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Experimental Measurements of TOF Histogram in High Energy Part of Neutron Spectrum

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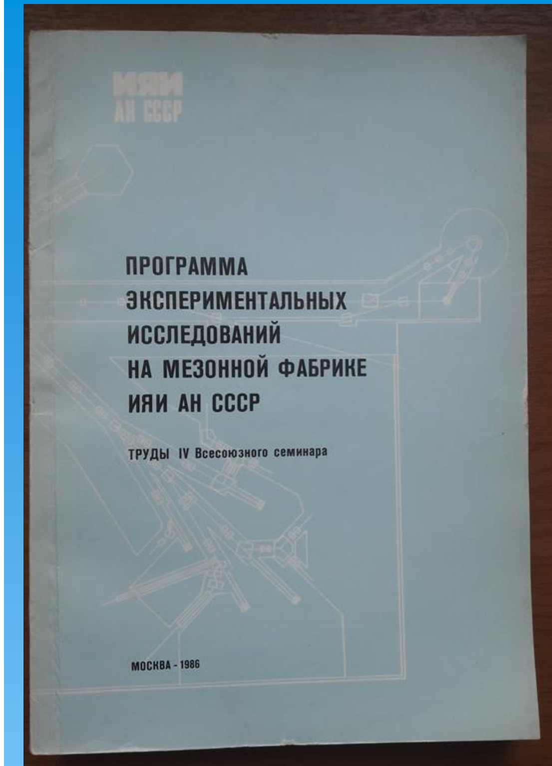
Abstract

An increase of detector's and data acquisition system's performance, made it possible for TOF spectrometer to distinguish the initial part of the histogram, which corresponds to cascade and fast neutrons.

The work presents experimentally measured initial parts of TOF spectra, obtained using samples-radiators of Au197 and other subjects as target materials. The possibility to reconstruct neutron target station's fast neutron spectrum, using experimental histogram, is discussed.

Measurements were carried out with a channel duration 100 nanoseconds of the data acquisition system, and proton linear accelerator operating with parameters: proton beam duration 250 nanoseconds at half-maximum current amplitude, proton beam energy 267 MeV, pulsed current 10 mA, flash frequency 50 Hz. TOF spectrometer base 50 meters provided resolution factor: 6 nanoseconds per meter.

Practical implementations for initial histogram's part



Already early works [1] were emphasizing, that high energy part of histogram is important not only for partial and total cross sections measurements. Measurement of initial part of spectra allows also to study experimentally neutron flux as function of neutron energy. It is own for each subcritical assembly used as proton beam target, which produces neutrons for TOF experiment.

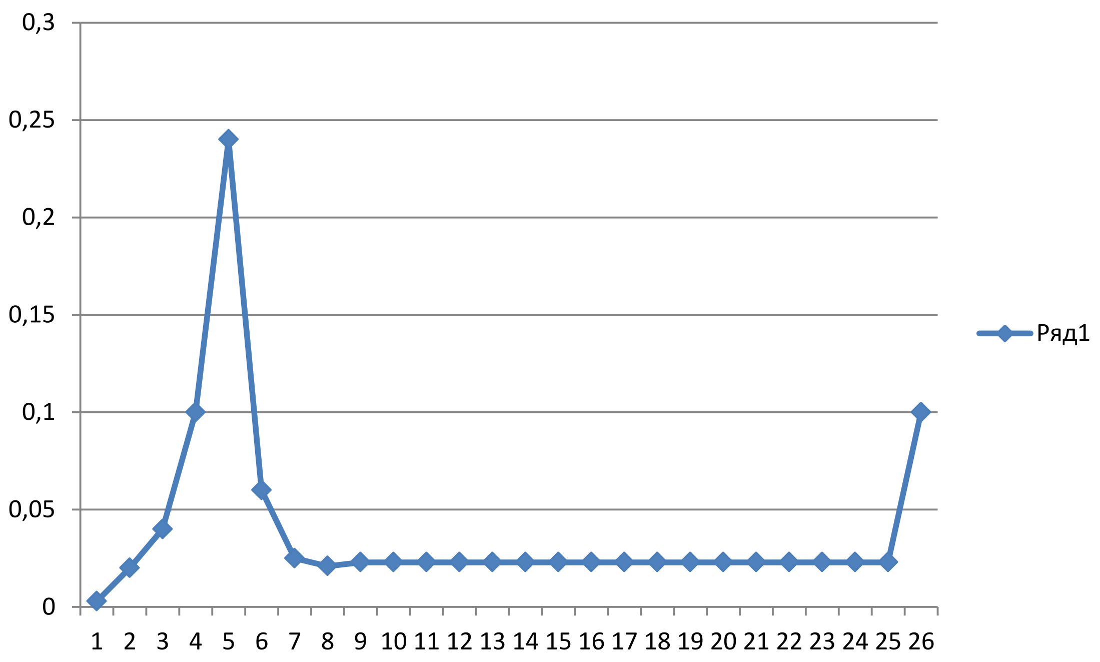
Research program [1] suggested to make macroscopic neutron TOF experiments for fast breeder reactors and electronuclear breeders, using several proton beam target stations with different isotope compositions.

'Creation of calculation codes, for nuclear energy devices, can rely not only on measurements of microscopic cross sections. Debugging of systems of multi-group constants is possible, basing on making 'macroscopic' experiments with model assemblies of nuclear energy devices. Comparison with calculation of experimental properties of such assemblies (neutron balance, spatial distribution of neutron reactions, averaged by energy spectrum of neutrons – fission, capture, threshold reactions) is base for adjustments and 'customization' of multi group constants.

At average heat release in assembly target ~1 kW, detailed measurements of neutron balance are possible using TOF method'.

IBR-30 spectrum and flux at 1000 meter TOF base [2]

ABBN-78 Group №	Energy interval	Delta(n)/n	Neutron flux, (1/cm*sec)
1	10.5 – 6.5 MeV	0.003	5
2	6.5 – 4.0 MeV	0.02	35
3	4.0 – 2.5 MeV	0.04	70
4	2.5 – 1.4 MeV	0.1	173
5	1.4 – 0.8 MeV	0.24	415
6	0.8 – 0.4 MeV	0.06	104
7	0.4 – 0.2 MeV	0.025	43
8	0.2 – 0.1 MeV	0.021	37
9	100 – 46.5 KeV	0.023	40
10	46.5 – 21.5 KeV	0.023	40
11	21.5 – 10 KeV	0.023	40
12	10 – 4.65 KeV	0.023	40
13	4.65 – 2.15 KeV	0.023	40
14	2.15 – 1 KeV	0.023	40
15	1 – 0.465 KeV	0.023	40
16	465 – 215 eV	0.023	40
17	215 – 100 eV	0.023	40
18	100 – 46.5 eV	0.023	40
19	46.5 – 21.5 eV	0.023	40
20	21.5 – 10 eV	0.023	40
21	10 – 4.65 eV	0.023	40
22	4.65 – 2.15 eV	0.023	40
23	2.15 – 1.0 eV	0.023	40
24	1.0 – 0.465 eV	0.023	40
25	0.465 – 0.215 eV	0.023	40
26	0.215 – 0.001 eV	0.1	174



Numerical modeling results

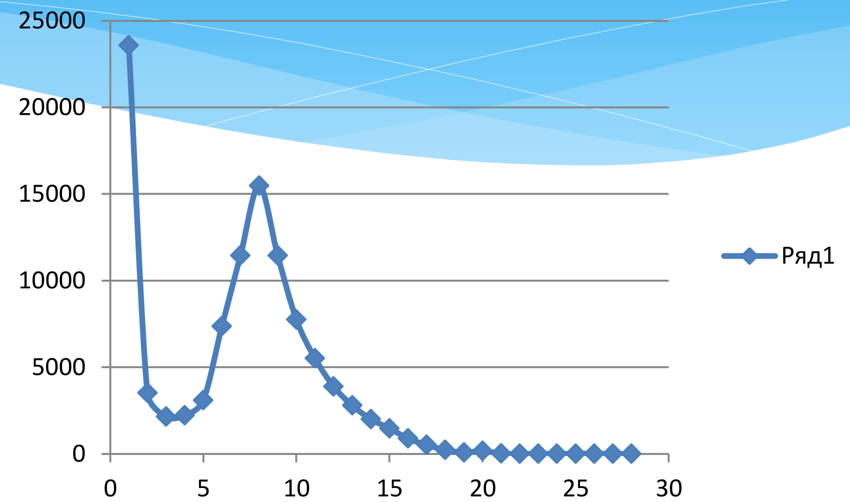
For calibration of numerical calculation method, neutron spectrums of subcritical assemblies were preliminary studied using spherical model with neutron source in the center.

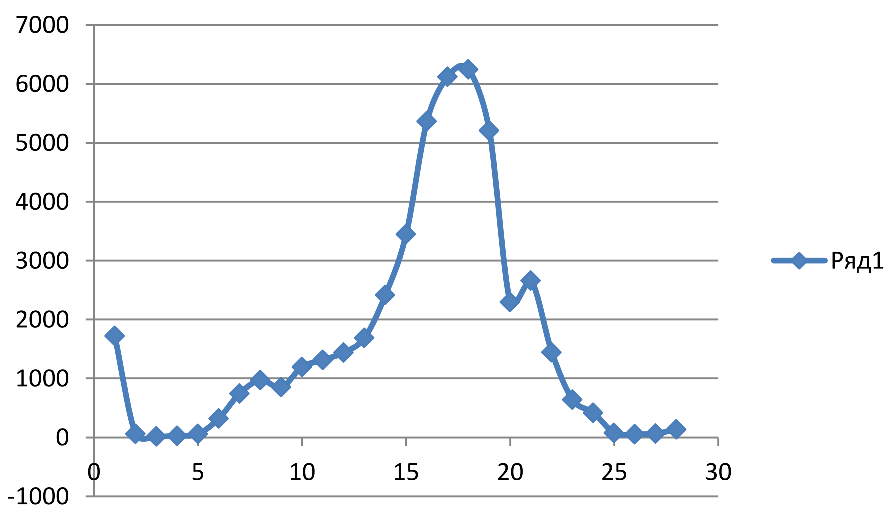
Using code ‘Shield’ [3,4] for spheres of different substances and different radiuses, were calculated for them:

* average leakage neutron spectrum lifetime,
* spectrum of absorbed neutrons, and
* spectrum of leakage neutron flux on external surface of the sphere.

Example of calculated spectrum
Sphere R=10 cm
Material: W(75%vol.)H2O(25%vol.)

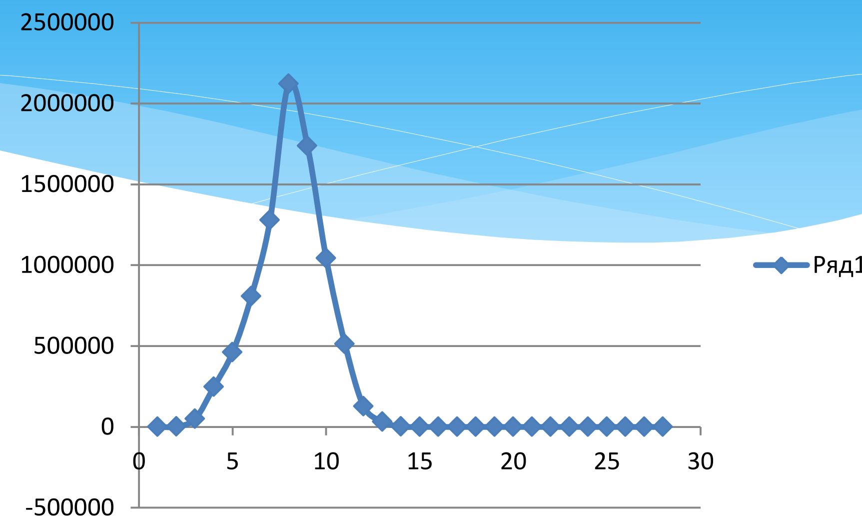
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	23586	1721
0	14.0-10.5 MeV	3515	60
1	10.5 – 6.5 MeV	2159	16
2	6.5 – 4.0 MeV	2233	29
3	4.0 – 2.5 MeV	3099	58
4	2.5 – 1.4 MeV	7362	320
5	1.4 – 0.8 MeV	11457	745
6	0.8 – 0.4 MeV	15482	971
7	0.4 – 0.2 MeV	11442	851
8	0.2 – 0.1 MeV	7755	1195
9	100 – 46.5 KeV	5526	1313
10	46.5 – 21.5 KeV	3895	1440
11	21.5 – 10 KeV	2804	1689
12	10 – 4.65 KeV	2010	2415
13	4.65 – 2.15 KeV	1477	3446
14	2.15 – 1 KeV	894	5365
15	1 – 0.465 KeV	519	6121
16	465 – 215 eV	229	6243
17	215 – 100 eV	79	5208
18	100 – 46.5 eV	171	2297
19	46.5 – 21.5 eV	22	2662
20	21.5 – 10 eV	1	1447
21	10 – 4.65 eV	17	641
22	4.65 – 2.15 eV	1	419
23	2.15 – 1.0 eV	15	76
24	1.0 – 0.465 eV	14	55
25	0.465 – 0.215 eV	11	65
26	0.215 – 0.001 eV	3	137

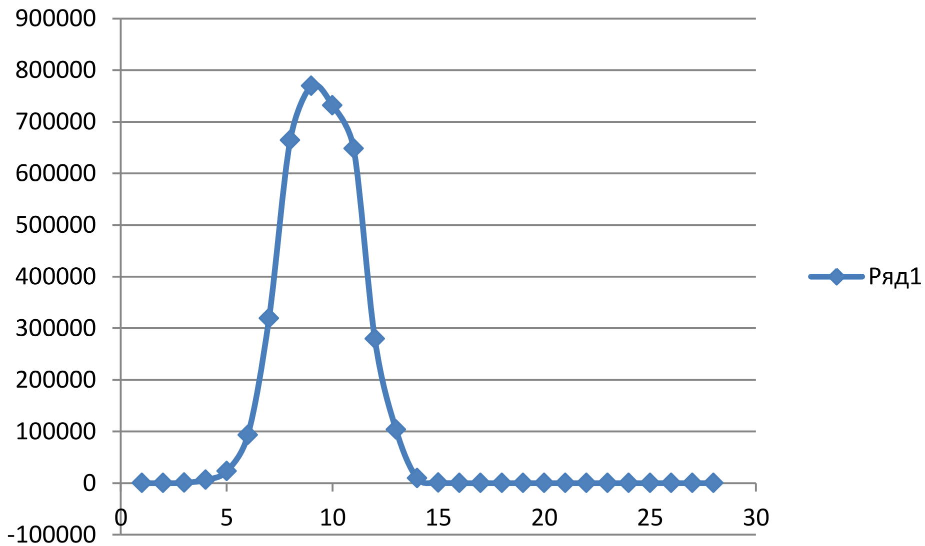




Example of calculated spectrums Sphere R=20.1 cm Material: U235(20%)U238(80%)

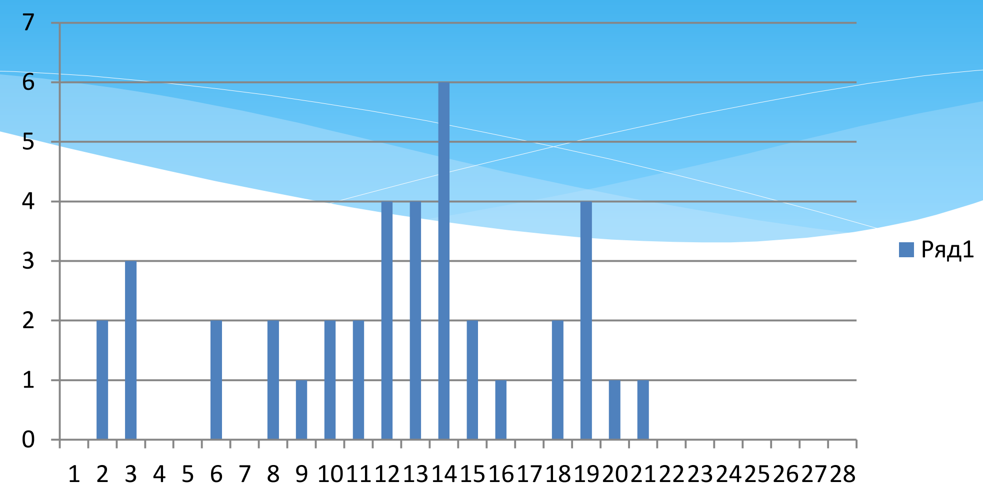
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	0	0
0	14.0-10.5 MeV	2225	10
1	10.5 – 6.5 MeV	50112	634
2	6.5 – 4.0 MeV	247693	6366
3	4.0 – 2.5 MeV	461785	23193
4	2.5 – 1.4 MeV	807517	93034
5	1.4 – 0.8 MeV	1278327	319074
6	0.8 – 0.4 MeV	2122993	664144
7	0.4 – 0.2 MeV	1737957	769338
8	0.2 – 0.1 MeV	1043284	731877
9	100 – 46.5 KeV	514137	648126
10	46.5 – 21.5 KeV	126712	279418
11	21.5 – 10 KeV	32802	103788
12	10 – 4.65 KeV	2038	9687
13	4.65 – 2.15 KeV	187	1179
14	2.15 – 1 KeV	6	47
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

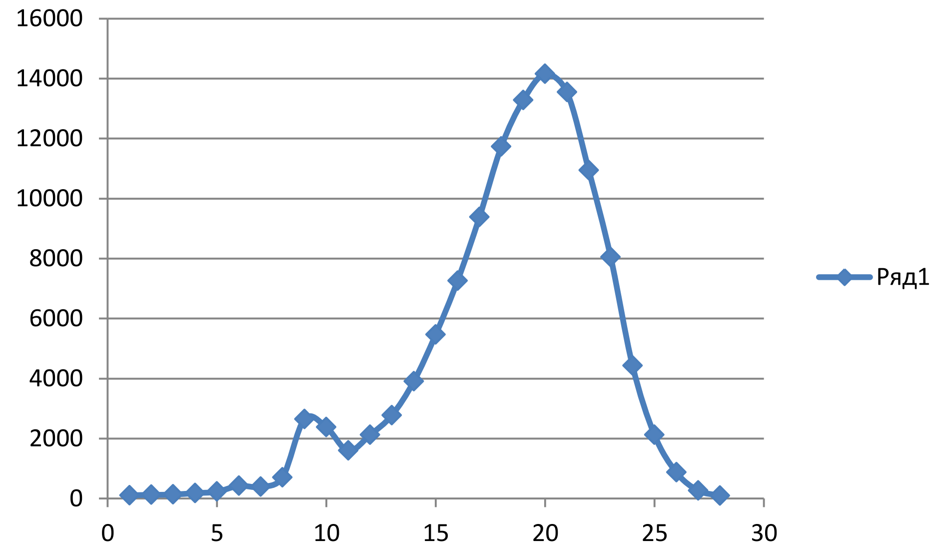




Example of calculated spectrums
Sphere R=0.1 cm
Material: LiD (p=880,000 kg/m^3 = 1000*p0)
Li6 (7.5%) Li7(92.5%)

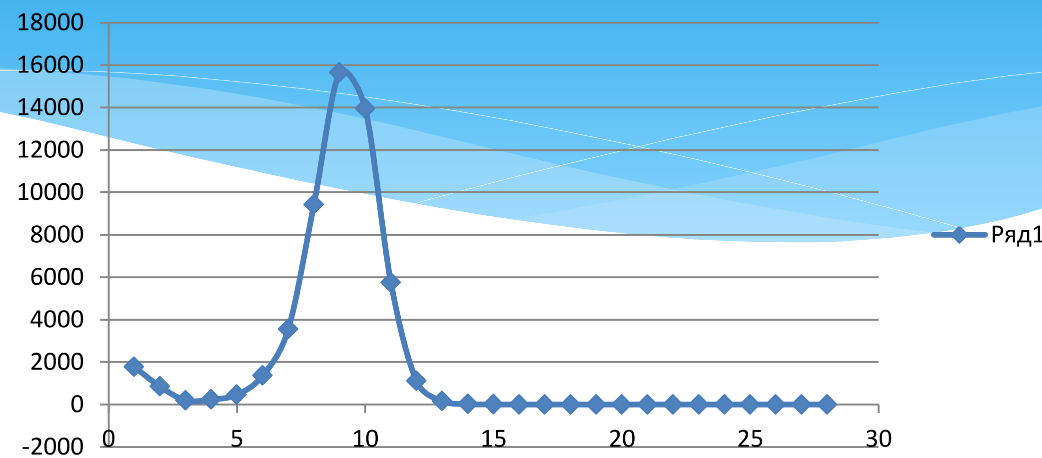
ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	0	108
0	14.0-10.5 MeV	2	124
1	10.5 – 6.5 MeV	3	134
2	6.5 – 4.0 MeV	0	181
3	4.0 – 2.5 MeV	0	227
4	2.5 – 1.4 MeV	2	423
5	1.4 – 0.8 MeV	0	390
6	0.8 – 0.4 MeV	2	705
7	0.4 – 0.2 MeV	1	2647
8	0.2 – 0.1 MeV	2	2380
9	100 – 46.5 KeV	2	1594
10	46.5 – 21.5 KeV	4	2118
11	21.5 – 10 KeV	4	2777
12	10 – 4.65 KeV	6	3902
13	4.65 – 2.15 KeV	2	5463
14	2.15 – 1 KeV	1	7256
15	1 – 0.465 KeV	0	9376
16	465 – 215 eV	2	11729
17	215 – 100 eV	4	13275
18	100 – 46.5 eV	1	14148
19	46.5 – 21.5 eV	1	13546
20	21.5 – 10 eV	0	10941
21	10 – 4.65 eV	0	8049
22	4.65 – 2.15 eV	0	4426
23	2.15 – 1.0 eV	0	2124
24	1.0 – 0.465 eV	0	872
25	0.465 – 0.215 eV	0	267
26	0.215 – 0.001 eV	0	97

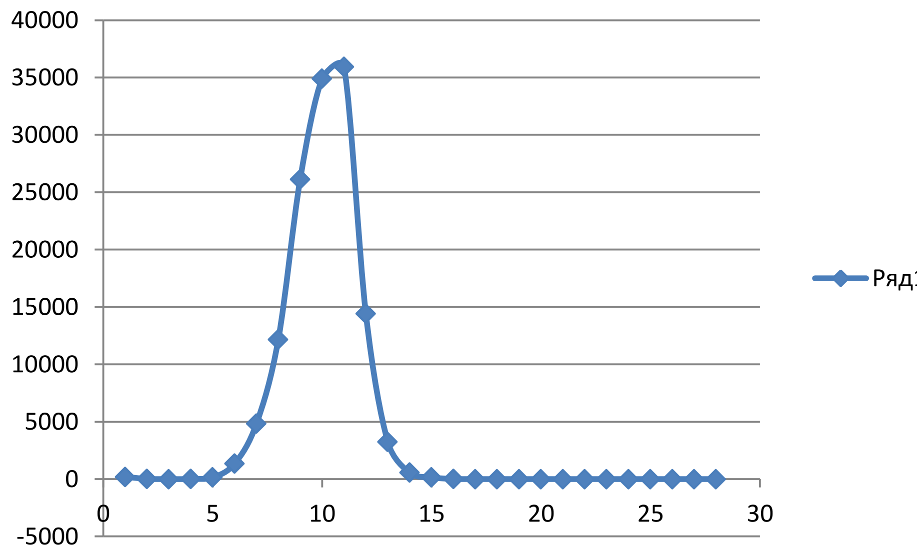




Example of calculated spectrums
Sphere R=25 cm
Material: Ta181 (metal)
Initial neutron's energy 14 MeV; 100,000 neutrons

ABBN-78 Group №	Energy interval	Outgoing spectrum	Capture spectrum
-1	14.5-14.0 MeV	1774	196
0	14.0-10.5 MeV	850	19
1	10.5 – 6.5 MeV	197	0
2	6.5 – 4.0 MeV	231	11
3	4.0 – 2.5 MeV	465	148
4	2.5 – 1.4 MeV	1359	1339
5	1.4 – 0.8 MeV	3545	4822
6	0.8 – 0.4 MeV	9430	12160
7	0.4 – 0.2 MeV	15643	26135
8	0.2 – 0.1 MeV	13949	34891
9	100 – 46.5 KeV	5748	35927
10	46.5 – 21.5 KeV	1104	14408
11	21.5 – 10 KeV	165	3255
12	10 – 4.65 KeV	21	565
13	4.65 – 2.15 KeV	3	151
14	2.15 – 1 KeV	0	14
15	1 – 0.465 KeV	0	1
16	465 – 215 eV	0	1
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





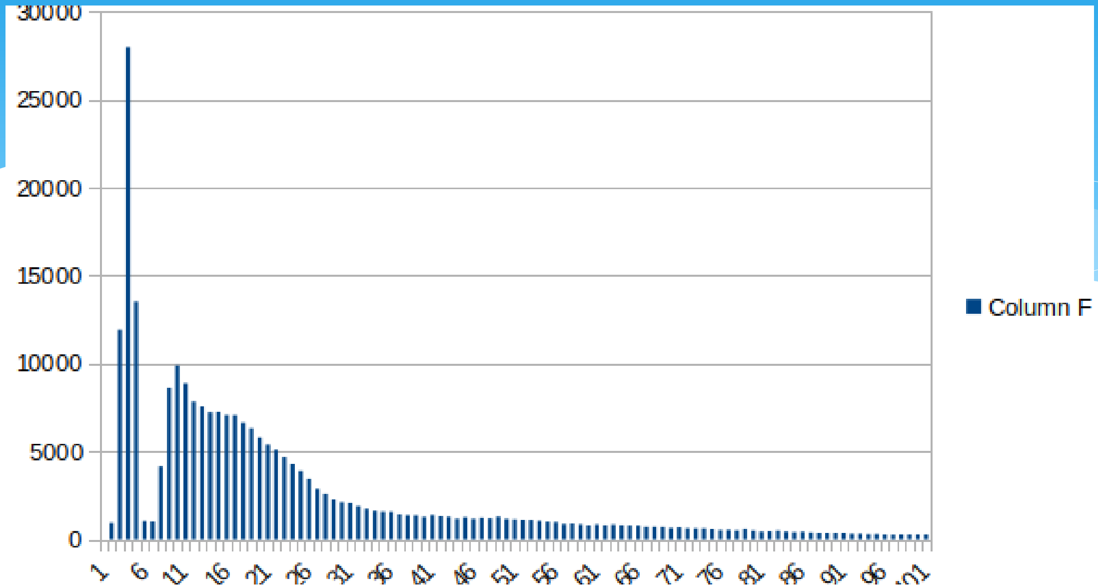
Modeling results

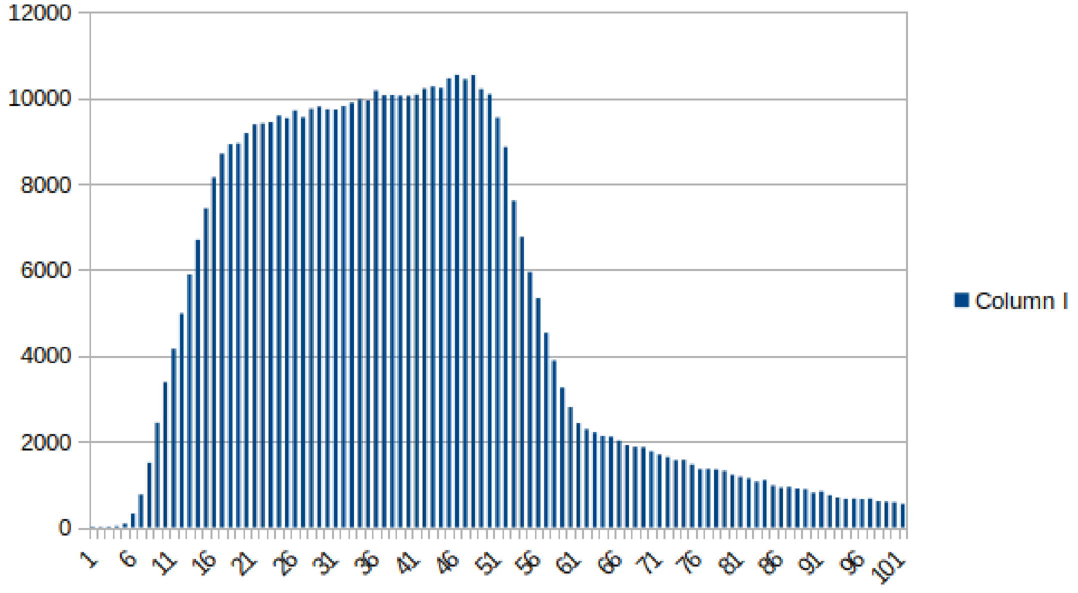
Numerical calculations show, that:

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

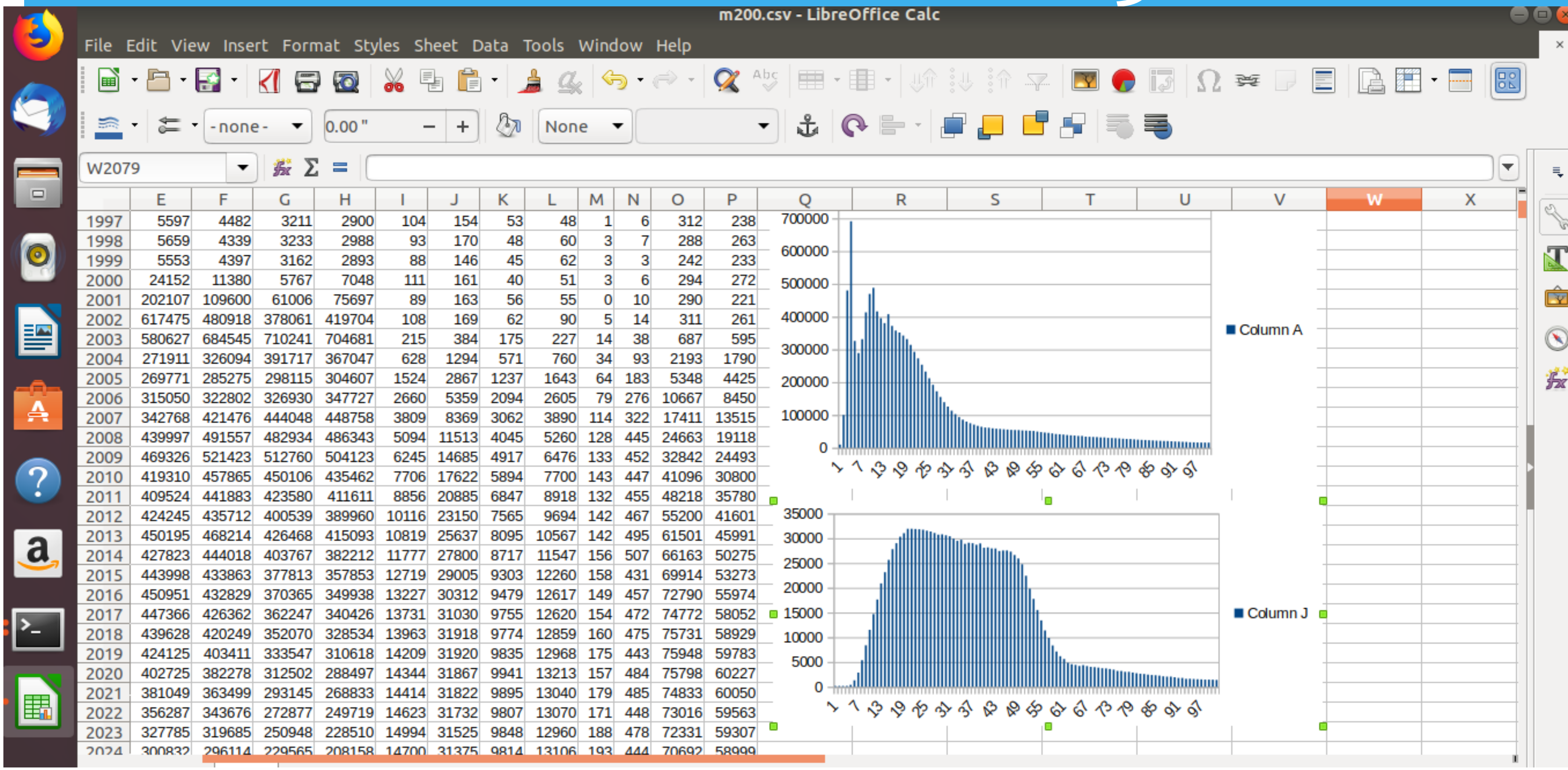
- In the case of big assemblies, which radius many times exceeds transport free path of neutrons, their spectrum has average energy around 100 keV. Such energies already can be measured by TOF spectrometer with resolution factor 6 nanoseconds/meter.

Initial parts of experimental histograms: first 100 channels of scintillator (upper curve) and He3 counter





First 100 channels of 8 gamma-detectors and 8 SNM-18 He3 counters



	E	F	G	H	I	J	K	L	M	N	O	P
1997	5597	4482	3211	2900	104	154	53	48	1	6	312	238
1998	5659	4339	3233	2988	93	170	48	60	3	7	288	263
1999	5553	4397	3162	2893	88	146	45	62	3	3	242	233
2000	24152	11380	5767	7048	111	161	40	51	3	6	294	272
2001	202107	109600	61006	75697	89	163	56	55	0	10	290	221
2002	617475	480918	378061	419704	108	169	62	90	5	14	311	261
2003	580627	684545	710241	704681	215	384	175	227	14	38	687	595
2004	271911	326094	391717	367047	628	1294	571	760	34	93	2193	1790
2005	269771	285275	298115	304607	1524	2867	1237	1643	64	183	5348	4425
2006	315050	322802	326930	347727	2660	5359	2094	2605	79	276	10667	8450
2007	342768	421476	444048	448758	3809	8369	3062	3890	114	322	17411	13515
2008	439997	491557	482934	486343	5094	11513	4045	5260	128	445	24663	19118
2009	469326	521423	512760	504123	6245	14685	4917	6476	133	452	32842	24493
2010	419310	457865	450106	435462	7706	17622	5894	7700	143	447	41096	30800
2011	409524	441883	423580	411611	8856	20885	6847	8918	132	455	48218	35780
2012	424245	435712	400539	389960	10116	23150	7565	9694	142	467	55200	41601
2013	450195	468214	426468	415093	10819	25637	8095	10567	142	495	61501	45991
2014	427823	444018	403767	382212	11777	27800	8717	11547	156	507	66163	50275
2015	443998	433863	377813	357853	12719	29005	9303	12260	158	431	69914	53273
2016	450951	432829	370365	349938	13227	30312	9479	12617	149	457	72790	55974
2017	447366	426362	362247	340426	13731	31030	9755	12620	154	472	74772	58052
2018	439628	420249	352070	328534	13963	31918	9774	12859	160	475	75731	58929
2019	424125	403411	333547	310618	14209	31920	9835	12968	175	443	75948	59783
2020	402725	382278	312502	288497	14344	31867	9941	13213	157	484	75798	60227
2021	381049	363499	293145	268833	14414	31822	9895	13040	179	485	74833	60050
2022	356287	343676	272877	249719	14623	31732	9807	13070	171	448	73016	59563
2023	327785	319685	250948	228510	14994	31525	9848	12960	188	478	72331	59307
2024	300832	296114	229565	208158	14700	31375	9814	13106	193	444	70692	58999

* Upper curve: gamma-detector FEU-110,
  Low curve: SNM-18 He3 counter

Upper curve: gamma detector's section
Second curve: neutron He3 counter
Au197 metal plate used as a sample-radiator inside gamma detector

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	D	E	F	G	H	I	J	K	L	M	N	O	P
922	106	98	97	90	58	0	18	35	32	5	7	0	0
923	86	97	83	73	70	0	23	34	38	6	11	0	0
924	96	100	99	79	81	0	12	27	44	5	5	0	0
925	97	95	83	93	74	0	18	31	50	9	10	0	0
926	1309	2047	428	133	332	1	14	31	27	4	13	0	0
927	36560	39005	21477	11767	14342	1	14	40	53	8	7	0	0
928	91794	91862	84484	72817	79394	1	18	45	45	8	14	0	0
929	78707	78329	84131	87898	86450	4	79	176	142	18	19	0	0
930	84776	92895	72960	70806	72445	10	264	797	551	46	48	0	0
931	392903	416872	269314	182000	210414	35	705	2182	1495	112	94	0	0
932	787050	785924	758172	679543	723167	51	1384	4322	2937	172	202	0	0
933	491429	473050	603358	693993	657601	93	2709	8663	5839	338	310	0	0
934	269000	266019	305013	349519	333667	210	5442	16464	11565	639	654	0	0
935	244425	243700	264475	274383	282719	371	9812	29825	20287	1113	1119	0	0
936	200935	202301	259827	288852	294986	487	15931	48232	32166	1676	1771	0	0
937	263760	266903	322647	323235	322745	563	22785	66803	45370	2301	2430	0	0
938	388408	383875	403978	371415	358419	620	29524	82955	58980	2807	2973	0	0
939	418343	405700	409485	376797	358692	668	34869	95454	70345	3258	3544	0	0
940	369788	357568	364320	341232	316981	788	39355	104024	79022	3848	3938	0	0
941	330455	317806	303455	271721	247636	810	42543	109057	85707	4035	4337	0	0
942	329255	317167	292981	252995	233076	868	45684	110396	90239	4442	4647	0	0
943	337812	325780	299406	255206	235705	956	47366	110362	91853	4628	4919	0	0
944	343988	332636	304721	257252	235533	1018	48484	108323	92783	4739	5121	0	0
945	341957	331501	297503	250615	227159	1081	48938	104886	93522	4899	5229	0	0
946	326380	316751	282876	236955	214211	1108	49146	100903	90795	5049	5117	0	0
947	305977	301449	267919	221970	200766	1172	48907	97241	88500	5138	5289	0	0
948	282455	280652	251646	208656	186459	1270	48155	92468	86350	5167	5311	0	0
949	259064	261719	233256	194086	170886	1407	47439	86846	83428	5134	5495	0	0

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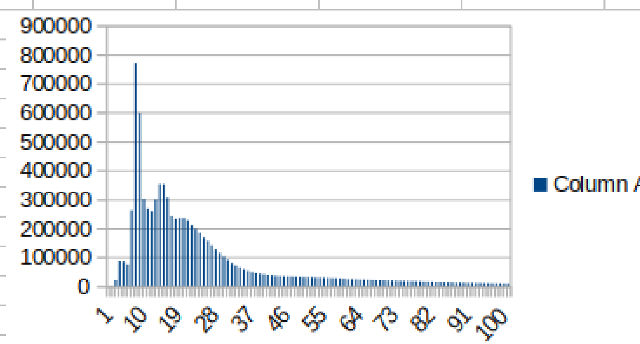

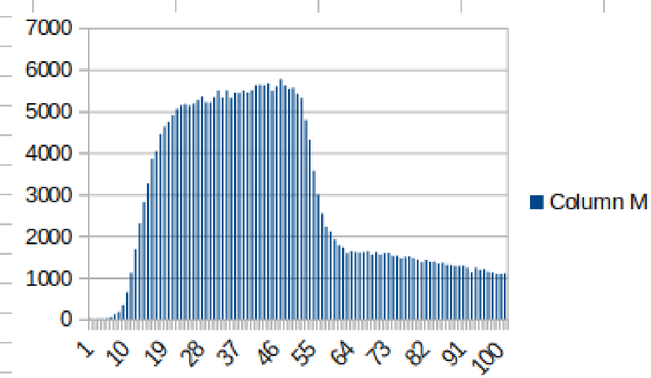

INR RAS Linear Proton Accelerator plans:

* Proton energy increase up to 423 MeV;
* Pulsed proton current increase up to 16 mA;
* Operations with minimal proton beam duration 50 nanoseconds, compared to existing mode 250 ns.

Conclusion

1. Neutron spectrums of large fast breeder reactors with diluted fissile material has average energy around ~150 KeV. This value turns out measurable already by 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. Thus, using experimentally observable TOF spectrum, it’s necessary to reconstruct capture spectrum using numerical modeling.
3. Due to activation of experimental assembly, average proton beam power is limited by value around 1 kW, for subcritical assemblies with easily changeable material composition. It’s necessary to note, that such beam power in the mode of short proton pulses, can be provided by proton linac, even without proton beam storage ring.
4. Helium-3 counters are traditionally used for total cross sections measurements. However, their average response time delay is around 2 microseconds and differs in large interval, depending on distance between scintillation point inside detector and central wire electrode. Thus, He-3 counters can be used only as accelerator’s intensity monitor, during measurements of spectrum’s upper energy part.
5. Measurement of subcritical assemblies neutron spectra in 28 energy groups of ABBN-78, with TOF resolution factor 6 ns/meter, is possible. Possibility to accumulate enough statistic per energy group is also proved. At the same time, for leaking neutron flux spectra measurements in 299 energy groups of ABBN-93 system, better energy resolution factor is required.

Authors express their gratitude for the ‘SHIELD’ program code creators [2,3] Sobolevsky N.M. and Latysheva L.N., 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 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!