22	4,65 eV	2,15 eV	24381,2	487625	156052	0,000022	0,0000102	0,0000280
25	23	2,15 eV	1 eV	35750	715000	227374	0,000007	0,0000069	0,0000191
26	24	1 eV	0,465 eV	52426	1048526	333526	0,000002	0,0000047	0,0000130
27	25	0,465 eV	0,215 eV	77100	1542008	493481	0,0000007	0,0000032	0,0000088
28	T	0,0253 eV	0,0253 eV	224758	4495166	2953157	-------	---------	0,0000036

Performance of group cross sections measurements on projected TOF base L = 500 meters, with tau = 125 nanoseconds. Energy resolution 0.25 nanoseconds/meter, histogram channel width 50 nanoseconds.

The same results for the 299 groups of the ABBN-93 energy interval standards

Performance of group cross sections measurements
on projected TOF base:
L = 500 meters, with
tau = 125 nanoseconds,
histogram channel width 50 nanoseconds
Energy resolution 0.25 nanoseconds/meter.

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
1	20000000	18618200	7,99394302	159,8788604	5,8267436	626099,0337	0,453103947
2	18618200	17331800	8,2852802	165,705604	6,0394375	562347,2516	0,43714805
3	17331800	16134300	8,587252076	171,7450415	6,259457	505083,921	0,42178198
4	16134300	15019500	8,900224924	178,0044985	6,4878266	453652,42	0,40693615
5	15019500	13981800	9,224616257	184,4923251	6,7237938	407456,5024	0,392653467
6	13981800	13015800	9,560805946	191,2161189	6,9688024	365967,6257	0,378848474
7	13015800	12116500	9,909246065	198,1849213	7,2231233	328703,5087	0,365510407
8	12116500	11279300	10,27040223	205,4080446	7,4867132	295232,266	0,352642458
9	11279300	10500000	10,64473789	212,8947578	7,7590326	265168,0909	0,340264456
10	10500000	9693420	11,03268952	220,6537904	8,996779	238167,2207	0,295280345
11	9693420	8948790	11,48252847	229,6505694	9,3637296	211258,2051	0,283708963
12	8948790	8261360	11,95071495	239,014299	9,7455406	187389,1818	0,272593838
13	8261360	7626740	12,43799198	248,7598396	10,1428554	166216,97	0,261915745
14	7626740	7040870	12,94513475	258,902695	10,55642	147436,9887	0,251654785
15	7040870	6500000	13,47295575	269,459115	10,9869582	130778,8544	0,241793508
16	6500000	5994750	14,02230366	280,4460732	11,5792434	116002,6939	0,229594644
17	5994750	5528770	14,60126583	292,0253166	12,0574306	102743,5706	0,220489228
18	5528770	5099020	15,20413736	304,0827472	12,5549978	90999,88115	0,211750742
19	5099020	4702670	15,83188725	316,637745	13,0735232	80598,71413	0,203352376
20	4702670	4337130	16,48556341	329,7112682	13,6132522	71386,28741	0,195289948
21	4337130	4000000	17,16622602	343,3245204	14,1754796	63226,87245	0,187544486
22	4000000	3698620	17,875	357,5	14,2801386	56000	0,185811932
23	3698620	3419950	18,58900693	371,7801386	14,8504078	49791,77525	0,178676482
24	3419950	3162280	19,33152732	386,6305464	15,4433524	44271,85047	0,171816084
25	3162280	2924020	20,10369494	402,0738988	16,060476	39363,93645	0,165214205
26	2924020	2703710	20,90671874	418,1343748	16,702122	35000,04061	0,158867235
27	2703710	2500000	21,74182484	434,8364968	17,3692086	31119,90059	0,152765699
28	2500000	2325220	22,61028527	452,2057054	16,6875834	27669,92952	0,158312905
29	2325220	2162650	23,44466444	468,8932888	17,3044358	24819,56209	0,152670001
30	2162650	2011460	24,30988623	486,1977246	17,9413286	22262,67772	0,147249671

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
31	2011460	1870830	25,20695266	504,1390532	18,6047332	19969,40573	0,141999614
32	1870830	1740030	26,13718932	522,7437864	19,291642	17912,22469	0,136943614
33	1740030	1618380	27,10177142	542,0354284	20,002715	16066,93897	0,132075125
34	1618380	1505240	28,10190717	562,0381434	20,7398802	14411,81884	0,127380403
35	1505240	1400000	29,13890118	582,7780236	21,5072688	12927,26542	0,122836045
36	1400000	1305410	30,21426462	604,2852924	21,5104068	11595,51638	0,122587127
37	1305410	1217220	31,28978496	625,7956992	22,2736802	10440,43137	0,11838566
38	1217220	1134980	32,40346897	648,0693794	23,0687874	9400,515273	0,114305876
39	1134980	1058300	33,55690834	671,1381668	23,8887814	8464,091566	0,110381998
40	1058300	986800	34,75134741	695,0269482	24,7392898	7620,987236	0,106587234
41	986800	920131	35,9883119	719,766238	25,619726	6861,858392	0,102924274
42	920131	857965	37,2692982	745,385964	26,5321922	6178,350382	0,099384718
43	857965	800000	38,59590781	771,9181562	27,4761458	5562,914657	0,095970235
44	800000	740700	39,9697151	799,394302	31,3834724	5008,79227	0,0844653
45	740700	685795	41,53888872	830,7777744	32,615944	4462,328693	0,081273631
46	685795	634960	43,16968592	863,3937184	33,8963446	3975,479439	0,078203589
47	634960	587894	44,86450315	897,290063	35,2264432	3541,747459	0,075250658
48	587894	544316	46,62582531	932,5165062	36,6100438	3155,343042	0,072406789
49	544316	503968	48,4563275	969,12655	38,047578	2811,089615	0,069671102
50	503968	466612	50,35870639	1007,174128	39,54001	2504,393005	0,067041252
51	466612	432024	52,33570688	1046,714138	41,093503	2231,166062	0,064506941
52	432024	400000	54,39038205	1087,807641	42,706622	1987,74125	0,062070361
53	400000	370350	56,52571317	1130,514263	44,382933	1770,87549	0,059725986
54	370350	342898	58,7448598	1174,897196	46,12502	1577,671439	0,057470182
55	342898	317480	61,05111079	1221,022216	47,937561	1405,547309	0,055297321
56	317480	293947	63,44798884	1268,959777	49,817714	1252,196823	0,05321025
57	293947	272158	65,93887454	1318,777491	51,77442	1115,582231	0,051199331
58	272158	251984	68,52759555	1370,551911	53,8074	993,8702645	0,049264909
59	251984	233306	71,21796554	1424,359311	55,918018	885,4366381	0,047405324
60	233306	216012	74,01386647	1480,277329	58,11409	788,836226	0,045613295

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
61	216012	200000	76,91961594	1538,392319	60,396285	702,7726586	0,043890373
62	200000	185175	79,9394302	1598,788604	62,766945	626,0990337	0,04223265
63	185175	171449	83,07777743	1661,555549	65,230628	557,7910865	0,040637555
64	171449	158740	86,33930887	1726,786177	67,793948	496,9360168	0,039101111
65	158740	146973	89,72900627	1794,580125	70,45606	442,7184323	0,03762373
66	146973	136079	93,25180924	1865,036185	73,216915	394,4158676	0,036204871
67	136079	125992	96,912655	1938,2531	76,095156	351,3862019	0,034835551
68	125992	116653	100,7174128	2014,348256	79,08002	313,0491256	0,033520626
69	116653	108006	104,6714138	2093,428276	82,187006	278,8957577	0,03225347
70	108006	100000	108,7807641	2175,615282	85,413244	248,4676563	0,031035181
71	100000	93804,2	113,0514263	2261,028526	73,476966	221,3594362	0,035727337
72	93804,2	87992,3	116,7252746	2334,505492	75,864472	201,1089812	0,034602967
73	87992,3	82540,4	120,5184982	2410,369964	78,331236	182,7111474	0,033513298
74	82540,4	77426,4	124,43506	2488,7012	80,875044	165,9961035	0,032459152
75	77426,4	72629,2	128,4788122	2569,576244	83,504158	150,810521	0,031437197
76	72629,2	68129,2	132,6540201	2653,080402	86,218334	137,0139954	0,030447555
77	68129,2	63908	136,9649368	2739,298736	89,02051	124,4795397	0,029489136
78	63908	59948,4	141,4159623	2828,319246	91,912	113,0917384	0,028561405
79	59948,4	56234,1	146,0115623	2920,231246	94,899626	102,7458844	0,027662247
80	56234,1	52750	150,7565436	3015,130872	97,98159	93,34641925	0,026792118
81	52750	49481,7	155,6556231	3113,112462	101,16776	84,80700693	0,025948354
82	49481,7	46415,9	160,7140111	3214,280222	104,455376	77,04863656	0,025131658
83	46415,9	43540	165,9367799	3318,735598	107,851928	70,00002639	0,024340216
84	43540	40842,4	171,3293763	3426,587526	111,352076	63,59612834	0,023575077
85	40842,4	38311,9	176,8969801	3537,939602	114,972286	57,7783216	0,022832769
86	38311,9	35938,1	182,6455944	3652,911888	118,712936	52,49265938	0,022113345
87	35938,1	33711,5	188,5812412	3771,624824	122,563976	47,6903719	0,021418473
88	33711,5	31622,8	194,70944	3894,1888	126,550188	43,32765211	0,020743837
89	31622,8	29663,5	201,0369494	4020,738988	130,663542	39,36393646	0,020090816
90	29663,5	27825,6	207,5701265	4151,40253	134,9094	35,7628094	0,019458518

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
91	27825,6	26101,6	214,3155965	4286,31193	139,291314	32,4911322	0,018846364
92	26101,6	24484,4	221,2801622	4425,603244	143,819182	29,51880247	0,018253031
93	24484,4	22967,4	228,4711213	4569,422426	148,492708	26,81836139	0,017678551
94	22967,4	21544,3	235,8957567	4717,915134	153,328462	24,36496499	0,017121049
95	21544,3	20209,5	243,5621798	4871,243596	158,296298	22,13587134	0,016583661
96	20209,5	18957,4	251,4769947	5029,539894	163,440164	20,11089476	0,016061732
97	18957,4	17782,8	259,6490029	5192,980058	168,76265	18,27116338	0,015555222
98	17782,8	16681	268,0871354	5361,742708	174,243514	16,59962419	0,015065914
99	16681	15647,5	276,7993111	5535,986222	179,899822	15,08103554	0,014592197
100	15647,5	14678	285,7943022	5715,886044	185,75241	13,70141687	0,014132457
101	14678	13768,6	295,0819227	5901,638454	191,782056	12,44796519	0,013688108
102	13768,6	12915,5	304,6710255	6093,42051	198,02486	11,30922163	0,013256619
103	12915,5	12115,3	314,5722685	6291,44537	204,449018	10,27459888	0,012840039
104	12115,3	11364,6	324,7947194	6495,894388	211,11578	9,334677086	0,01243463
105	11364,6	10660,5	335,3505084	6707,010168	217,949602	8,480652565	0,012044671
106	10660,5	10000	346,2479885	6924,95977	225,04023	7,704853779	0,011665184
107	10000	9380,42	357,5	7150	232,354566	7	0,011297976
108	9380,42	8799,23	369,1177283	7382,354566	239,904528	6,359624386	0,010942419
109	8799,23	8254,04	381,1129547	7622,259094	247,705116	5,777833792	0,010597835
110	8254,04	7742,64	393,4982105	7869,96421	255,749336	5,249257698	0,010264485
111	7742,64	7262,92	406,2856773	8125,713546	264,063342	4,769047415	0,009941315
112	7262,92	6812,92	419,4888444	8389,776888	272,64631	4,332762967	0,009628362
113	6812,92	6390,8	433,1211599	8662,423198	281,507562	3,936388677	0,009325284
114	6390,8	5994,84	447,196538	8943,93076	290,651276	3,576274778	0,009031909
115	5994,84	5623,41	461,7291018	9234,582036	300,098962	3,249110148	0,008747571
116	5623,41	5275	476,7340499	9534,680998	309,84499	2,951872963	0,008472412
117	5275	4948,17	492,2262994	9844,525988	319,920552	2,681833034	0,00820559
118	4948,17	4641,59	508,2223268	10164,44654	330,3169	2,436491821	0,007947328
119	4641,59	4354	524,7381722	10494,76344	341,05774	2,213595197	0,007697052
120	4354	4084,24	541,7910591	10835,82118	352,12619	2,011086159	0,007455094

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
121	4084,24	3831,19	559,3973685	11187,94737	363,57428	1,827110955	0,007220355
122	3831,19	3593,81	577,5760827	11551,52165	375,40327	1,659963642	0,006992854
123	3593,81	3371,15	596,3462462	11926,92492	387,58133	1,508101976	0,006773116
124	3371,15	3162,28	615,7253123	12314,50625	400,18683	1,370140663	0,006559777
125	3162,28	2966,35	635,7346538	12714,69308	413,1944	1,244796968	0,006353274
126	2966,35	2782,56	656,394374	13127,88748	426,62098	1,130919333	0,006153324
127	2782,56	2610,16	677,725423	13554,50846	440,47782	1,027459818	0,005959744
128	2610,16	2448,44	699,7493138	13994,98628	454,79618	0,933466496	0,005772115
129	2448,44	2296,74	722,4891231	14449,78246	469,57518	0,848071051	0,005590449
130	2296,74	2154,43	745,9678819	14919,35764	484,86716	0,770487844	0,005414151
131	2154,43	2020,95	770,21124	15404,2248	500,57685	0,699997714	0,005244214
132	2020,95	1895,74	795,2400824	15904,80165	516,84318	0,635962332	0,005079166
133	1895,74	1778,28	821,0822416	16421,64483	533,67435	0,577784917	0,004918993
134	1778,28	1668,1	847,765959	16955,31918	551,00638	0,524926208	0,00476426
135	1668,1	1564,75	875,3162779	17506,32556	568,89318	0,476904218	0,004614458
136	1564,75	1467,8	903,760937	18075,21874	587,4007	0,433276845	0,004469075
137	1467,8	1376,86	933,130972	18662,61944	606,46813	0,393639222	0,00432856
138	1376,86	1291,55	963,4543783	19269,08757	626,20957	0,357628989	0,004192111
139	1291,55	1211,53	994,7648572	19895,29714	646,52456	0,324911345	0,004060377
140	1211,53	1136,46	1027,091085	20541,8217	667,60672	0,295188408	0,003932175
141	1136,46	1066,05	1060,471421	21209,42842	689,21714	0,268181782	0,003808859
142	1066,05	1000	1094,932278	21898,64556	711,6397	0,24364887	0,003688855
143	1000	938,042	1130,514263	22610,28526	734,76966	0,221359436	0,003572734
144	938,042	879,923	1167,252746	23345,05492	758,64472	0,201108981	0,003460297
145	879,923	825,404	1205,184982	24103,69964	783,31236	0,182711147	0,00335133
146	825,404	774,264	1244,3506	24887,012	808,75044	0,165996104	0,003245915
147	774,264	726,292	1284,788122	25695,76244	835,04158	0,150810521	0,00314372
148	726,292	681,292	1326,540201	26530,80402	862,18334	0,137013995	0,003044755
149	681,292	639,08	1369,649368	27392,98736	890,20508	0,12447954	0,002948914

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
151	599,484	562,341	1460,115623	29202,31246	948,99626	0,102745884	0,002766225
152	562,341	527,5	1507,565436	30151,30872	979,81588	0,093346419	0,002679212
153	527,5	494,817	1556,55623	31131,1246	1011,67762	0,084807007	0,002594835
154	494,817	464,159	1607,140111	32142,80222	1044,55376	0,077048637	0,002513166
155	464,159	435,4	1659,367799	33187,35598	1078,51926	0,070000026	0,002434022
156	435,4	408,424	1713,293762	34265,87524	1113,52078	0,063596128	0,002357508
157	408,424	383,119	1768,969801	35379,39602	1149,72286	0,057778322	0,002283277
158	383,119	359,381	1826,455944	36529,11888	1187,12936	0,052492659	0,002211335
159	359,381	337,115	1885,812412	37716,24824	1225,63976	0,047690372	0,002141847
160	337,115	316,228	1947,0944	38941,888	1265,50188	0,043327652	0,002074384
161	316,228	296,635	2010,369494	40207,38988	1306,63542	0,039363936	0,002009082
162	296,635	278,256	2075,701265	41514,0253	1349,094	0,035762809	0,001945852
163	278,256	261,016	2143,155965	42863,1193	1392,91314	0,032491132	0,001884636
164	261,016	244,844	2212,801622	44256,03244	1438,19182	0,029518802	0,001825303
165	244,844	229,674	2284,711213	45694,22426	1484,92708	0,026818361	0,001767855
166	229,674	215,443	2358,957567	47179,15134	1533,28462	0,024364965	0,001712105
167	215,443	202,095	2435,621798	48712,43596	1582,96298	0,022135871	0,001658366
168	202,095	189,574	2514,769947	50295,39894	1634,40164	0,020110895	0,001606173
169	189,574	177,828	2596,490029	51929,80058	1687,6265	0,018271163	0,001555522
170	177,828	166,81	2680,871354	53617,42708	1742,43514	0,016599624	0,001506591
171	166,81	156,475	2767,993111	55359,86222	1798,99822	0,015081036	0,00145922
172	156,475	146,78	2857,943022	57158,86044	1857,52408	0,013701417	0,001413246
173	146,78	137,686	2950,819226	59016,38452	1917,82058	0,012447965	0,001368811
174	137,686	129,155	3046,710255	60934,2051	1980,2486	0,011309222	0,001325662
175	129,155	121,153	3145,722685	62914,4537	2044,49018	0,010274599	0,001284004
176	121,153	113,646	3247,947194	64958,94388	2111,1578	0,009334677	0,001243463
177	113,646	106,605	3353,505084	67070,10168	2179,49602	0,008480653	0,001204467
178	106,605	100	3462,479885	69249,5977	2250,4023	0,007704854	0,001166518
179	100	93,8042	3575	71500	2323,54566	0,007	0,001129798

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
181	87,9923	82,5404	3811,129547	76222,59094	2477,05116	0,005777834	0,001059784
182	82,5404	77,4264	3934,982105	78699,6421	2557,49336	0,005249258	0,001026449
183	77,4264	72,6292	4062,856773	81257,13546	2640,63342	0,004769047	0,000994131
184	72,6292	68,1292	4194,888444	83897,76888	2726,4631	0,004332763	0,000962836
185	68,1292	63,908	4331,211599	86624,23198	2815,07562	0,003936389	0,000932528
186	63,908	59,9484	4471,96538	89439,3076	2906,51276	0,003576275	0,000903191
187	59,9484	56,2341	4617,291018	92345,82036	3000,98962	0,00324911	0,000874757
188	56,2341	52,75	4767,340499	95346,80998	3098,44994	0,002951873	0,000847241
189	52,75	49,4817	4922,262996	98445,25992	3199,20548	0,002681833	0,000820559
190	49,4817	46,4159	5082,223268	101644,4654	3303,169	0,002436492	0,000794733
191	46,4159	43,54	5247,381722	104947,6344	3410,5774	0,002213595	0,000769705
192	43,54	40,8424	5417,910591	108358,2118	3521,2619	0,002011086	0,000745509
193	40,8424	38,3119	5593,973685	111879,4737	3635,7428	0,001827111	0,000722036
194	38,3119	35,9381	5775,760827	115515,2165	3754,0327	0,001659964	0,000699285
195	35,9381	33,7115	5963,462462	119269,2492	3875,8133	0,001508102	0,000677312
196	33,7115	31,6228	6157,253123	123145,0625	4001,8683	0,001370141	0,000655978
197	31,6228	29,6635	6357,346538	127146,9308	4131,944	0,001244797	0,000635327
198	29,6635	27,8256	6563,94374	131278,8748	4266,2098	0,001130919	0,000615332
199	27,8256	26,1016	6777,25423	135545,0846	4404,7782	0,00102746	0,000595974
200	26,1016	24,4844	6997,493138	139949,8628	4547,9618	0,000933466	0,000577212
201	24,4844	22,9674	7224,891231	144497,8246	4695,7518	0,000848071	0,000559045
202	22,9674	21,5443	7459,678819	149193,5764	4848,6716	0,000770488	0,000541415
203	21,5443	20,2095	7702,1124	154042,248	5005,7685	0,000699998	0,000524421
204	20,2095	18,9574	7952,400824	159048,0165	5168,4318	0,000635962	0,000507917
205	18,9574	17,7828	8210,822416	164216,4483	5336,7435	0,000577785	0,000491899
206	17,7828	16,681	8477,65959	169553,1918	5510,0638	0,000524926	0,000476426
207	16,681	15,6475	8753,162779	175063,2556	5688,9318	0,000476904	0,000461446
208	15,6475	14,678	9037,60937	180752,1874	5874,007	0,000433277	0,000446908
209	14,678	13,7686	9331,30972	186626,1944	6064,6813	0,000393639	0,000432856

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
211	12,9155	12,1153	9947,648572	198952,9714	6465,2456	0,000324911	0,000406038
212	12,1153	11,3646	10270,91085	205418,217	6676,0672	0,000295188	0,000393218
213	11,3646	10,6605	10604,71421	212094,2842	6892,1714	0,000268182	0,000380886
214	10,6605	10	10949,32278	218986,4556	7116,397	0,000243649	0,000368885
215	10	9,38042	11305,14263	226102,8526	7347,6966	0,000221359	0,000357273
216	9,38042	8,79923	11672,52746	233450,5492	7586,4472	0,000201109	0,00034603
217	8,79923	8,25404	12051,84982	241036,9964	7833,1236	0,000182711	0,000335133
218	8,25404	7,74264	12443,506	248870,12	8087,5044	0,000165996	0,000324592
219	7,74264	7,26292	12847,88122	256957,6244	8350,4158	0,000150811	0,000314372
220	7,26292	6,81292	13265,40201	265308,0402	8621,8334	0,000137014	0,000304476
221	6,81292	6,3908	13696,49368	273929,8736	8902,0508	0,00012448	0,000294891
222	6,3908	5,99484	14141,59622	282831,9244	9191,2002	0,000113092	0,000285614
223	5,99484	5,62341	14601,15623	292023,1246	9489,9626	0,000102746	0,000276622
224	5,62341	5,275	15075,65436	301513,0872	9798,1588	9,33464E-05	0,000267921
225	5,275	4,94817	15565,5623	311311,246	10116,7762	8,4807E-05	0,000259484
226	4,94817	4,64159	16071,40111	321428,0222	10445,5376	7,70486E-05	0,000251317
227	4,64159	4,354	16593,67799	331873,5598	10785,1926	7E-05	0,000243402
228	4,354	4,08424	17132,93762	342658,7524	11135,2078	6,35961E-05	0,000235751
229	4,08424	3,83119	17689,69801	353793,9602	11497,2286	5,77783E-05	0,000228328
230	3,83119	3,59381	18264,55944	365291,1888	11871,2936	5,24927E-05	0,000221133
231	3,59381	3,37115	18858,12412	377162,4824	12256,3976	4,76904E-05	0,000214185
232	3,37115	3,16228	19470,944	389418,88	12655,0188	4,33277E-05	0,000207438
233	3,16228	2,96635	20103,69494	402073,8988	13066,3542	3,93639E-05	0,000200908
234	2,96635	2,78256	20757,01265	415140,253	13490,94	3,57628E-05	0,000194585
235	2,78256	2,61016	21431,55965	428631,193	13929,1314	3,24911E-05	0,000188464
236	2,61016	2,44844	22128,01622	442560,3244	14381,9182	2,95188E-05	0,00018253
237	2,44844	2,29674	22847,11213	456942,2426	14849,2708	2,68184E-05	0,000176786
238	2,29674	2,15443	23589,57567	471791,5134	15332,8462	2,4365E-05	0,00017121
239	2,15443	2,02095	24356,21798	487124,3596	15829,6298	2,21359E-05	0,000165837
240	2,02095	1,89574	25147,69947	502953,9894	16344,0164	2,01109E-05	0,000160617

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
242	1,77828	1,6681	26808,71354	536174,2708	17424,3514	1,65996E-05	0,000150659
243	1,6681	1,56475	27679,93111	553598,6222	18575,2408	1,5081E-05	0,000145922
244	1,56475	1,4678	28579,43022	571588,6044	19178,2058	1,37014E-05	0,000141325
245	1,4678	1,37686	29508,19226	590163,8452	19802,486	1,2448E-05	0,000136881
246	1,37686	1,29155	30467,10255	609342,051	20444,9018	1,13092E-05	0,000132566
247	1,29155	1,21153	31457,22685	629144,537	21111,578	1,02746E-05	0,0001284
248	1,21153	1,13646	32479,47194	649589,4388	21794,9602	9,33468E-06	0,000124346
249	1,13646	1,06605	33535,05084	670701,0168	22504,023	8,48065E-06	0,000120447
250	1,06605	1	34624,79885	692495,977	23235,4566	7,70485E-06	0,000116652
251	1	0,938042	35750	715000	23990,4528	0,0000071	0,00011298
252	0,938042	0,879923	36911,77283	738235,4566	24770,5116	6,35962E-06	0,000109424
253	0,879923	0,825404	38111,29547	762225,9094	25574,9336	5,77783E-06	0,000105978
254	0,825404	0,774264	39349,82105	786996,421	26406,3342	5,24926E-06	0,000102645
255	0,774264	0,726292	40628,56773	812571,3546	27264,631	4,76905E-06	9,94131E-05
256	0,726292	0,681292	41948,88444	838977,6888	28150,7562	---	9,62836E-05
257	0,681292	0,63908	43312,11599	866242,3198	29065,1276	---	9,32528E-05
258	0,63908	0,599484	44719,6538	894393,076	30009,8962	---	9,03191E-05
259	0,599484	0,562341	46172,91018	923458,2036	30984,4994	---	8,74757E-05
260	0,562341	0,5275	47673,40499	953468,0998	31992,0548	---	8,47241E-05
261	0,5275	0,494817	49222,62996	984452,5992	33031,69	---	8,20559E-05
262	0,494817	0,464159	50822,23268	1016444,654	34105,774	---	7,94733E-05
263	0,464159	0,4354	52473,81722	1049476,344	35212,619	---	7,69705E-05
264	0,4354	0,408424	54179,10591	1083582,118	36357,428	---	7,45509E-05
265	0,408424	0,383119	55939,73685	1118794,737	37540,327	---	7,22036E-05
266	0,383119	0,359381	57757,60827	1155152,165	38758,133	---	6,99285E-05
267	0,359381	0,337115	59634,62462	1192692,492	40018,683	---	6,77312E-05
268	0,337115	0,316228	61572,53123	1231450,625	41319,44	---	6,55978E-05
269	0,316228	0,296635	63573,46538	1271469,308	42662,098	---	6,35327E-05
270	0,296635	0,278256	65639,4374	1312788,748	44047,782	---	6,15332E-05

Group №	Upper Energy, eV	Low Energy, eV	Tau, mksek	Number of 50ns Channel	Channels per group	(Delta E), eV	(Delta E)/ (Channel width)
271	0,278256	0,261016	67772,5423	1355450,846	45479,618	---	5,95974E-05
272	0,261016	0,244844	69974,93138	1399498,628	46957,518	---	5,77212E-05
273	0,244844	0,229674	72248,91231	1444978,246	48486,716	---	5,59045E-05
274	0,229674	0,215443	74596,78819	1491935,764	101742,003	---	5,41415E-05
275	0,215443	0,189574	77021,124	1540422,48	108468,073	---	2,70593E-05
276	0,189574	0,16681	82108,22416	1642164,483	115629,388	---	2,53815E-05
277	0,16681	0,14678	87531,62779	1750632,556	123267,77	---	2,38095E-05
278	0,14678	0,129155	93313,0972	1866261,944	131413,128	---	2,23341E-05
279	0,129155	0,113646	99476,48572	1989529,714	140085,684	---	2,09499E-05
280	0,113646	0,1	106047,1421	2120942,842	227672,674	---	1,96528E-05
281	0,1	0,0825404	113051,4263	2261028,526	250597,536	---	1,26784E-05
282	0,0825404	0,0681292	124435,06	2488701,2	275832,136	---	1,15185E-05
283	0,0681292	0,0562341	136964,9368	2739298,736	303604,726	---	1,04648E-05
284	0,0562341	0,0464159	150756,5436	3015130,872	334176,29	---	9,50749E-06
285	0,0464159	0,0383119	165936,7799	3318735,598	367827,1	---	8,63771E-06
286	0,0383119	0,0316228	182645,5944	3652911,888	404864,256	---	7,84749E-06
287	0,0316228	0,0261016	201036,9494	4020738,988	445640,352	---	7,1296E-06
288	0,0261016	0,0215443	221280,1622	4425603,244	490499,112	---	6,47726E-06
289	0,0215443	0,0177828	243562,1798	4871243,596	539895,744	---	5,88485E-06
290	0,0177828	0,014678	268087,1354	5361742,708	594255,936	---	5,34644E-06
291	0,014678	0,0121153	295081,9226	5901638,452	654105,612	---	4,85736E-06
292	0,0121153	0,01	324794,7194	6495894,388	1512423	---	4,41293E-06
293	0,01	0,00681292	357500	7150000	1832340,242	---	2,19637E-06
294	0,00681292	0,00464159	433121,1599	8662423,198	2219929	---	1,81289E-06
295	0,00464159	0,00316228	524738.1722	10494763	2689531,72	---	1,49637E-06
296	0,00316228	0,00215443	635734,6538	12714693,08	7206060,46	---	1,2351E-06
297	0,00215443	0,001	770211,2401	15404224,8	48889714,74	---	6,06358E-07
298	0,001	0,0001	1130514,263	22610285,26	-------	---	2,45955E-07

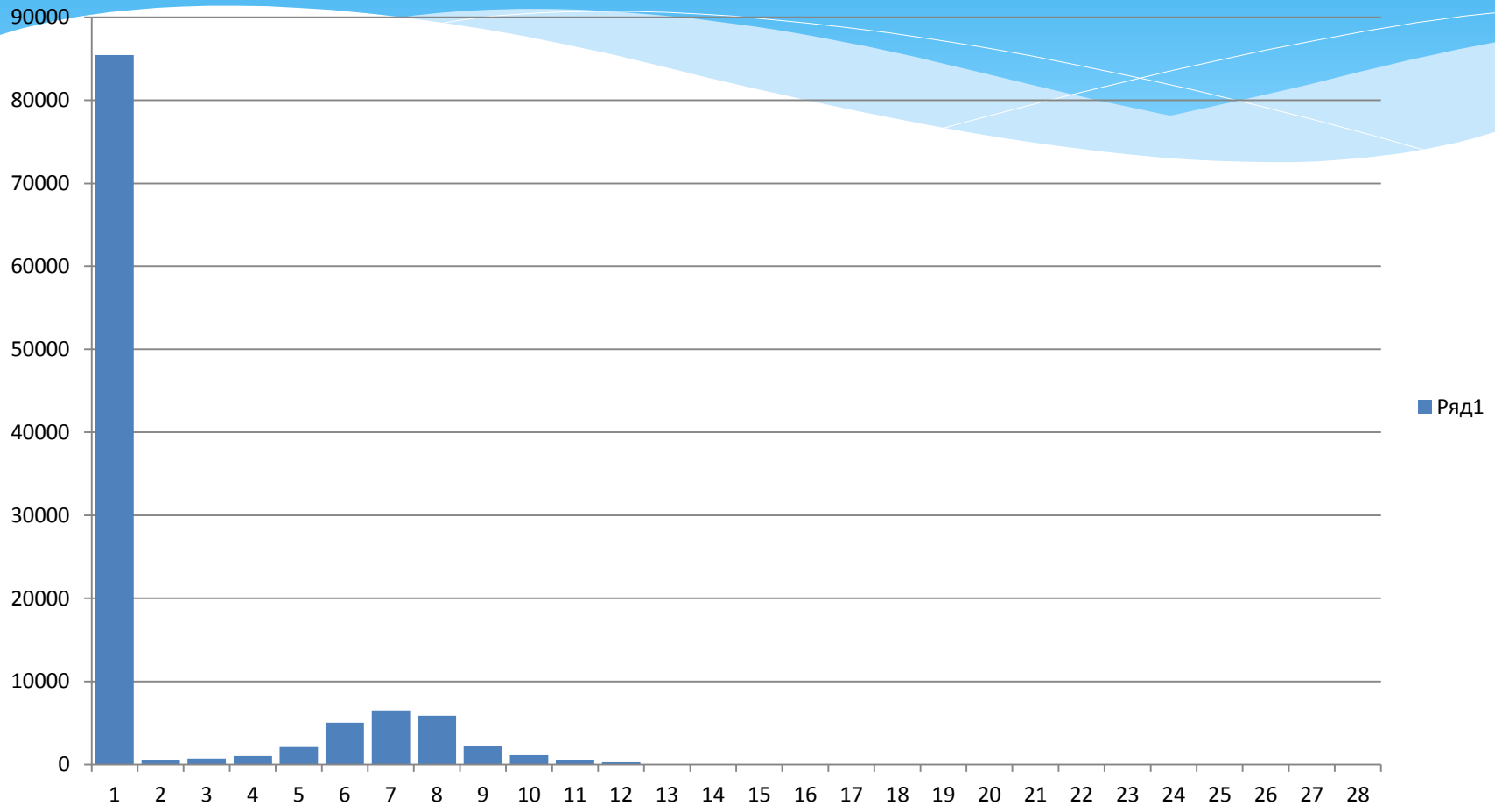
Energy borders on horizontal axis:

On pictures	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
ABBN-78	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26

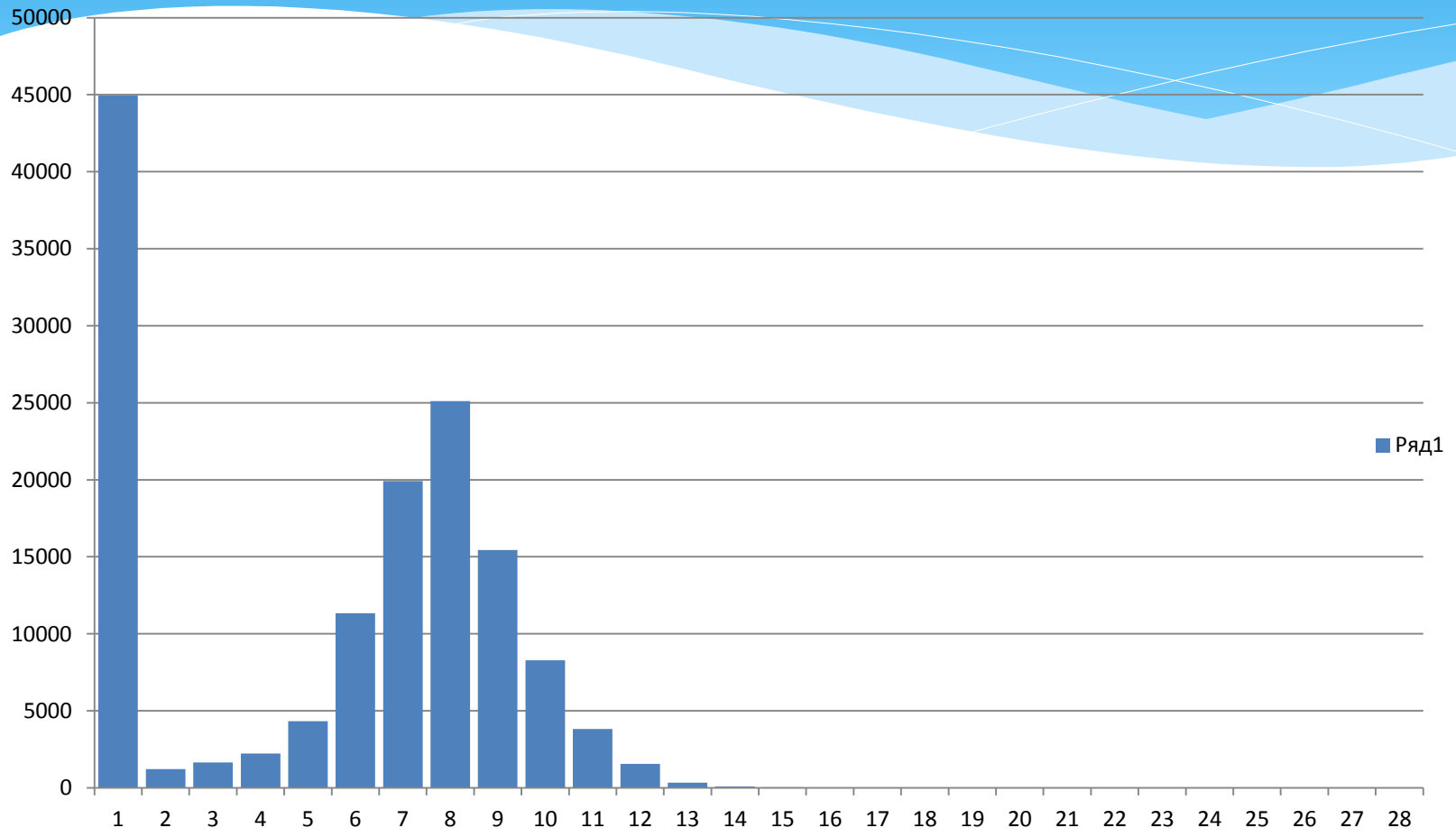
* Was also investigated the task:
  how long will be minimal duration of neutron flash of the proton accelerator's spallation target, if target's length is equal to the ionization free run of protons of given energy, in metal tungsten.
* During calibration of the model, spherical model was calculated.
* Description of the spherical calculation model:

in the center of tungsten metal sphere with radius R, in the moment t=0 were injected 100000 neutrons, energy En = 14 MeV.
Were calculated: neutron energy spectrum, average neutron energy and average diffusion time of the leaking neutron flux.

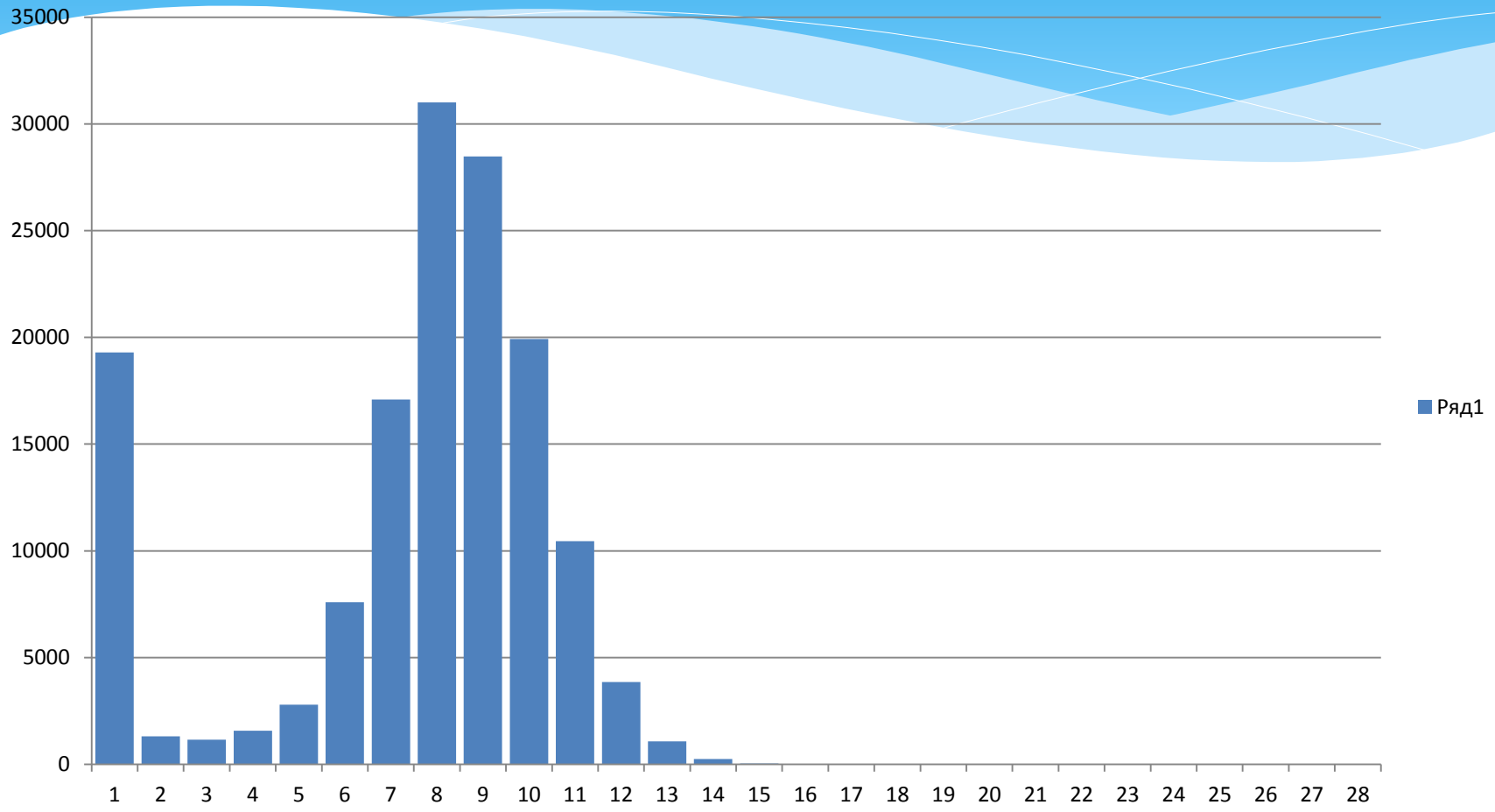
Tungsten sphere R = 1 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 0.36 nanoseconds



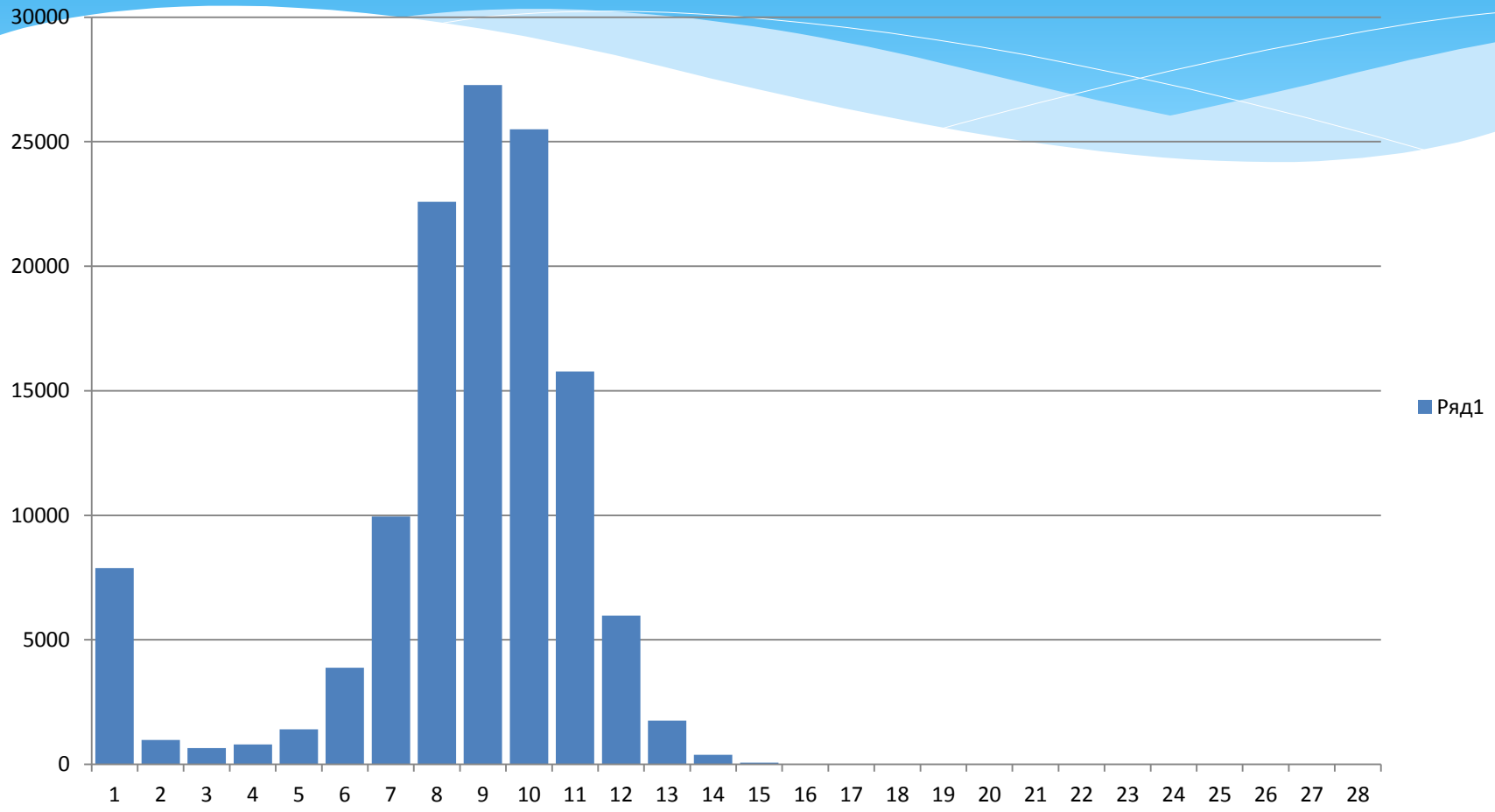
Tungsten sphere R = 5 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 5.96 nanoseconds



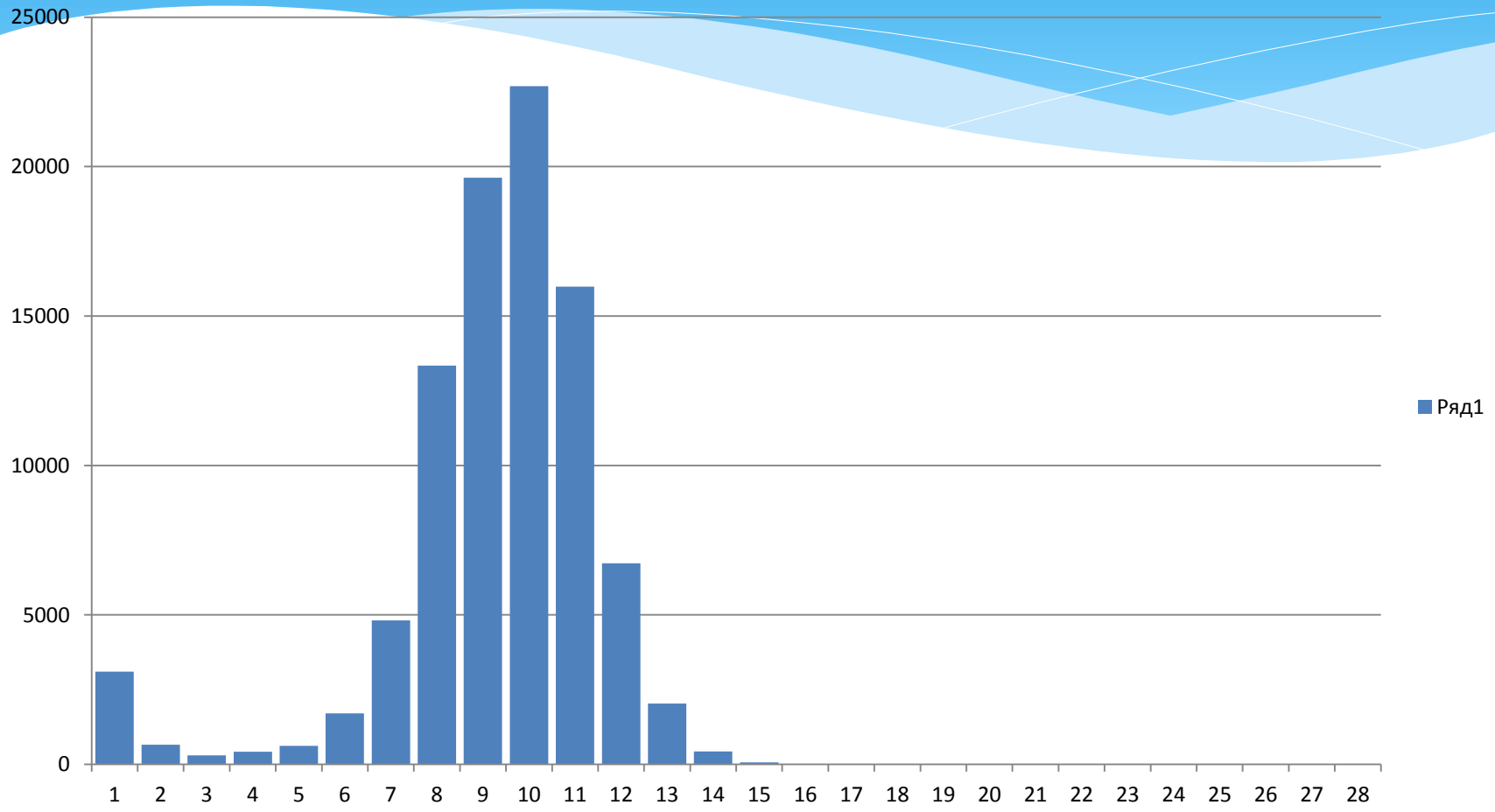
Tungsten sphere R = 10 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 25.2 nanoseconds



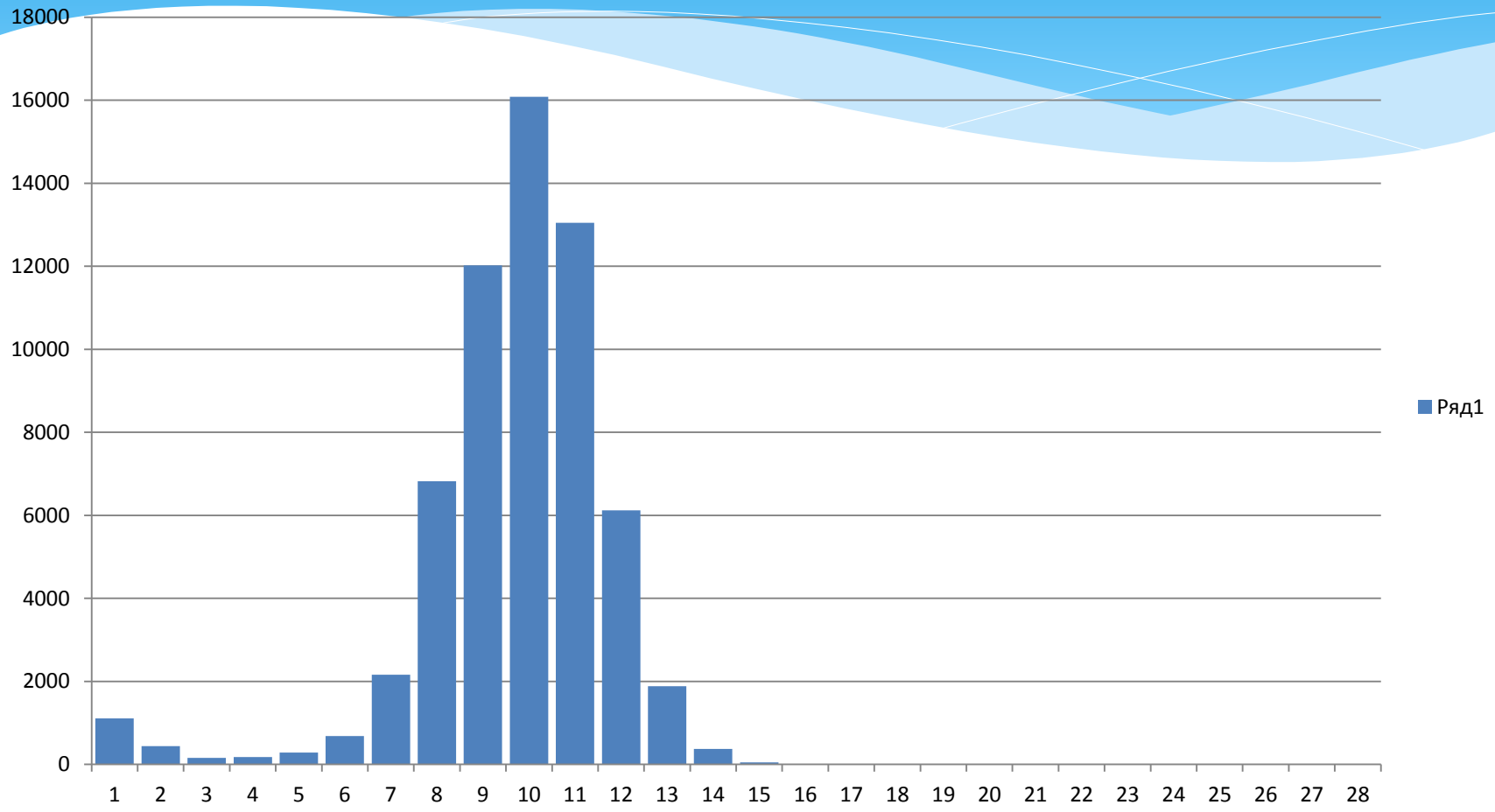
Tungsten sphere R = 15 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 56.3 nanoseconds



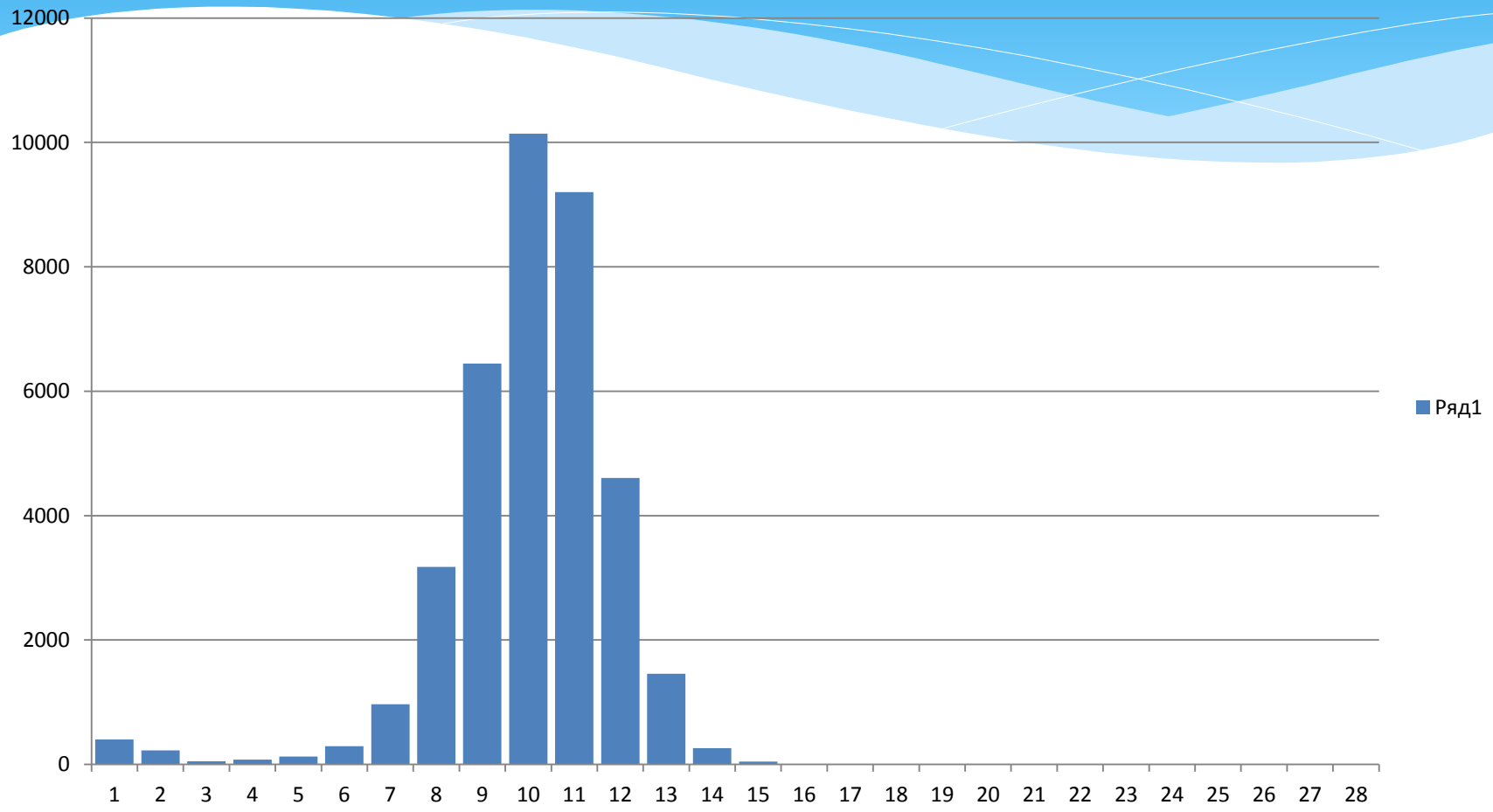
Tungsten sphere R = 20 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 91.7 nanoseconds



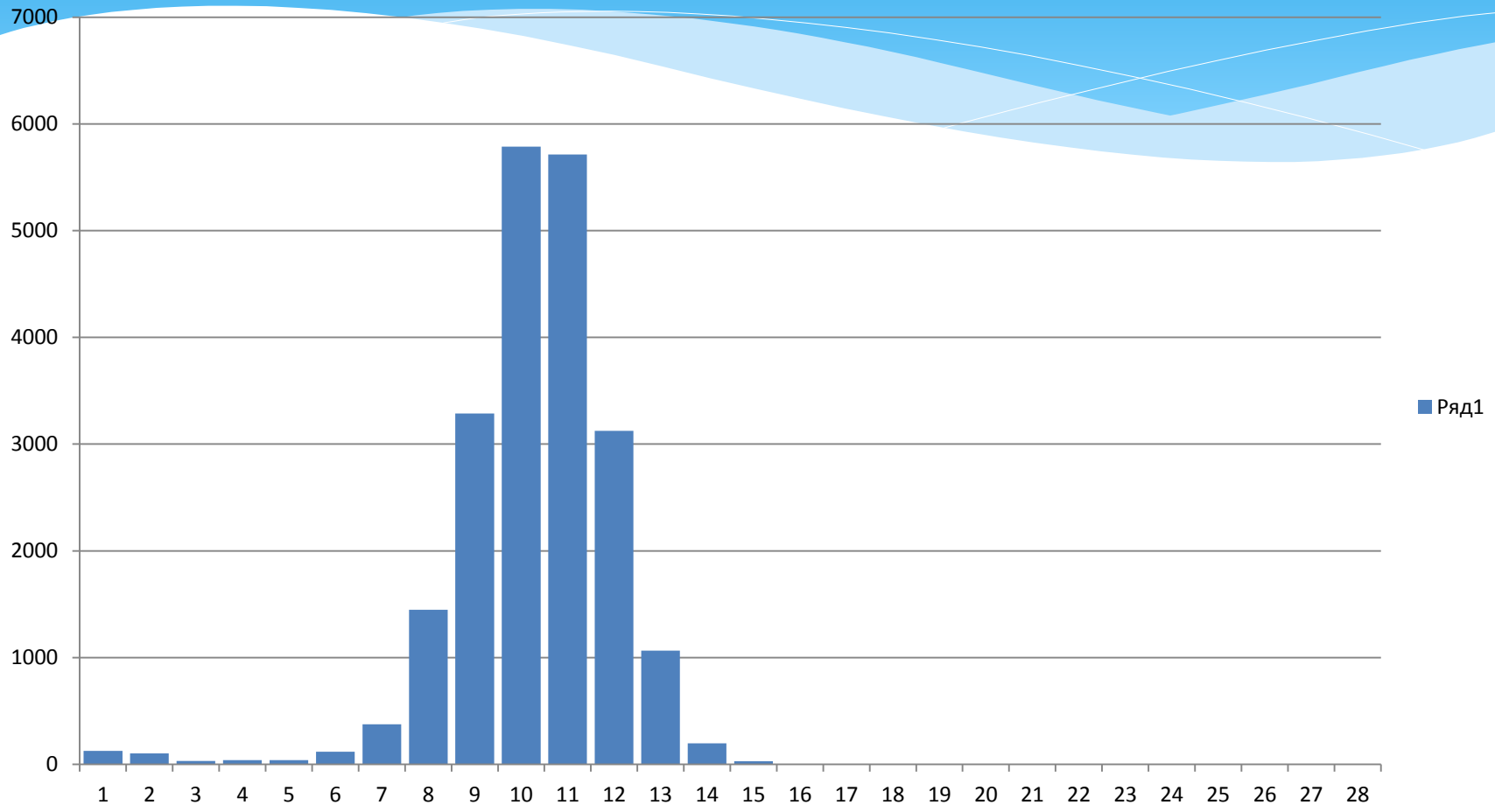
Tungsten sphere R = 25 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 128 nanoseconds



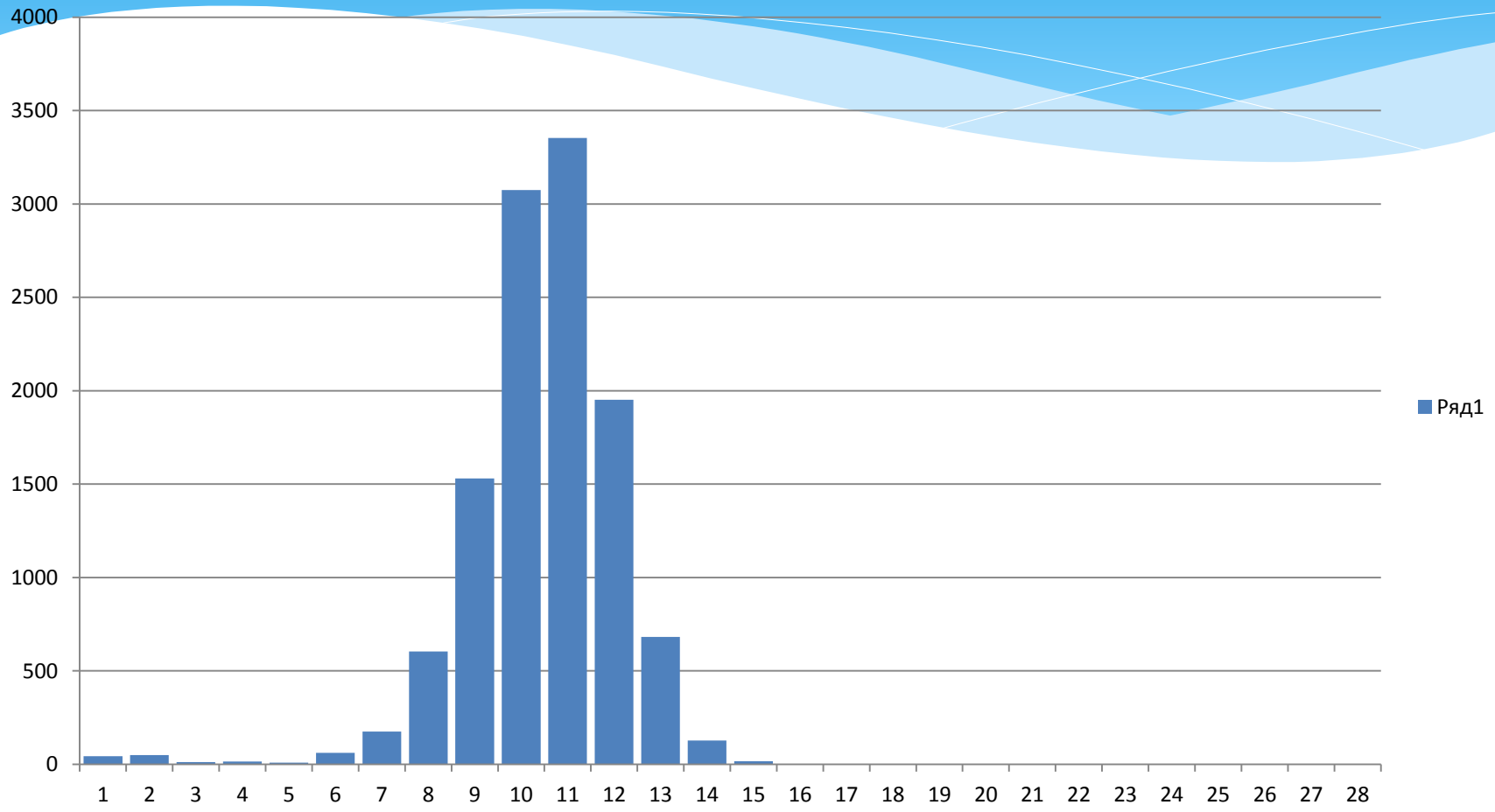
Tungsten sphere R = 30 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 164 nanoseconds



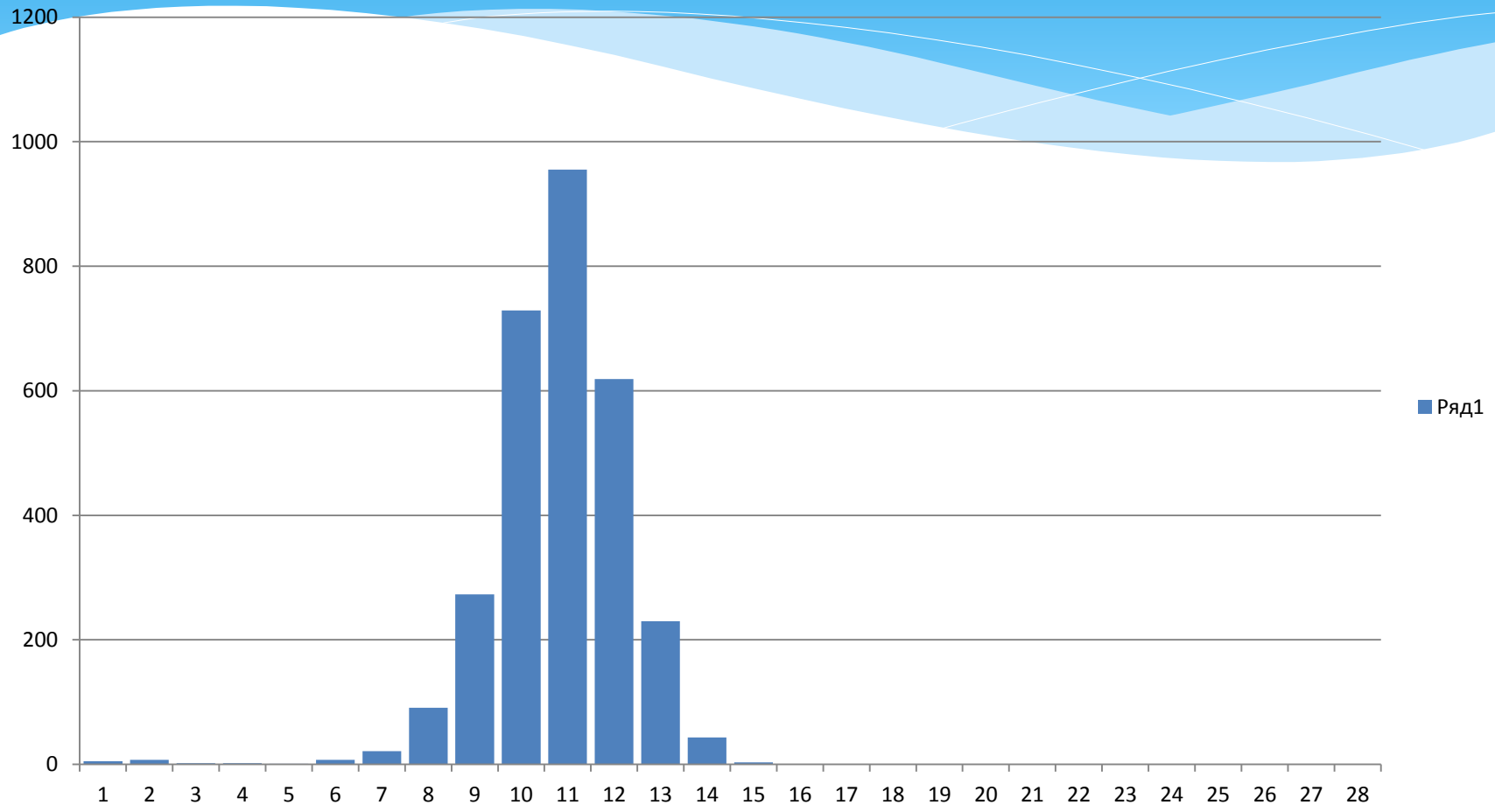
Tungsten sphere R = 35 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 201 nanoseconds



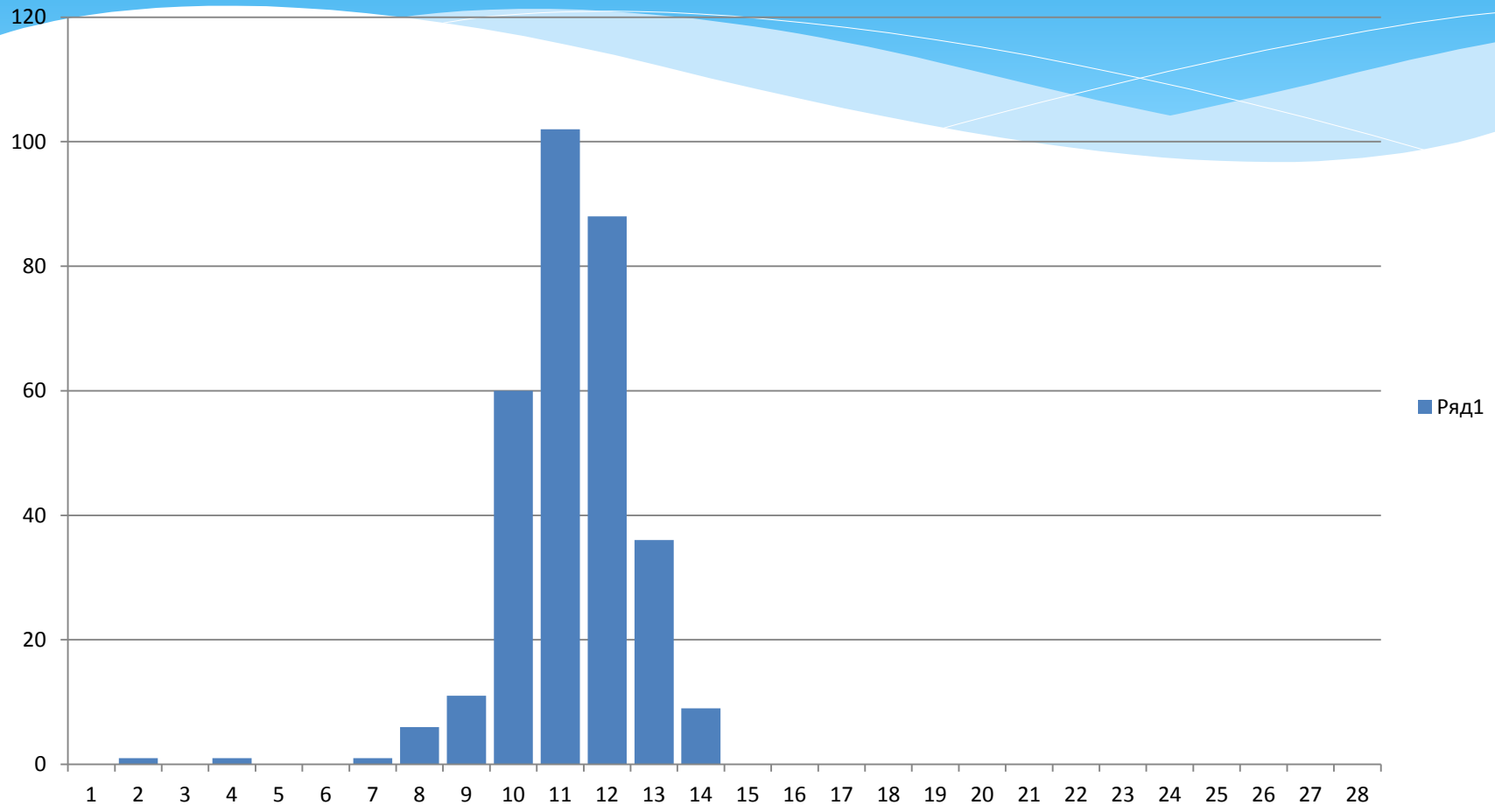
Tungsten sphere R = 40 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 235 nanoseconds



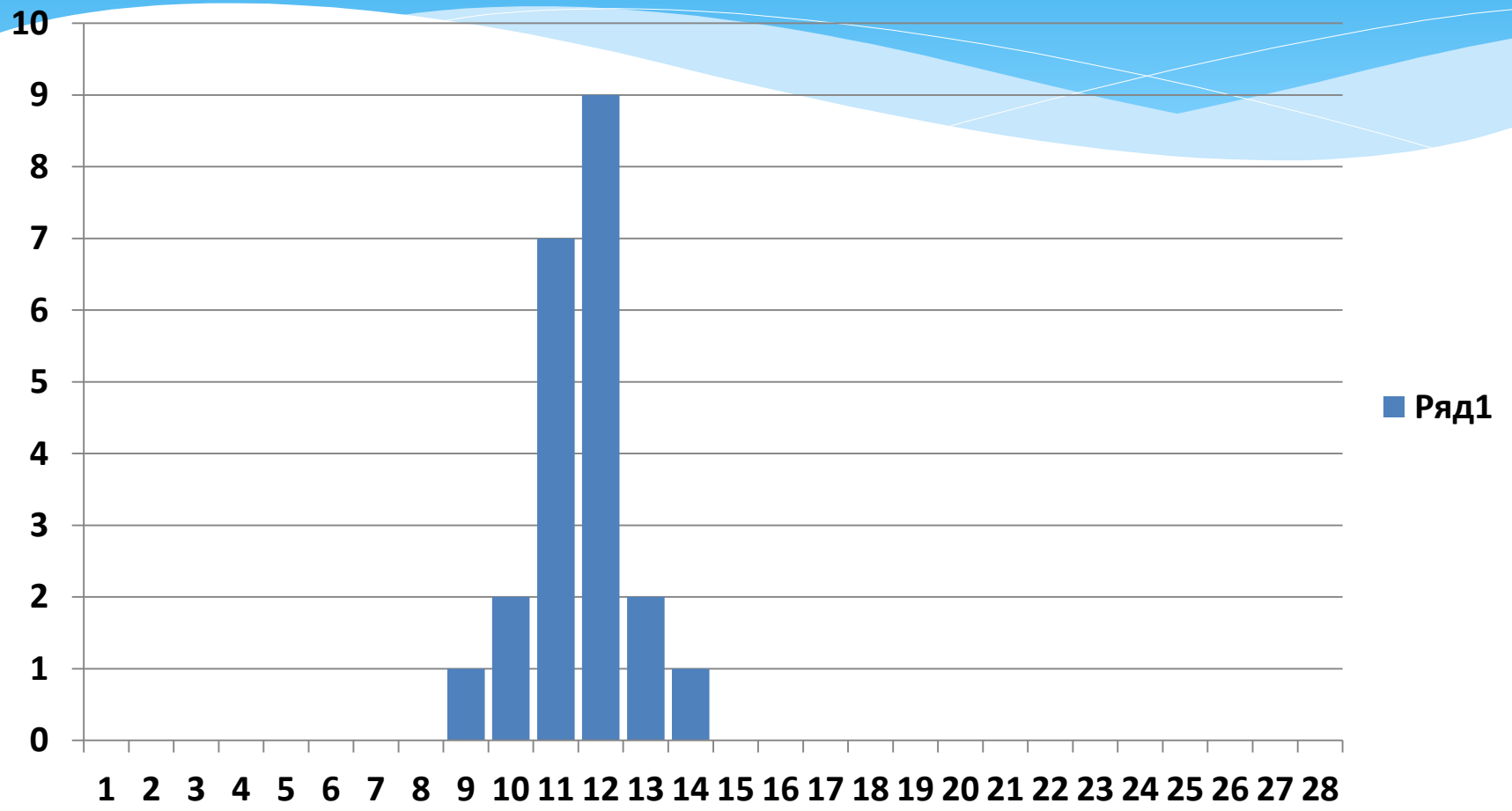
Tungsten sphere R = 50 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 304 nanoseconds



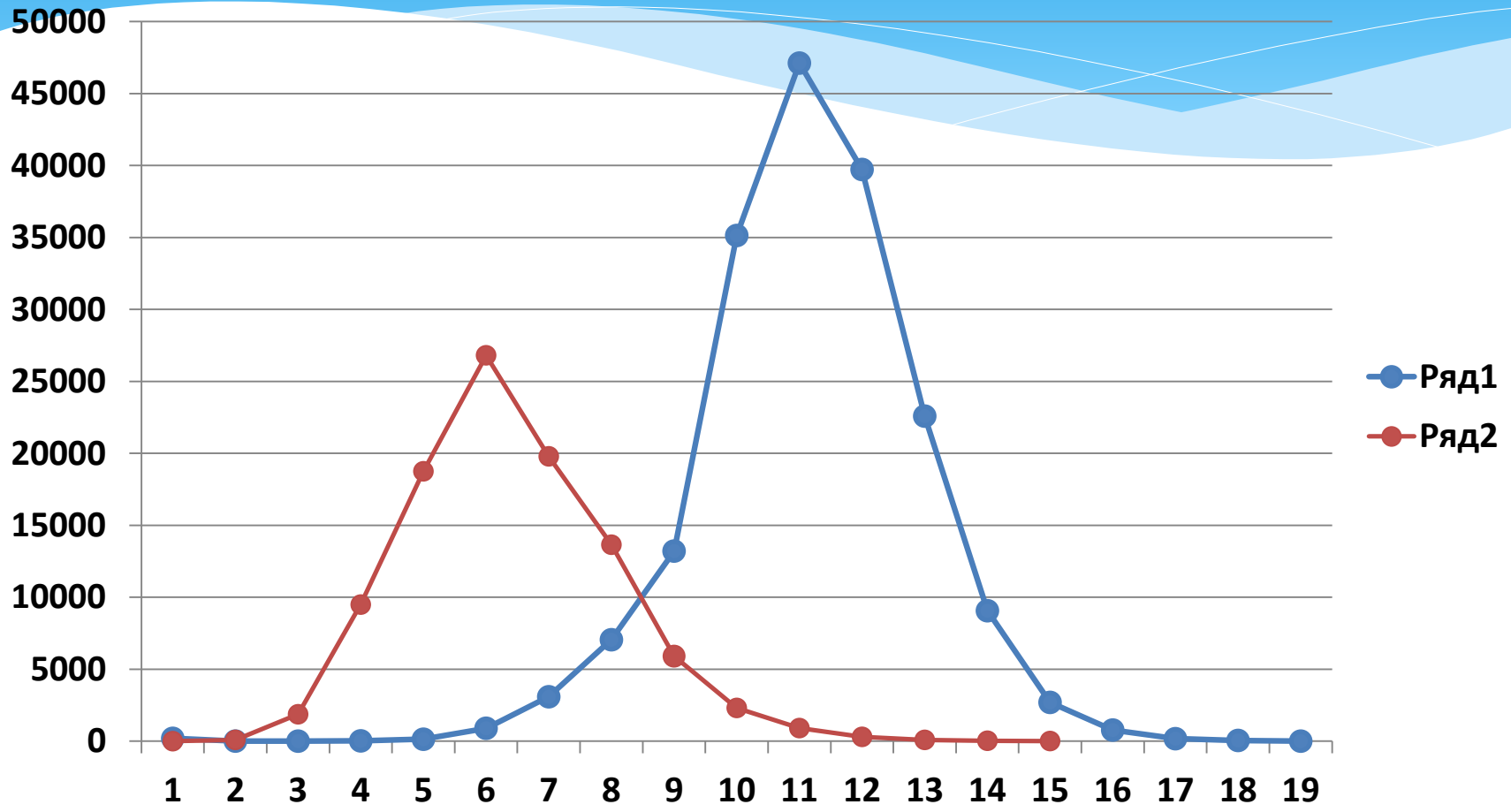
Tungsten sphere R = 65 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 427 nanoseconds



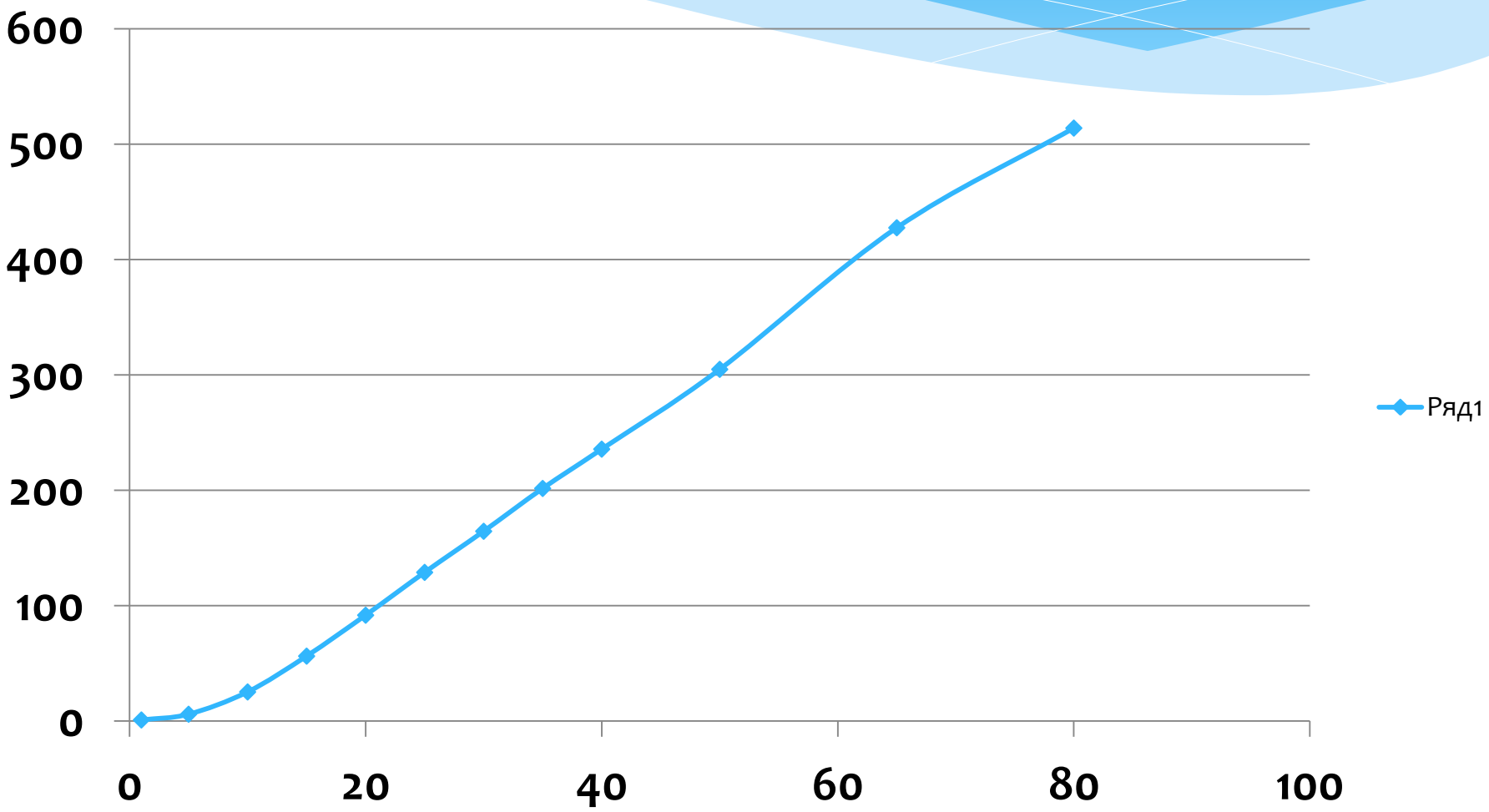
Tungsten sphere R = 80 cm, outgoing spectrum from external surface
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Diffusion time 514 nanoseconds



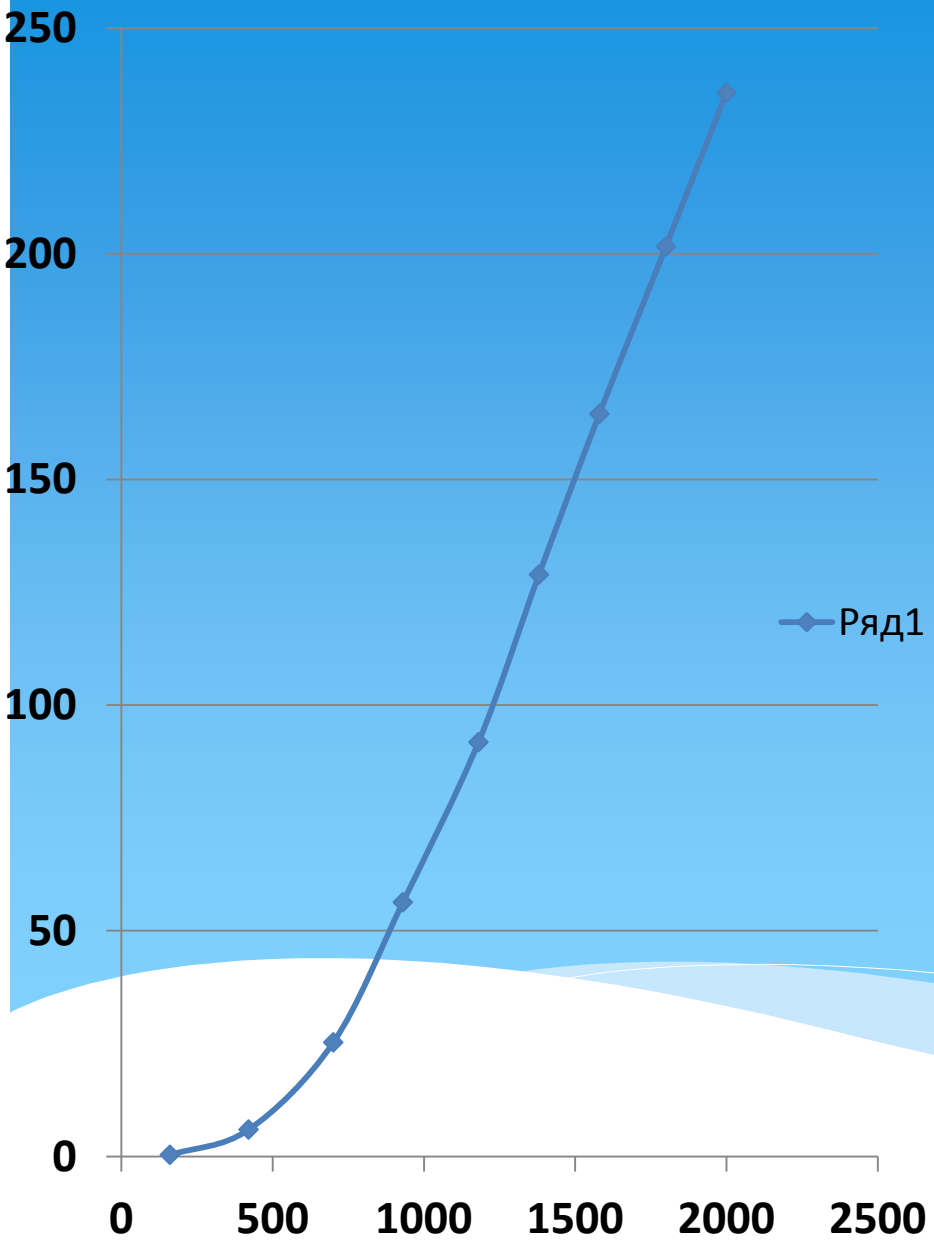
Initial Pu239 fission neutron spectrum (red line)
Capture spectrum in tungsten sphere R = 80 cm (blue line)
100000 neutrons in the center at t=0, start E(n) = 14 MeV
Horizontal axis: ABBN-78 energy groups
Vertical axis: neutrons per group



Axis ‘X’ : radius of the tungsten sphere, cm
Axis ‘Y’: diffusion time of the neutron flux
from the center point to external surface, nanoseconds
Dependence of proton’s ionization path in metal tungsten as function of energy, MeV, by data of [5].



Duration of neutron flash, nanoseconds (vertical axis) as function of proton energy, Mev (horizontal axis).



Data of the curve were calculated using ABBN-78 neutron constants with the code 'Shield' [1,2] for the tungsten spheres with 14 Mev neutron source in the center.

Real spallation neutron target of proton accelerator differs from this idealized model due to two factors.

Firstly, exist small quantity of neutrons which were born near the back surface of the target, near the end of the proton's ionization fly path, they easily escape tungsten into neutron guide to the detector.

Second, proton beam target can be done not as a sphere with radius equal to ionization path of proton, but as a cylinder with diameter comparable to proton beam's aperture.

At the same time, proton beam in tungsten target diverges during penetrating the metal material. Due to this, diameter of cylindrical target must be still big enough.

Thus, numerical values for real beam target, which emits spallation neutrons, can differ from showed values.

In any case, diffusion time of the neutron flux grows non-linearly fast with increasing of proton beam energy, especially after proton beam energy exceeds 1 Gev. This effect of non-linear growth of the diffusion time, was found by authors during numerical calculations of targets which use materials with small neutron absorption like lead (Pb).

For 2 GeV proton accelerator, even very short single proton pulses of beam microstructure will produce, in full absorption beam target, long neutron pulses with duration comparable with 100 nanoseconds.

Conclusion

Authors expressed in this work their view on ability to measure 299-group neutron cross sections, in energy group intervals of the ABBN-93 system, by TOF spectrometers based on pulsed spallation neutron sources of proton accelerators with energies around 1 GeV.

Calculations showed (tau/L) parameter, measured in nanoseconds per meter, after exceeding which, TOF measurements provide high enough precision to use experimental results for calculations of fast breeder reactors and their radiation shields .

Considering practically achievable values of flash duration tau, and vacuum neutron guide length L, required (tau/L) parameter was found as practically achievable on slightly modified existing equipment.

Special positive feature of TOF method is that usage of one and the same neutron and gamma detector, allows to measure in one experiment all the curve sigma(En) between 14 Mev and thermal 0.025 eV neutrons for selected isotope or their alloy mixture.

Duration of neutron flux flash, emitted by proton accelerator's target, is in the area 10- 100 nanoseconds. It is much longer then 1 nanosecond, achievable by electron accelerators. However, proton accelerator has bigger intensity, and around 8% high energy cascade neutrons valuable for experiment. Intensity of proton accelerator, using long TOF base, allows to reach resolution around 0.25 nanoseconds/meter, which is enough for measurements of neutron cross sections in 299-group energy intervals of the ABBN-93 system.

Measurement of neutron group cross sections ABBN-93, in all 299 groups including high energies up to 20 MeV, can be recognized as a practically achievable task on slightly modified existing experimental equipment. Including proton accelerator, proton beam target, vacuum neutron guide and all the spectrometry channel: gamma-detectors, electronics of pre-amplifiers and data acquisition system.

Authors express their gratitude for creators of the ‘SHIELD’ code [1,2] Sobolevsky N.M. and Latysheva L.N., who wrote program code, using which authors did variant calculations of the spallation target neutron spectrums, and neutron flux diffusion durations.

With statistics around 1,000,000 neutrons, providing discreteness calculation precision component around 0.1%, performance of the program allows to calculate big quantity of variants using modern personal computer.

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Thank you for your attention!