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**Evolution of the Neutron Spectrum
During Propagation of the Neutron Flux in Solid Bodies**

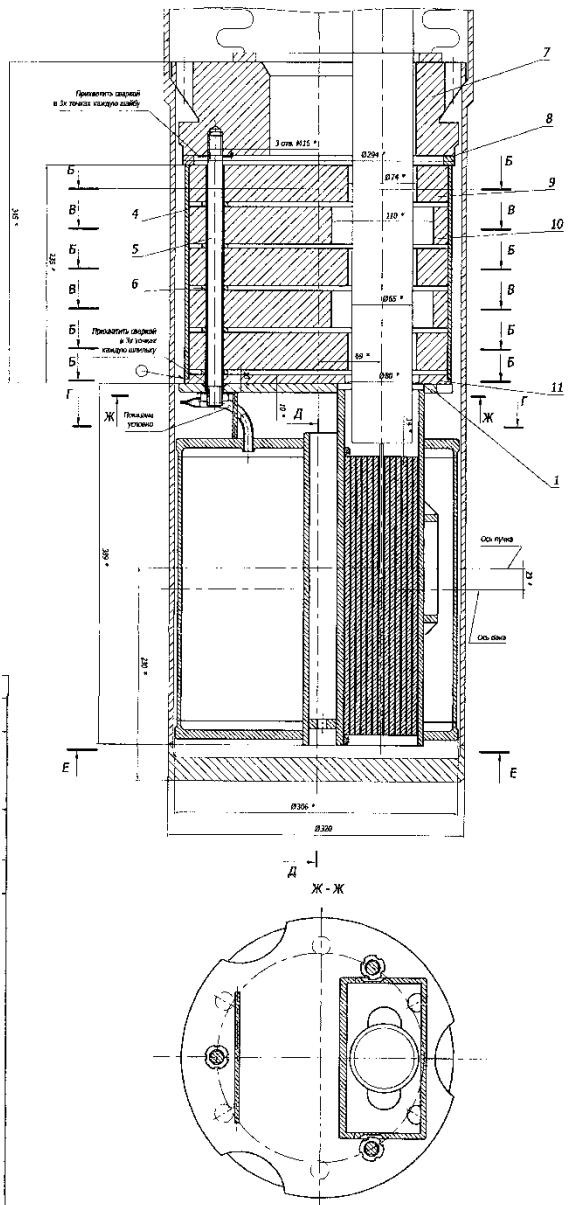
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Abstract

The results of numerical modeling of leakage spectra, diffusion time and absorption spectra during propagation of neutron fluxes in solid bodies are presented. The spherically symmetric task of neutron flux diffusion from a central source to the outer surface of spheres, made of various materials, is reviewed. The simulation was carried out using the Monte Carlo code 'Shield' [1,2] with ABBN-78 neutron group constants [3].

The task was carried out within the framework of modeling the spectrum of a tungsten-water proton beam target of the pulsed neutron source RADEX, which is used as proton beam target of the INR RAS proton linear accelerator. Modeling was carried out in order to determine the effect of the target material choice on the neutron spectrum, on the value of neutron flux and on its diffusion time. Possibility to reconstruct capture spectrums, using experimentally measured leakage spectrums, is discussed.



Integral experiments are integral check of all main types of nuclear constants, of cross sections for interactions of neutrons with nuclei. This idea was expressed already in early works [5].

The idea of this work appeared during modeling of the target station of the spallation neutron source RADEX, which is used as a beam target of the INR RAS proton linear accelerator.

Modeling of real spallation neutron source includes many physical processes, such as: propagation of accelerated proton beam inside tungsten plates, inside water layers and steel casing, producing cascade and spallation neutrons in 3D geometry of target, diffusion of initial spallation neutron flux into experimental vacuum neutron guide considering elastic and inelastic scattering, $(n,2n)$ reaction and capture of neutrons.

Aim of this work is to describe pure effect of spectrum's evolution during propagation of the neutron flux inside solid body of chosen material with known group cross sections [3]. Obtained data allow to compare, how choice of target station's material influences on outgoing spectrum in neutron guide.

As examples of media we chose natural isotope composition metal spheres of tungsten ^{74}W , steel ^{26}Fe , and sodium ^{23}Na .

Neutron flux in metal sphere: description of the model

There is a sphere of metal, which has density ρ , radius $1 < R < 140$ cm and consists of defined isotope or their mixture with known cross sections. At time $t=0$ in the center of the sphere are emitted N neutrons which have energy E_0 , MeV. Must be calculated:

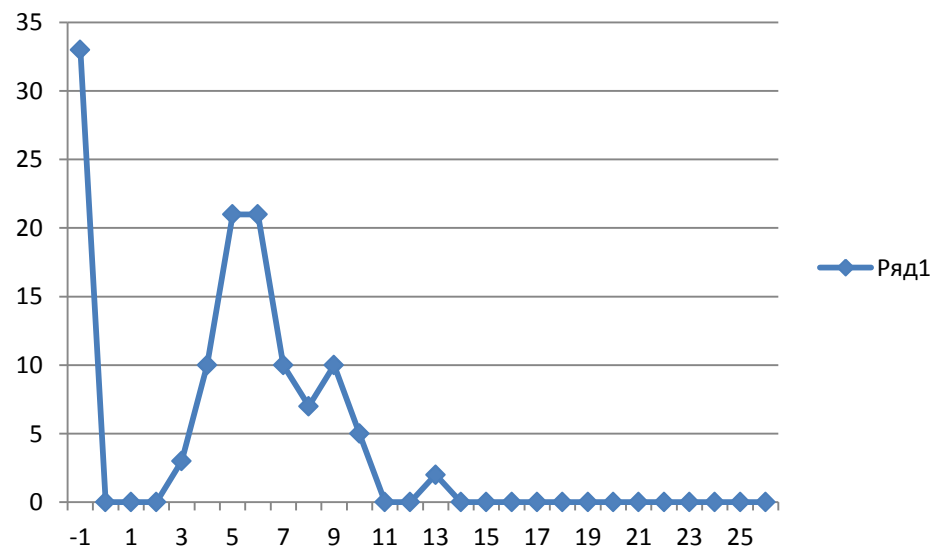
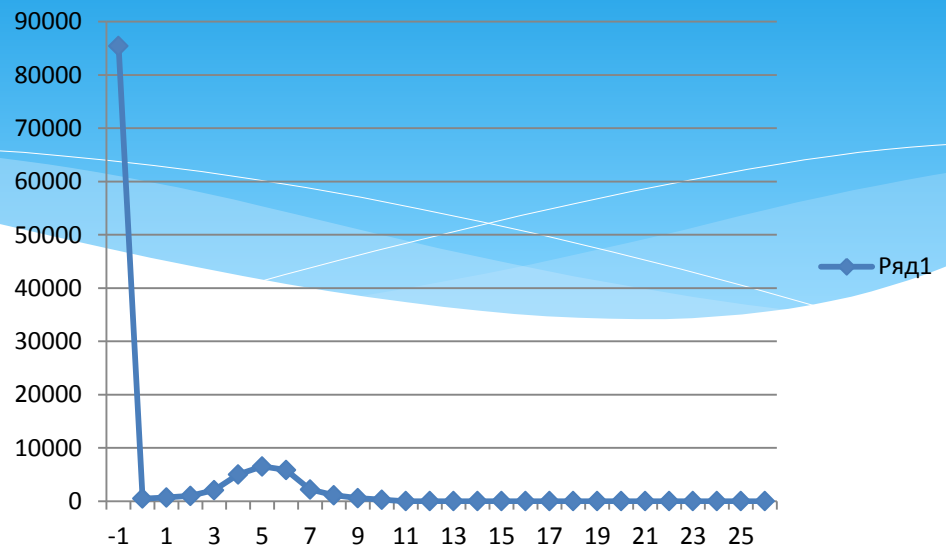
- * Average time of neutron's diffusion to external surface of the sphere (when $r = R$ for each neutron);
- * Energy spectrum of leaking neutron flux, which is flying from sphere's external surface and can be measured by TOF method;
- * Energy spectrum of absorbed neutrons.

Start number of neutrons is taken $N=100,000$ for each variant spectrum.
Start energy of neutrons is taken $E_0=14.1$ MeV.

Authors also calculated spectrums with start energies 3.0 MeV and 0.6 MeV typical for spallation neutrons and for photonuclear (γ, n) neutron sources correspondingly. These spectrums with start energies in 3rd and 6th ABBN-78 energy groups allowed to appreciate, how results depends on start energy of neutron.

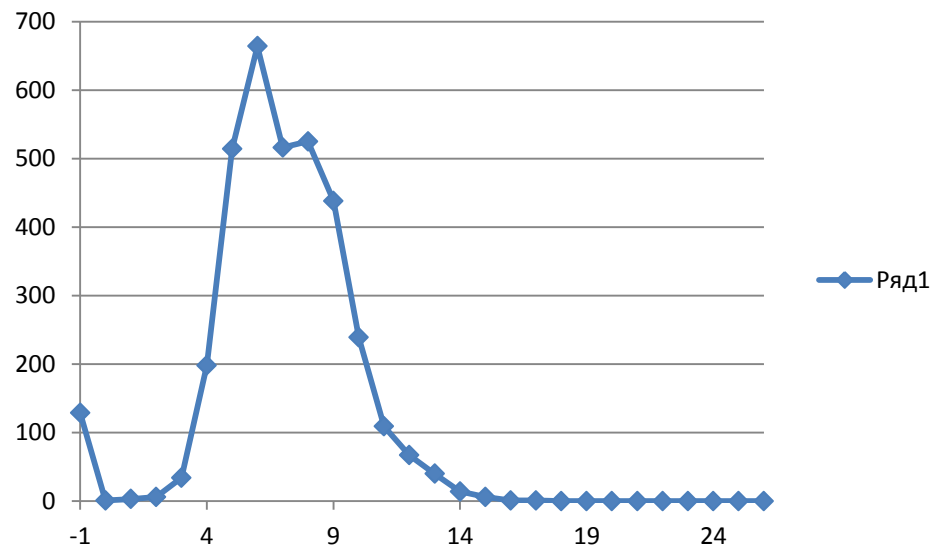
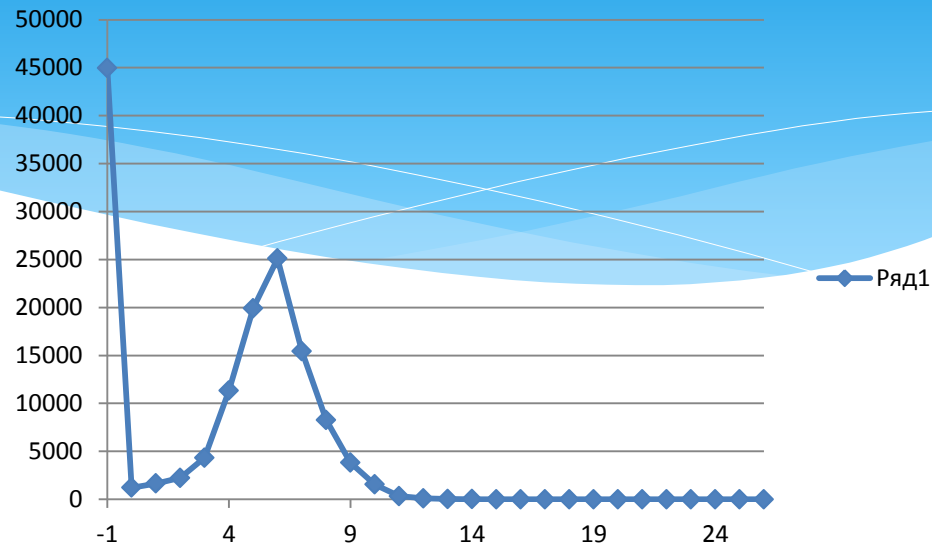
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	85435	33
0	14.0-10.5 MeV	477	0
1	10.5 – 6.5 MeV	710	0
2	6.5 – 4.0 MeV	996	0
3	4.0 – 2.5 MeV	2088	3
4	2.5 – 1.4 MeV	5029	10
5	1.4 – 0.8 MeV	6526	21
6	0.8 – 0.4 MeV	5872	21
7	0.4 – 0.2 MeV	2189	10
8	0.2 – 0.1 MeV	1117	7
9	100 – 46.5 KeV	574	10
10	46.5 – 21.5 KeV	265	5
11	21.5 – 10 KeV	18	0
12	10 – 4.65 KeV	6	0
13	4.65 – 2.15 KeV	2	2
14	2.15 – 1 KeV	0	0
15	1 – 0.465 KeV	0	0
16	465 – 215 eV	0	0
17	215 – 100 eV	0	0
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 1 cm



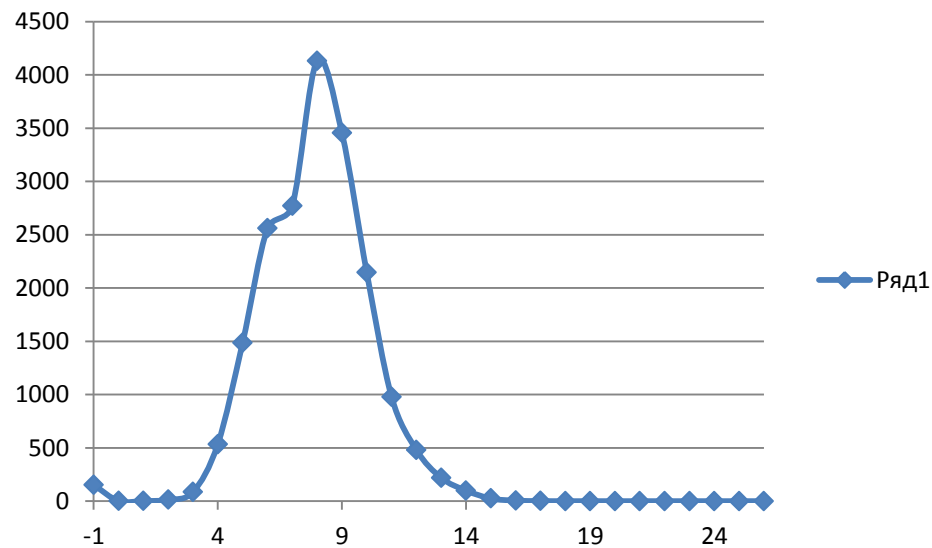
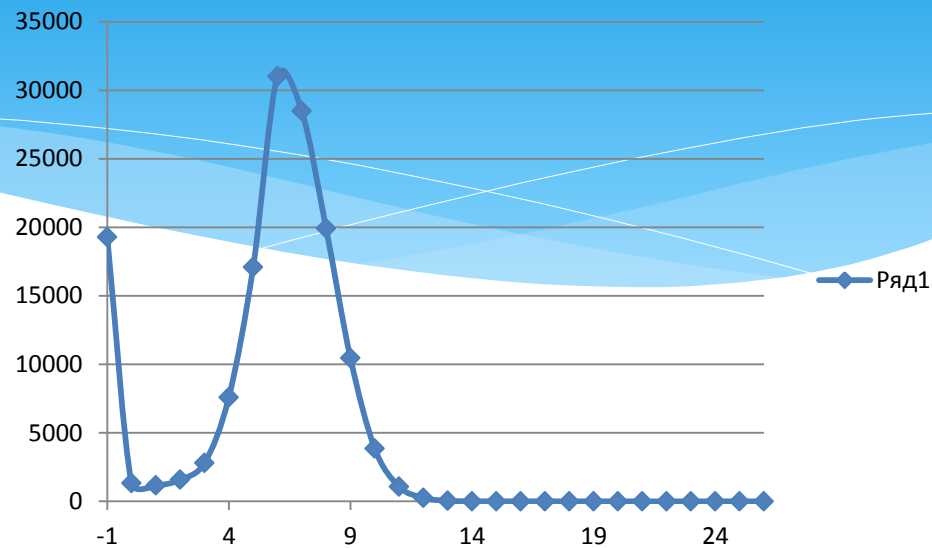
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	44951	129
0	14.0-10.5 MeV	1224	1
1	10.5 – 6.5 MeV	1658	3
2	6.5 – 4.0 MeV	2237	6
3	4.0 – 2.5 MeV	4334	34
4	2.5 – 1.4 MeV	11330	198
5	1.4 – 0.8 MeV	19910	514
6	0.8 – 0.4 MeV	25100	664
7	0.4 – 0.2 MeV	15440	516
8	0.2 – 0.1 MeV	8280	525
9	100 – 46.5 KeV	3824	438
10	46.5 – 21.5 KeV	1558	239
11	21.5 – 10 KeV	337	109
12	10 – 4.65 KeV	94	67
13	4.65 – 2.15 KeV	31	40
14	2.15 – 1 KeV	9	14
15	1 – 0.465 KeV	0	6
16	465 – 215 eV	0	1
17	215 – 100 eV	0	1
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74 R= 5 cm



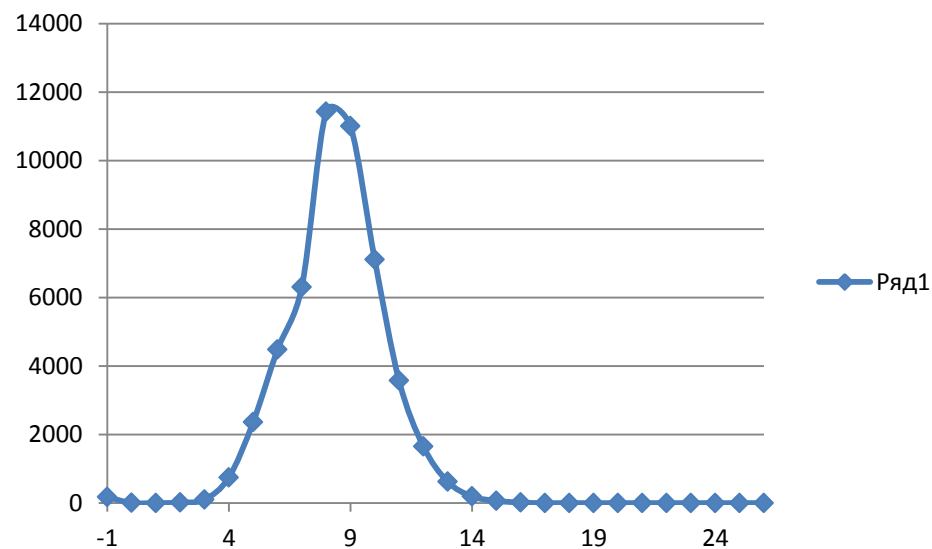
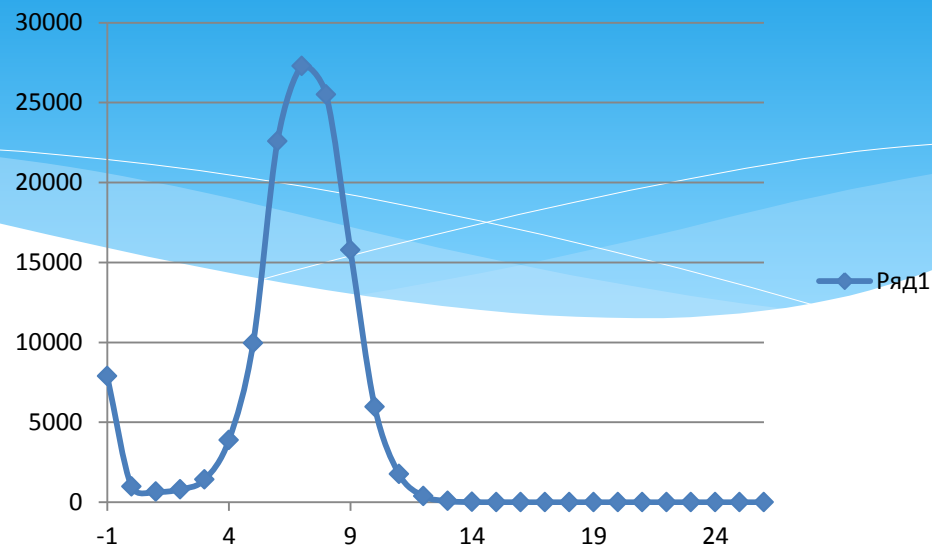
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	19290	152
0	14.0-10.5 MeV	1314	2
1	10.5 – 6.5 MeV	1158	1
2	6.5 – 4.0 MeV	1576	13
3	4.0 – 2.5 MeV	2799	86
4	2.5 – 1.4 MeV	7595	535
5	1.4 – 0.8 MeV	17084	1486
6	0.8 – 0.4 MeV	31011	2559
7	0.4 – 0.2 MeV	28480	2770
8	0.2 – 0.1 MeV	19920	4132
9	100 – 46.5 KeV	10459	3455
10	46.5 – 21.5 KeV	3857	2146
11	21.5 – 10 KeV	1075	979
12	10 – 4.65 KeV	251	481
13	4.65 – 2.15 KeV	44	219
14	2.15 – 1 KeV	5	99
15	1 – 0.465 KeV	2	25
16	465 – 215 eV	0	5
17	215 – 100 eV	0	1
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 10 cm



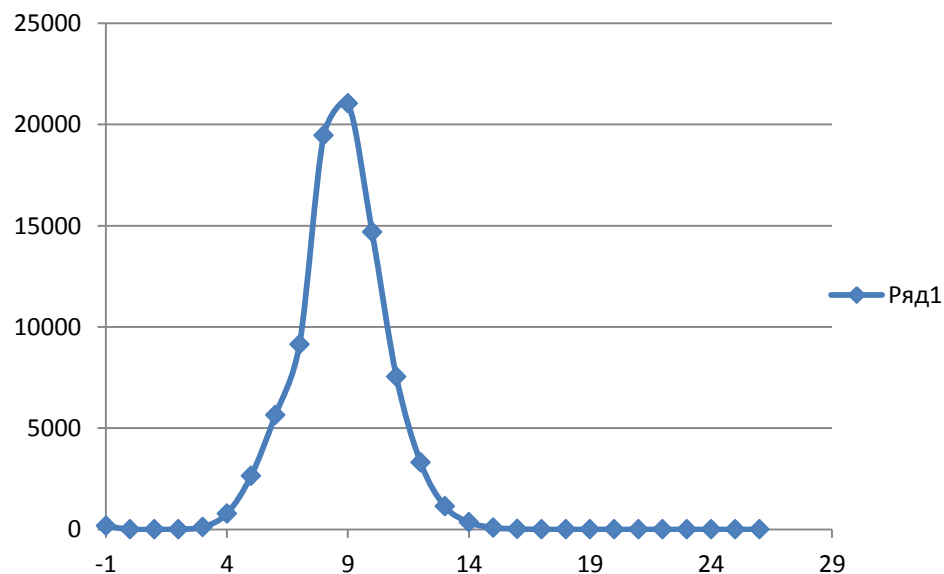
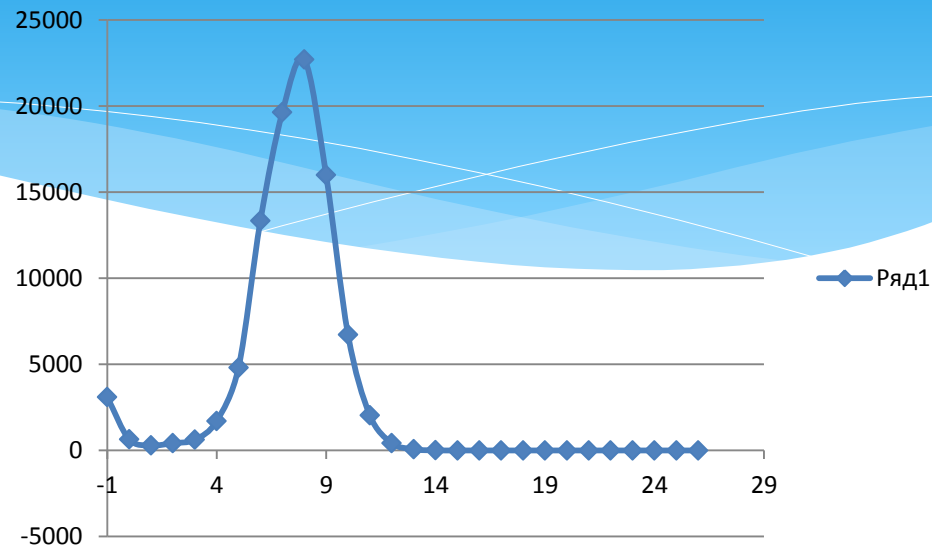
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	7882	179
0	14.0-10.5 MeV	975	5
1	10.5 – 6.5 MeV	656	2
2	6.5 – 4.0 MeV	802	14
3	4.0 – 2.5 MeV	1408	104
4	2.5 – 1.4 MeV	3876	749
5	1.4 – 0.8 MeV	9948	2364
6	0.8 – 0.4 MeV	22581	4481
7	0.4 – 0.2 MeV	27276	6304
8	0.2 – 0.1 MeV	25502	11423
9	100 – 46.5 KeV	15770	11005
10	46.5 – 21.5 KeV	5968	7105
11	21.5 – 10 KeV	1756	3576
12	10 – 4.65 KeV	385	1654
13	4.65 – 2.15 KeV	70	625
14	2.15 – 1 KeV	8	197
15	1 – 0.465 KeV	4	66
16	465 – 215 eV	1	17
17	215 – 100 eV	0	0
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 15 cm



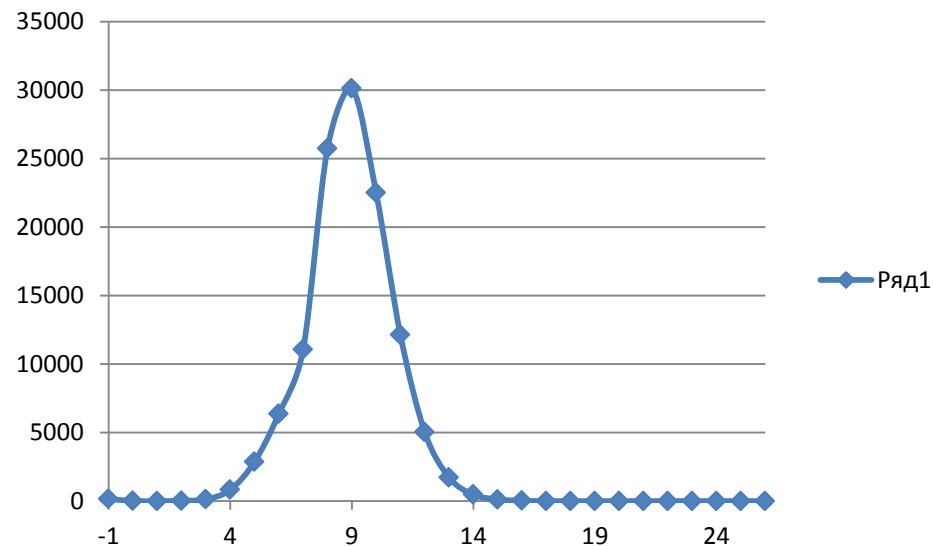
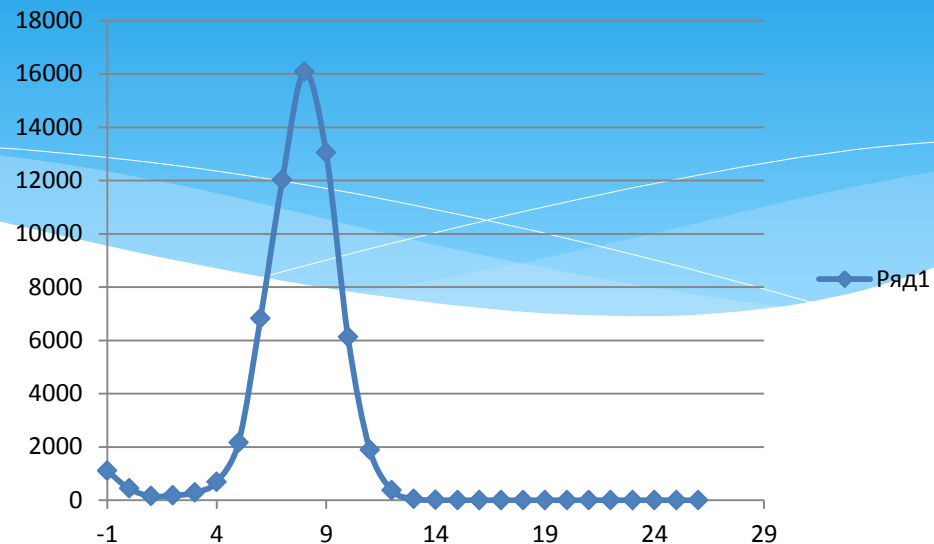
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	3101	173
0	14.0-10.5 MeV	655	3
1	10.5 – 6.5 MeV	299	3
2	6.5 – 4.0 MeV	421	12
3	4.0 – 2.5 MeV	621	123
4	2.5 – 1.4 MeV	1706	786
5	1.4 – 0.8 MeV	4812	2649
6	0.8 – 0.4 MeV	13340	5643
7	0.4 – 0.2 MeV	19626	9148
8	0.2 – 0.1 MeV	22694	19454
9	100 – 46.5 KeV	15984	21045
10	46.5 – 21.5 KeV	6726	14679
11	21.5 – 10 KeV	2035	7550
12	10 – 4.65 KeV	427	3314
13	4.65 – 2.15 KeV	67	1145
14	2.15 – 1 KeV	6	356
15	1 – 0.465 KeV	1	90
16	465 – 215 eV	0	23
17	215 – 100 eV	0	1
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 20 cm



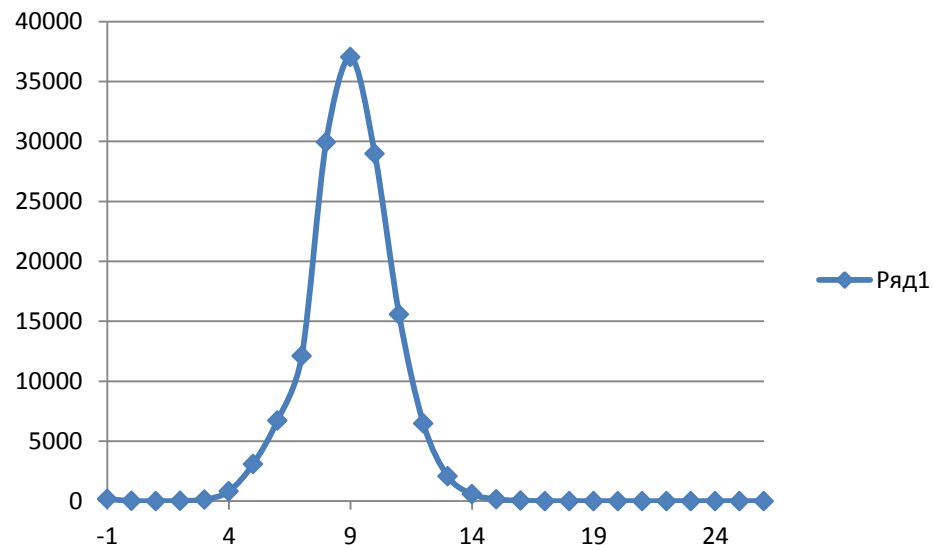
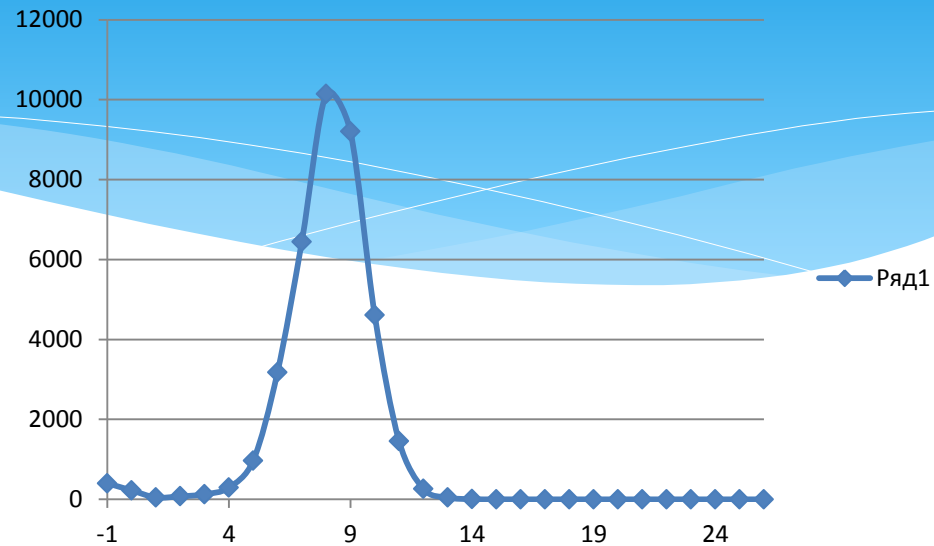
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	1105	168
0	14.0-10.5 MeV	438	9
1	10.5 – 6.5 MeV	155	2
2	6.5 – 4.0 MeV	174	26
3	4.0 – 2.5 MeV	286	129
4	2.5 – 1.4 MeV	684	823
5	1.4 – 0.8 MeV	2157	2868
6	0.8 – 0.4 MeV	6820	6368
7	0.4 – 0.2 MeV	12019	11059
8	0.2 – 0.1 MeV	16081	25736
9	100 – 46.5 KeV	13043	30126
10	46.5 – 21.5 KeV	6121	22501
11	21.5 – 10 KeV	1883	12129
12	10 – 4.65 KeV	374	5039
13	4.65 – 2.15 KeV	49	1729
14	2.15 – 1 KeV	6	478
15	1 – 0.465 KeV	1	119
16	465 – 215 eV	0	32
17	215 – 100 eV	0	2
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 25 cm



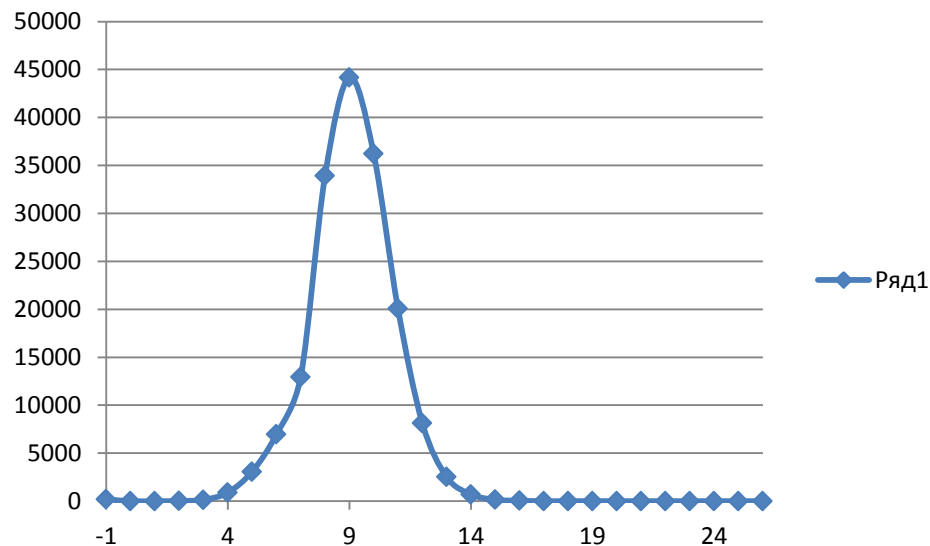
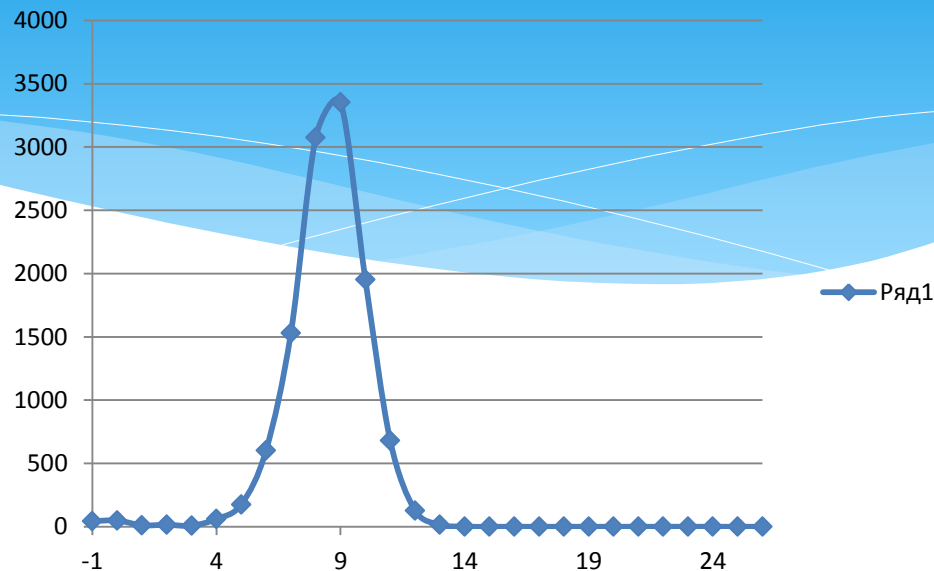
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	402	188
0	14.0-10.5 MeV	224	10
1	10.5 – 6.5 MeV	49	2
2	6.5 – 4.0 MeV	75	21
3	4.0 – 2.5 MeV	126	129
4	2.5 – 1.4 MeV	292	818
5	1.4 – 0.8 MeV	965	3094
6	0.8 – 0.4 MeV	3176	6719
7	0.4 – 0.2 MeV	6443	12105
8	0.2 – 0.1 MeV	10140	29934
9	100 – 46.5 KeV	9202	37031
10	46.5 – 21.5 KeV	4606	28991
11	21.5 – 10 KeV	1457	15583
12	10 – 4.65 KeV	261	6476
13	4.65 – 2.15 KeV	46	2084
14	2.15 – 1 KeV	4	592
15	1 – 0.465 KeV	1	146
16	465 – 215 eV	0	36
17	215 – 100 eV	0	3
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 30 cm



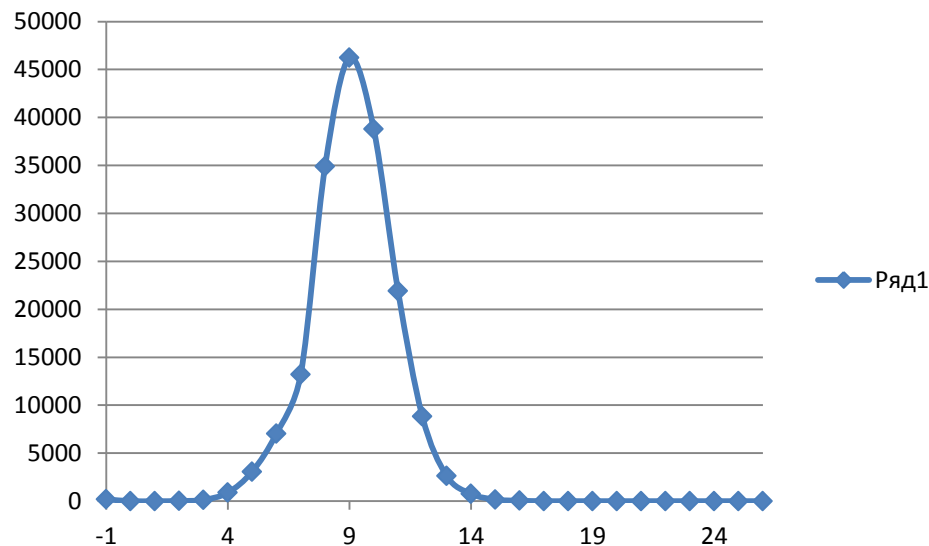
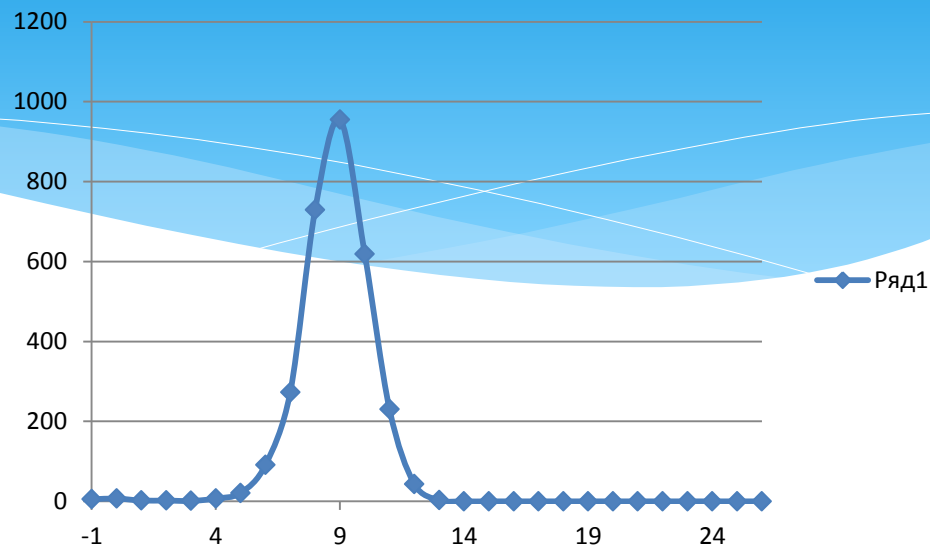
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	44	194
0	14.0-10.5 MeV	49	4
1	10.5 – 6.5 MeV	12	0
2	6.5 – 4.0 MeV	15	18
3	4.0 – 2.5 MeV	9	140
4	2.5 – 1.4 MeV	61	896
5	1.4 – 0.8 MeV	176	3071
6	0.8 – 0.4 MeV	604	6959
7	0.4 – 0.2 MeV	1530	12944
8	0.2 – 0.1 MeV	3075	33912
9	100 – 46.5 KeV	3353	44177
10	46.5 – 21.5 KeV	1952	36236
11	21.5 – 10 KeV	682	20062
12	10 – 4.65 KeV	128	8146
13	4.65 – 2.15 KeV	17	2534
14	2.15 – 1 KeV	1	706
15	1 – 0.465 KeV	0	147
16	465 – 215 eV	0	44
17	215 – 100 eV	0	1
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 40 cm



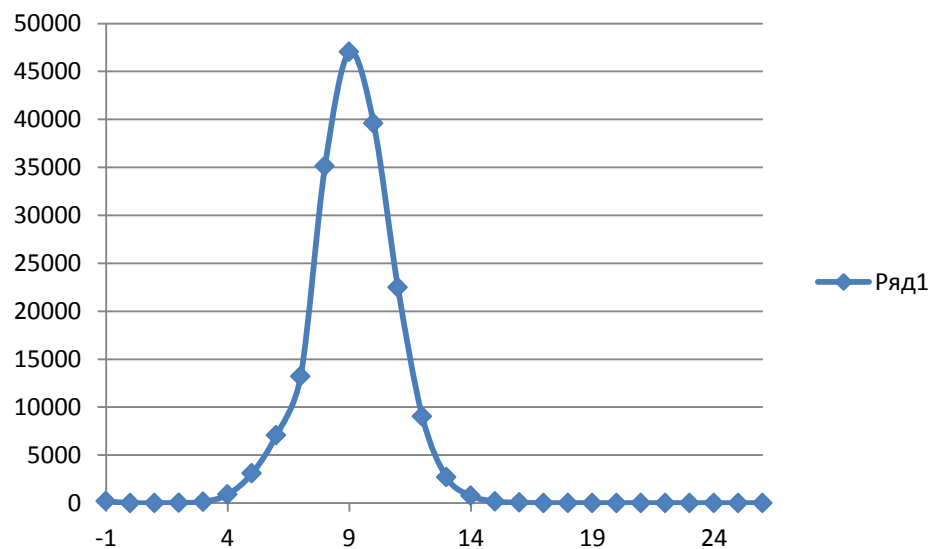
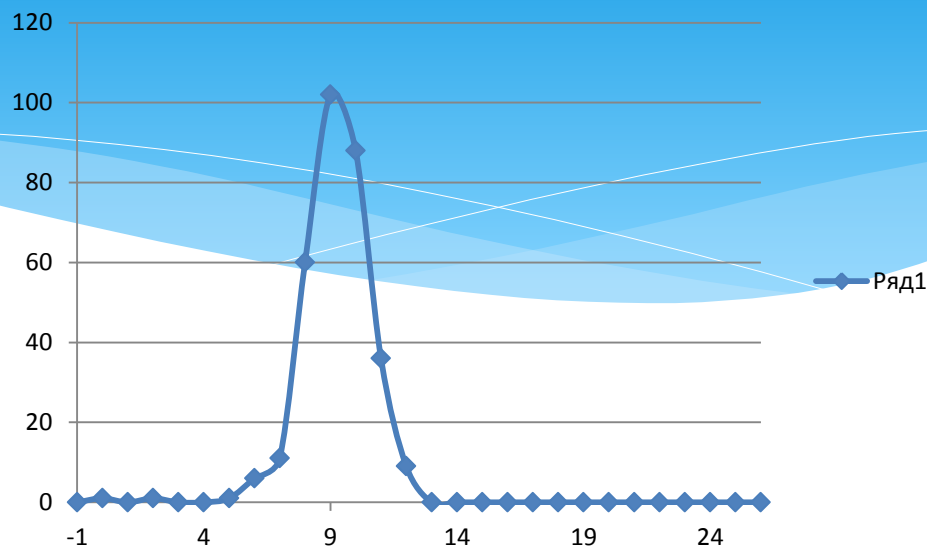
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	5	193
0	14.0-10.5 MeV	7	4
1	10.5 – 6.5 MeV	2	0
2	6.5 – 4.0 MeV	2	17
3	4.0 – 2.5 MeV	1	136
4	2.5 – 1.4 MeV	7	884
5	1.4 – 0.8 MeV	21	3071
6	0.8 – 0.4 MeV	91	7042
7	0.4 – 0.2 MeV	273	13216
8	0.2 – 0.1 MeV	729	34898
9	100 – 46.5 KeV	955	46223
10	46.5 – 21.5 KeV	619	38796
11	21.5 – 10 KeV	230	21923
12	10 – 4.65 KeV	43	8829
13	4.65 – 2.15 KeV	3	2635
14	2.15 – 1 KeV	0	771
15	1 – 0.465 KeV	0	165
16	465 – 215 eV	0	46
17	215 – 100 eV	0	2
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 50 cm



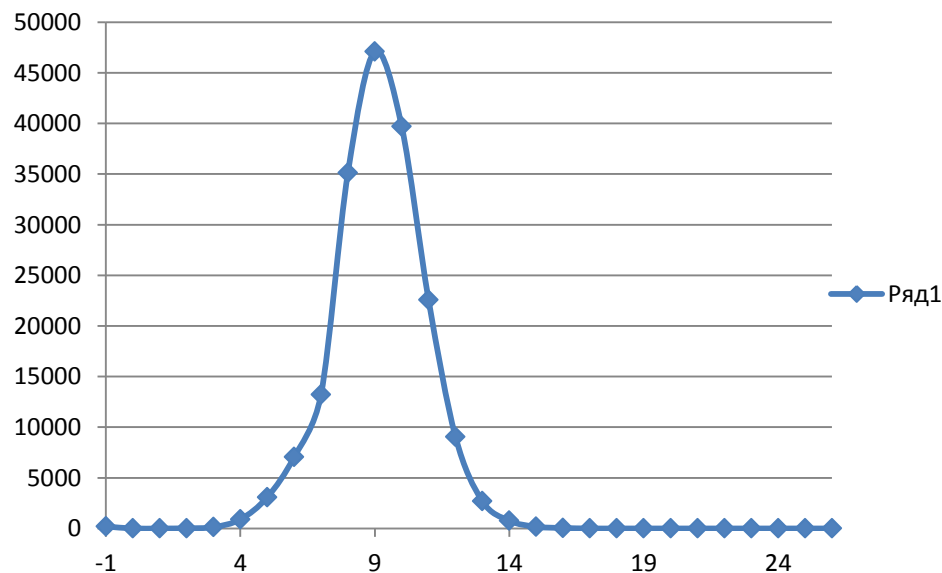
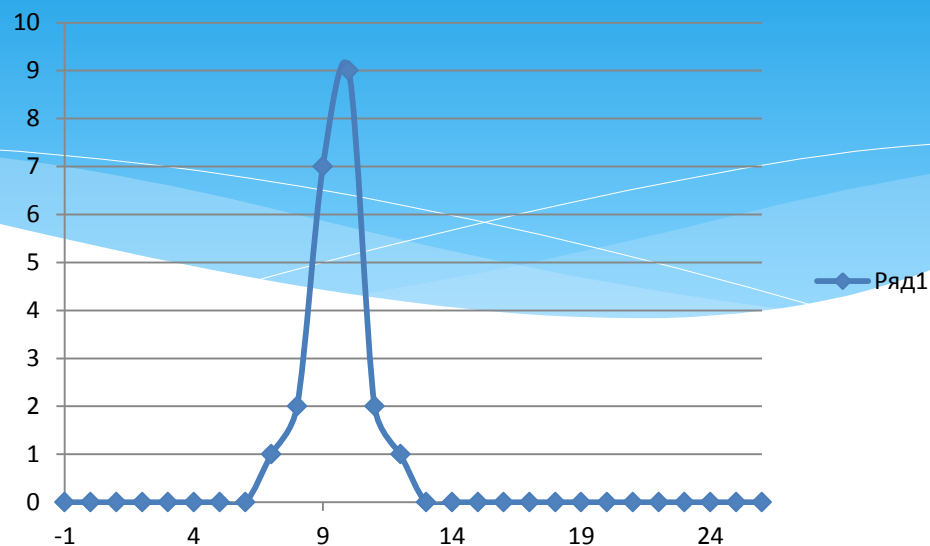
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	0	198
0	14.0-10.5 MeV	1	5
1	10.5 – 6.5 MeV	0	1
2	6.5 – 4.0 MeV	1	20
3	4.0 – 2.5 MeV	0	133
4	2.5 – 1.4 MeV	0	892
5	1.4 – 0.8 MeV	1	3096
6	0.8 – 0.4 MeV	6	7063
7	0.4 – 0.2 MeV	11	13212
8	0.2 – 0.1 MeV	60	35112
9	100 – 46.5 KeV	102	47025
10	46.5 – 21.5 KeV	88	39604
11	21.5 – 10 KeV	36	22475
12	10 – 4.65 KeV	9	9044
13	4.65 – 2.15 KeV	0	2689
14	2.15 – 1 KeV	0	769
15	1 – 0.465 KeV	0	170
16	465 – 215 eV	0	48
17	215 – 100 eV	0	2
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 65 cm



ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	0	197
0	14.0-10.5 MeV	0	5
1	10.5 – 6.5 MeV	0	2
2	6.5 – 4.0 MeV	0	20
3	4.0 – 2.5 MeV	0	135
4	2.5 – 1.4 MeV	0	897
5	1.4 – 0.8 MeV	0	3081
6	0.8 – 0.4 MeV	0	7048
7	0.4 – 0.2 MeV	1	13214
8	0.2 – 0.1 MeV	2	35136
9	100 – 46.5 KeV	7	47100
10	46.5 – 21.5 KeV	9	39707
11	21.5 – 10 KeV	2	22573
12	10 – 4.65 KeV	1	9062
13	4.65 – 2.15 KeV	0	2698
14	2.15 – 1 KeV	0	773
15	1 – 0.465 KeV	0	172
16	465 – 215 eV	0	50
17	215 – 100 eV	0	2
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Outgoing spectrum (upper picture) and capture spectrum. Sphere 74W R= 80 cm

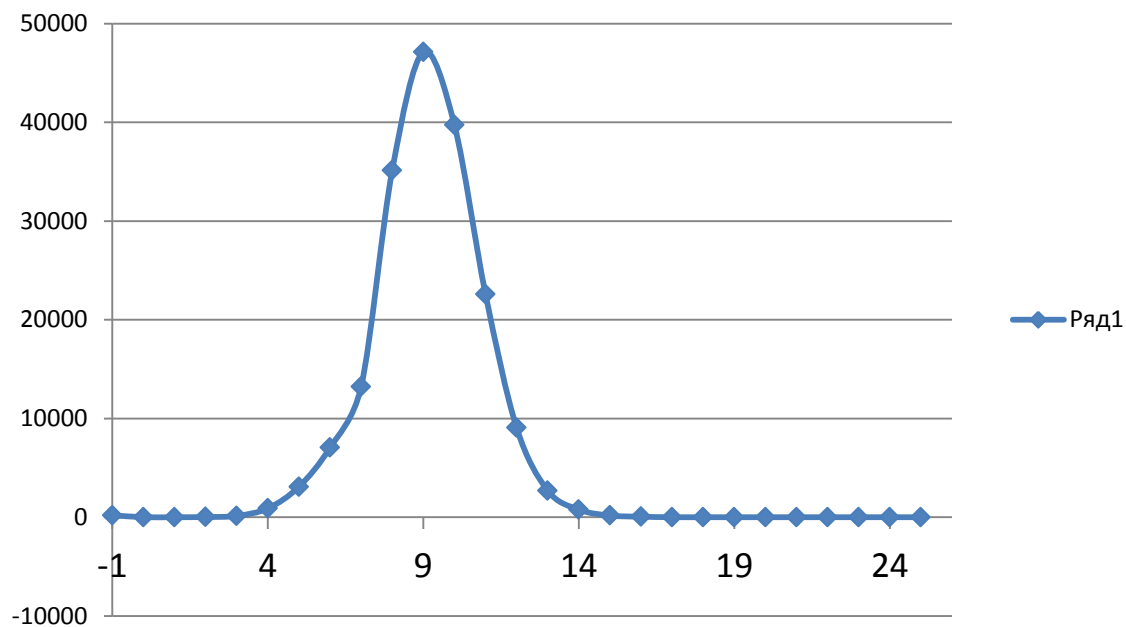


ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	0	196
0	14.0-10.5 MeV	0	5
1	10.5 – 6.5 MeV	0	2
2	6.5 – 4.0 MeV	0	20
3	4.0 – 2.5 MeV	0	135
4	2.5 – 1.4 MeV	0	897
5	1.4 – 0.8 MeV	0	3085
6	0.8 – 0.4 MeV	0	7048
7	0.4 – 0.2 MeV	0	13208
8	0.2 – 0.1 MeV	0	35134
9	100 – 46.5 KeV	0	47113
10	46.5 – 21.5 KeV	0	39720
11	21.5 – 10 KeV	0	22585
12	10 – 4.65 KeV	0	9062
13	4.65 – 2.15 KeV	0	2695
14	2.15 – 1 KeV	0	772
15	1 – 0.465 KeV	0	172
16	465 – 215 eV	0	50
17	215 – 100 eV	0	2
18	100 – 46.5 eV	0	0
19	46.5 – 21.5 eV	0	0
20	21.5 – 10 eV	0	0
21	10 – 4.65 eV	0	0
22	4.65 – 2.15 eV	0	0
23	2.15 – 1.0 eV	0	0
24	1.0 – 0.465 eV	0	0
25	0.465 – 0.215 eV	0	0
26	0.215 – 0.001 eV	0	0

Sphere 74W R= 100 cm

Capture spectrum

Majority of initial 14 MeV neutrons in infinite tungsten media are captured at energies from 400 KeV to 4.65 KeV



Spectrums in tungsten 74W spheres

ABBN-78 Group №	Energy Interval	R = 1 cm		R = 5 cm		R = 10 cm		R = 15 cm		R = 20 cm		R = 25 cm	
		Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum
-1	14.5-14.0 MeV	85435	33	44951	129	19290	152	7882	179	3101	173	1105	168
0	14.0-10.5 MeV	477	0	1224	1	1314	2	975	5	655	3	438	9
1	10.5-6.5 MeV	710	0	1658	3	1158	1	656	2	299	3	155	2
2	6.5-4.0 MeV	996	0	2237	6	1576	13	802	14	421	12	174	26
3	4.0-2.5 MeV	2088	3	4334	34	2799	86	1408	104	621	123	286	129
4	2.5-1.4 MeV	5029	10	11330	198	7595	535	3876	749	1706	786	684	823
5	1.4-0.8 MeV	6526	21	19910	514	17084	1486	9948	2364	4812	2649	2157	2868
6	0.8-0.4 MeV	5872	21	25100	664	31011	2559	22581	4481	13340	5643	6820	6368
7	0.4-0.2 MeV	2189	10	15440	516	28480	2770	27276	6304	19626	9148	12019	11059
8	0.2-0.1 MeV	1117	7	8280	525	19920	4132	25502	11423	22694	19454	16081	25736
9	100-46.5 KeV	574	10	3824	438	10459	3455	15770	11005	15984	21045	13043	30126
10	46.5-21.5 KeV	265	5	1558	239	3857	2146	5968	7105	6726	14679	6121	22501
11	21.5-10 KeV	18	0	337	109	1075	979	1756	3576	2035	7550	1883	12129
12	10-4.65 KeV	6	0	94	67	251	481	385	1654	427	3314	374	5039
13	4.65-2.15 KeV	2	2	31	40	44	219	70	625	67	1145	49	1729
14	2.15-1 KeV	0	0	9	14	5	99	8	197	6	356	6	478
15	1-0.465 KeV	0	0	0	6	2	25	4	66	1	90	1	119
16	465-215 eV	0	0	0	1	0	5	1	17	0	23	0	32
17	215-100 eV	0	0	0	1	0	1	0	0	0	1	0	2
18	100-46.5 eV	0	0	0	0	0	0	0	0	0	0	0	0
19	46.5-21.5 eV	0	0	0	0	0	0	0	0	0	0	0	0
20	21.5-10 eV	0	0	0	0	0	0	0	0	0	0	0	0
21	10-4.65 eV	0	0	0	0	0	0	0	0	0	0	0	0
22	4.6-2.15 eV	0	0	0	0	0	0	0	0	0	0	0	0
23	2.1-1.0 eV	0	0	0	0	0	0	0	0	0	0	0	0
24	1.0-0.465 eV	0	0	0	0	0	0	0	0	0	0	0	0
25	0.46-0.215 eV	0	0	0	0	0	0	0	0	0	0	0	0
26	0.215-0.001 eV	0	0	0	0	0	0	0	0	0	0	0	0
Average Neutron Energy		11.23 MeV	4.37 MeV	5.35 MeV	1.01 MeV	2.57 MeV	430 KeV	1.44 MeV	278 KeV	0.91 MeV	206 KeV	626 KeV	176 KeV
Diffusion time of outgoing neutrons, nanoseconds		0.36		5.96		25.27		56.32		91.79		128.91	
Number of neutrons		111304	122	140317	3505	145920	19146	124868	49870	92521	86197	61396	119343

Spectrums in tungsten 74W spheres

ABBN-78 Group №	Energy Interval	R = 30 cm		R = 40 cm		R = 50 cm		R = 65 cm		R = 80 cm		R = 100 cm	
		Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum
-1	14.5-14.0 MeV	402	188	44	194	5	193	0	198	0	197	0	196
0	14.0-10.5 MeV	224	10	49	4	7	4	1	5	0	5	0	5
1	10.5-6.5 MeV	49	2	12	0	2	0	0	1	0	2	0	2
2	6.5-4.0 MeV	75	21	15	18	2	17	1	20	0	20	0	20
3	4.0-2.5 MeV	126	129	9	140	1	136	0	133	0	135	0	135
4	2.5-1.4 MeV	292	818	61	896	7	884	0	892	0	897	0	897
5	1.4-0.8 MeV	965	3094	176	3071	21	3071	1	3096	0	3081	0	3085
6	0.8-0.4 MeV	3176	6719	604	6959	91	7042	6	7063	0	7048	0	7048
7	0.4-0.2 MeV	6443	12105	1530	12944	273	13216	11	13212	1	13214	0	13208
8	0.2-0.1 MeV	10140	29934	3075	33912	729	34898	60	35112	2	35136	0	35134
9	100-46.5 KeV	9202	37031	3353	44177	955	46223	102	47025	7	47100	0	47113
10	46.5-21.5 KeV	4606	28991	1952	36236	619	38796	88	39604	9	39707	0	39720
11	21.5-10 KeV	1457	15583	682	20062	230	21923	36	22475	2	22573	0	22585
12	10-4.65 KeV	261	6476	128	8146	43	8829	9	9044	1	9062	0	9062
13	4.65-2.15 KeV	46	2084	17	2534	3	2635	0	2689	0	2698	0	2695
14	2.15-1 KeV	4	592	1	706	0	771	0	769	0	773	0	772
15	1-0.465 KeV	1	146	0	147	0	165	0	170	0	172	0	172
16	465-215 eV	0	36	0	44	0	46	0	48	0	50	0	50
17	215-100 eV	0	3	0	1	0	2	0	2	0	2	0	2
18	100-46.5 eV	0	0	0	0	0	0	0	0	0	0	0	0
19	46.5-21.5 eV	0	0	0	0	0	0	0	0	0	0	0	0
20	21.5-10 eV	0	0	0	0	0	0	0	0	0	0	0	0
21	10-4.65 eV	0	0	0	0	0	0	0	0	0	0	0	0
22	4.6-2.15 eV	0	0	0	0	0	0	0	0	0	0	0	0
23	2.1-1.0 eV	0	0	0	0	0	0	0	0	0	0	0	0
24	1.0-0.465 eV	0	0	0	0	0	0	0	0	0	0	0	0
25	0.46-0.215 eV	0	0	0	0	0	0	0	0	0	0	0	0
26	0.215-0.001 eV	0	0	0	0	0	0	0	0	0	0	0	0
Average Neutron Energy		457 KeV	162 KeV	278 KeV	148 KeV	182 KeV	143 KeV	138 KeV	142 KeV	65 KeV	142 KeV	-----	142 KeV
Diffusion time of outgoing neutrons, nanoseconds		164		235		304		427		514		-----	
Number of neutrons		37469	143961	11708	170191	2988	178851	315	181558	22	181872	0	181901

Spectrums in ^{26}Fe spheres

ABBN-78 Group №	Energy Interval	R = 1 cm		R = 5 cm		R = 10 cm		R = 15 cm		R = 20 cm		R = 25 cm	
		Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum
-1	14.5-14.0 MeV	85185	1571	44672	5759	19098	8442	7866	9702	3285	9959	1367	10066
0	14.0-10.5 MeV	3123	24	8804	449	8473	1172	6197	1758	3855	2178	2170	2335
1	10.5-6.5 MeV	582	3	1351	50	1171	129	722	159	392	207	197	214
2	6.5-4.0 MeV	1945	2	4907	68	4338	149	2672	227	1550	281	820	311
3	4.0-2.5 MeV	3400	2	10063	55	9308	152	6242	226	3654	283	1956	290
4	2.5-1.4 MeV	3670	0	13879	15	16811	84	13473	147	9165	171	5583	193
5	1.4-0.8 MeV	2302	0	11512	15	19529	61	21426	135	18599	181	14158	234
6	0.8-0.4 MeV	1089	1	7445	24	17129	109	24207	300	26583	489	24866	820
7	0.4-0.2 MeV	375	0	2802	15	8499	75	16476	228	24250	567	28992	1061
8	0.2-0.1 MeV	109	0	906	3	2945	34	5405	124	8417	329	11003	618
9	100-46.5 KeV	51	1	312	3	1074	18	2474	105	4261	262	6054	601
10	46.5-21.5 KeV	6	0	37	3	106	11	304	24	560	107	964	271
11	21.5-10 KeV	0	0	18	0	246	2	923	7	2584	47	4938	153
12	10-4.65 KeV	0	0	0	0	1	0	52	7	195	42	503	136
13	4.65-2.15 KeV	0	0	0	0	1	0	42	3	251	11	711	69
14	2.15-1 KeV	0	0	0	0	0	0	12	15	88	140	353	822
15	1-0.465 KeV	0	0	0	0	0	0	3	0	29	2	98	20
16	465-215 eV	0	0	0	0	0	0	1	0	22	5	71	25
17	215-100 eV	0	0	0	0	0	0	3	0	17	6	44	46
18	100-46.5 eV	0	0	0	0	0	0	0	0	5	6	44	43
19	46.5-21.5 eV	0	0	0	0	0	0	0	0	6	5	40	39
20	21.5-10 eV	0	0	0	0	0	0	0	0	5	8	21	51
21	10-4.65 eV	0	0	0	0	0	0	0	0	2	10	21	50
22	4.6-2.15 eV	0	0	0	0	0	0	0	0	2	8	17	44
23	2.1-1.0 eV	0	0	0	0	0	0	0	0	2	6	5	28
24	1.0-0.465 eV	0	0	0	0	0	0	0	0	0	4	3	12
25	0.46-0.215 eV	0	0	0	0	0	0	0	0	1	1	0	14
26	0.215-0.001 eV	0	0	0	0	0	0	0	0	0	1	0	2
Average Neutron Energy		12.58 MeV	14.04 MeV	8.12 MeV	13.69 MeV	4.73 MeV	13.21 MeV	2.80 MeV	12.53 MeV	1.70 MeV	11.47 MeV	1.05 MeV	9.70 MeV
Diffusion time of outgoing neutrons, nanoseconds		0.25		2.64		10.71		29.00		66.78		135.15	
Number of neutrons		101837	1604	106708	6459	108729	10438	108501	13167	107780	15316	104999	18568

Spectrums in ^{26}Fe spheres

ABBN-78 Group №	Energy Interval	R = 40 cm		R = 65 cm		R = 80 cm		R = 100 cm		R = 120 cm		R = 140 cm	
		Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum
-1	14.5-14.0 MeV	93	10319	0	10392	0	10315	0	10319	0	10326	0	10298
0	14.0-10.5 MeV	345	2623	14	2616	0	2668	0	2652	0	2657	0	2662
1	10.5-6.5 MeV	29	259	0	245	0	246	0	257	0	247	0	249
2	6.5-4.0 MeV	109	342	1	323	0	350	0	339	0	344	0	347
3	4.0-2.5 MeV	253	286	3	320	0	347	0	337	0	343	0	339
4	2.5-1.4 MeV	970	208	23	235	2	228	0	227	0	228	0	229
5	1.4-0.8 MeV	4044	336	253	326	38	379	2	376	0	376	0	375
6	0.8-0.4 MeV	11212	1399	1189	1668	264	1707	18	1674	1	1684	0	1695
7	0.4-0.2 MeV	24097	2500	5497	3767	1598	3795	233	3819	28	3833	2	3817
8	0.2-0.1 MeV	12862	1871	4755	3260	1693	3533	327	3626	47	3624	4	3629
9	100-46.5 KeV	8658	2208	4065	4240	1610	4747	366	4944	60	5009	3	5030
10	46.5–21.5 KeV	1541	1217	788	2544	325	2819	77	2939	14	2933	6	2957
11	21.5– 10 KeV	10593	855	6901	2106	3354	2482	876	2574	182	2636	35	2630
12	10– 4.65 KeV	1629	1062	1310	3154	665	3833	196	4141	41	4211	12	4203
13	4.65– 2.15 KeV	2643	653	2414	1893	1257	2243	403	2552	76	2630	24	2636
14	2.15 – 1 KeV	1460	8961	1424	29465	813	36481	263	40197	49	41229	11	41422
15	1– 0.465 KeV	512	246	523	970	317	1236	116	1329	23	1357	3	1363
16	465– 215 eV	376	308	427	1251	257	1525	85	1752	19	1814	5	1818
17	215– 100 eV	323	392	394	1678	223	2023	84	2296	13	2370	7	2388
18	100– 46.5 eV	242	534	298	2064	190	2714	90	3098	20	3169	3	3205
19	46.5– 21.5 eV	228	655	295	2753	196	3593	75	4145	20	4283	4	4311
20	21.5– 10 eV	186	795	226	3235	144	4278	50	4878	11	5058	5	5092
21	10– 4.65 eV	108	863	168	3641	124	4884	47	5623	8	5773	3	5852
22	4.6 – 2.15 eV	86	904	114	3748	110	4980	32	5741	11	5965	1	6031
23	2.1 – 1.0 eV	40	705	59	3241	55	4307	17	4957	9	5207	0	5214
24	1.0– 0.465 eV	29	448	25	2134	22	2836	10	3349	3	3455	0	3475
25	0.46 – 0.215 eV	6	216	15	1087	5	1457	5	1753	1	1837	1	1851
26	0.215– 0.001 eV	0	73	0	381	0	495	0	587	0	621	0	626
Average Neutron Energy		352 KeV	4.59 MeV	119 KeV	2.06 MeV	77.13 KeV	1.73 MeV	47.65 KeV	1.58 MeV	34.51 KeV	1.55 MeV	15.64 KeV	1.54 MeV
Diffusion time of outgoing neutrons, nanoseconds		502		1262		1926		2526		3267		3532	
Number of neutrons		82674	41238	31181	92737	13262	110501	3372	120481	636	123219	129	123744

Spectrums in Na23 spheres

ABBN-78 Group №	Energy Interval	R = 1 cm		R = 5 cm		R = 10 cm		R = 15 cm		R = 20 cm		R = 25 cm	
		Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum
-1	14.5-14.0 MeV	96189	447	82060	2050	67413	3862	55455	5280	45668	6262	37504	7153
0	14.0-10.5 MeV	1450	2	6705	96	11126	355	14128	666	15936	1040	16738	1628
1	10.5-6.5 MeV	8	0	56	0	116	2	166	4	240	3	308	14
2	6.5-4.0 MeV	49	0	212	0	325	1	474	1	583	4	596	4
3	4.0-2.5 MeV	256	0	1004	0	1730	0	2339	1	2685	0	2844	0
4	2.5-1.4 MeV	573	0	2561	0	4666	0	6122	0	7146	1	7779	2
5	1.4-0.8 MeV	491	0	2523	0	4685	0	6202	1	7589	1	8310	0
6	0.8-0.4 MeV	410	0	2017	0	3819	0	5530	0	6891	2	7918	2
7	0.4-0.2 MeV	150	0	780	1	1797	0	3111	2	4576	4	6366	10
8	0.2-0.1 MeV	56	0	251	0	640	0	1140	1	1949	0	3064	3
9	100-46.5 KeV	9	0	102	0	178	0	321	0	521	0	766	2
10	46.5-21.5 KeV	6	0	15	0	57	0	103	0	201	0	384	0
11	21.5-10 KeV	0	0	2	0	1	0	11	0	27	0	80	0
12	10-4.65 KeV	0	0	0	0	0	0	0	0	1	0	12	0
13	4.65-2.15 KeV	0	0	0	0	0	0	0	0	0	0	1	0
14	2.15-1 KeV	0	0	0	0	0	0	0	0	2	0	6	0
15	1-0.465 KeV	0	0	0	0	0	0	0	0	1	0	1	0
16	465-215 eV	0	0	0	0	0	0	0	0	0	0	0	0
17	215-100 eV	0	0	0	0	0	0	0	0	0	0	0	0
18	100-46.5 eV	0	0	0	0	0	0	0	0	0	0	0	0
19	46.5-21.5 eV	0	0	0	0	0	0	0	0	0	0	0	0
20	21.5-10 eV	0	0	0	0	0	0	0	0	0	0	0	0
21	10-4.65 eV	0	0	0	0	0	0	0	0	0	0	0	0
22	4.6-2.15 eV	0	0	0	0	0	0	0	0	0	0	0	0
23	2.1-1.0 eV	0	0	0	0	0	0	0	0	0	0	0	0
24	1.0-0.465 eV	0	0	0	0	0	0	0	0	0	0	0	0
25	0.46-0.215 eV	0	0	0	0	0	0	0	0	0	0	0	0
26	0.215-0.001 eV	0	0	0	0	0	0	0	0	0	0	0	0
Average Neutron Energy		13.84 MeV	14.10 MeV	12.85 MeV	14.07 MeV	11.67 MeV	14.04 MeV	10.60 MeV	14.01 MeV	9.58 MeV	13.99 MeV	8.63 MeV	13.93 MeV
Diffusion time of outgoing neutrons, nanoseconds		0.20		1.29		3.42		6.67		11.64		19.03	
Number of neutrons		99647	449	98288	2147	96553	4220	95102	5956	94016	7317	92677	8818

Spectrums in Na23 spheres

ABBN-78 Group №	Energy Interval	R = 40 cm		R = 65 cm		R = 80 cm		R = 100 cm		R = 120 cm		R = 140 cm	
		Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum	Outgoing Spectrum	Capture Spectrum
-1	14.5-14.0 MeV	20581	9236	7555	10800	4209	11228	1907	11341	909	11456	384	11461
0	14.0-10.5 MeV	15534	3003	10615	4913	7596	5685	4599	6355	2708	6827	1556	7076
1	10.5-6.5 MeV	397	24	404	71	336	80	248	85	185	114	142	119
2	6.5-4.0 MeV	678	3	544	10	381	5	235	16	172	18	87	21
3	4.0-2.5 MeV	2831	0	2137	0	1535	1	976	1	570	1	363	1
4	2.5-1.4 MeV	7982	4	5380	10	4076	7	2487	4	1450	5	832	7
5	1.4-0.8 MeV	8871	2	6648	5	4889	4	3014	7	1838	9	1053	11
6	0.8-0.4 MeV	9411	9	7403	13	5672	21	3451	22	2104	28	1220	22
7	0.4-0.2 MeV	10698	11	11751	24	9809	50	6775	63	4195	85	2472	84
8	0.2-0.1 MeV	7731	18	13120	71	13160	90	10954	131	7820	159	5080	186
9	100-46.5 KeV	2317	11	5455	54	6366	92	5967	166	4531	186	3056	232
10	46.5-21.5 KeV	1624	3	5812	29	7526	62	8001	101	6745	155	5134	191
11	21.5- 10 KeV	581	0	3011	1	4429	2	5304	3	5030	3	4087	9
12	10- 4.65 KeV	116	0	950	14	1498	18	1970	39	1913	63	1571	102
13	4.65- 2.15 KeV	3	2	23	41	30	111	51	240	40	306	51	455
14	2.15 - 1 KeV	118	3	926	82	1562	203	2176	429	2258	710	1885	845
15	1- 0.465 KeV	124	1	2135	49	4267	140	6585	375	7478	608	7042	866
16	465- 215 eV	35	0	1151	29	2886	109	5420	324	7066	549	7210	802
17	215- 100 eV	7	0	551	9	1643	77	3746	242	5355	444	6188	781
18	100- 46.5 eV	0	0	251	6	1035	56	2490	199	4133	472	5154	789
19	46.5- 21.5 eV	0	0	130	11	545	41	1751	188	3013	496	4225	848
20	21.5- 10 eV	0	0	48	3	307	28	1152	171	2206	545	3157	977
21	10- 4.65 eV	0	0	21	3	171	29	735	187	1602	563	2429	1124
22	4.6 - 2.15 eV	0	0	7	1	85	16	452	152	1105	574	1815	1288
23	2.1 - 1.0 eV	0	0	1	1	37	11	273	166	725	560	1221	1248
24	1.0- 0.465 eV	0	0	2	0	22	6	158	121	479	499	807	1220
25	0.46 - 0.215 eV	0	0	0	1	8	6	63	94	255	377	509	1014
26	0.215- 0.001 eV	0	0	0	0	5	11	29	118	105	582	196	1687
Average Neutron Energy		6.13 MeV	13.86 MeV	3.35 MeV	13.47 MeV	2.28 MeV	12.93 MeV	1.33 MeV	11.52 MeV	809 KeV	9.62 MeV	491 KeV	7.69 MeV
Diffusion time of outgoing neutrons, nanoseconds		71.42		633.82		2054		6650		14733		24880	
Number of neutrons		89639	12330	86031	16251	84085	18189	80969	21340	75990	26394	68926	33466

Modeling results of numerical calculation show, that:

1)

Leakage neutron spectrum which can be measured by TOF method, and absorption spectrum, are two different neutron spectrums. In common case, they have maximum number of neutrons in different energy groups. Their correlation can be found making variant numerical calculations.

2)

In the case of big assemblies, which radius many times exceeds transport free path of neutrons, their spectrum has average energy around 100 keV. This energy many times smaller than average energy of initial fission spectrum which is ~2 MeV. Such energies around ~100 KeV can be measured by existing TOF spectrometers which have resolution factor ~ 6 nanoseconds/meter and better.

3)

Substances with small absorption cross section and intermediate masses of nuclei, including ^{26}Fe and ^{23}Na , in the case of big enough thicknesses, produce spectrum similar to spectrum Fermi. Fermi spectrum, in which neutron flux $\Phi \sim (1/E)$ is analytical idealization for the case, when exist no leakage and no absorption. Integration $(1/E) \cdot dE$ results, that if lethargy interval on energy axis is constant, then each of 28 energy groups has equal quantity of neutrons.

4)

During propagating of neutrons from the center to external surface of the sphere, their average energy decrease: at first rapidly due to inelastic cross section until energy is above it's threshold for selected nuclide. After energy becomes smaller than inelastic threshold, spectrum continues to moderate slowly due to elastic cross section. Substances like ^{74}W with high capture cross section in resonance area, absorb majority of neutrons above 14th group i.e. above 1 KeV.

Conclusion

1.

Integral experiments are integral check of all main types of nuclear constants, of cross sections for interaction of neutrons with nuclei, as suggested in [5].

Such experiments can be made also with subcritical assemblies. Neutron spectrums of large fast breeder reactors with diluted fissile material has average energy around ~ 140 KeV. This value turns out measureable already by existing TOF spectrometers, which have resolution factor 6 nanoseconds per meter and better.

2.

Outgoing spectrum and capture spectrum differ one from another. Outgoing spectrum can be measured by TOF method, while capture spectrum is needed to calculate fast neutron reactor's breeding ratio. Using experimentally observable TOF spectrum, it's possible to reconstruct capture spectrum using numerical modeling.

3.

Due to big durations of diffusion time in the case of big assemblies, comparable to microsecond, spectrums of large subcritical assemblies with radius comparable to 1 meter, can be measured by TOF method only using long TOF bases. Their length must be several hundreds meters to provide energy resolution, high enough for spectrum average neutron energy around 140 KeV.

4.

Authors currently stockpiled calculated data, in 28-group calculation, on 52 isotopes and isotope mixtures. This is about 20% of existing in nature 286 stable isotopes and 62 their mixtures.

Future work includes comparing this data with 299-group ABBN-93 calculation results. Also comparing with calculation results of codes, which use introduction of cross sections as continuous curves instead of energy groups.

5.

With statistics around 1,000,000 neutrons, providing discreteness calculation precision component better than value of delayed neutron's share, performance of the program allows to calculate big quantity of variants using modern personal computer.

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Thank you for your attention!