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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Simulation of an Accelerator Driven System with Different Spallation Targets

A. I. Dubrouski[a], *, A. I. Kiyavitskaya[a], and S. I. Tyutyunnikov[b]

[a] *ISEI BSU, Minsk, Belarus*

[b] *JINR, Dubna, Moscow oblast, 141980 Russia*

**e-mail: a1dubrovskii@gmail.com*

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Abstract—A number of neutronics of JNIR big uranium target are simulated towards the planning of experimental investigations aimed to the transmutation of radioactive waste. Integral data of the neutron yield and energy spectra are given for several homogeneous spallation targets which are planned to be used as insertions in uranium blanket. Combined spallation targets are also of interest, because it can help to obtain an optimal neutron energy spectrum for effective burning of long-lived fission products and minor-actinides. For this purpose, uranium-beryllium dual insertion was also considered and described in this work.

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1. INTRODUCTION

Today, electro-nuclear systems based on high-current accelerators are considered as most promising ones for transmutation of spent nuclear fuel and energy production. The main reason is related to the usage of an accelerator as an external source which makes such systems safer to operate and easy to control the chain fission reaction.

A spallation target in Accelerator Driven System (ADS) is the main component due to generation of neutrons which then multiply in a subcritical reactor. Thus, it is necessary to calculate such characteristics as neutron yield and energy spectra, energy deposition, heating and activation of the target and production of long-lived fission fragments. These parameters can be defined using modern transport codes developed for simulation of the hadron-nucleus interactions over a wide energy range. These parameters can be defined using modern transport codes developed for simulation of the hadron-nucleus interactions over a wide energy range.

This work is a continuation of the research published in the article “Simulation of Neutronics of an Accelerator Driven System” in Physics of Particles and Nuclei Letters, 2020, vol. 17, no. 1, pp. 19–26.

2. SETUP DESCRIPTION

The big uranium target is assumed to be a cylinder with 120 cm external diameter and 100 cm thickness along the beam direction. The proton beam passes through a channel 6 × 40 cm and impinges on the spallation target 20 × 60 cm inserted in uranium blanket. The blanket consists of depleted uranium containing 0.4% of U-235 and 99.6% of U-238.

Figure 1 shows the scheme of simplified model of the big uranium target developed in the previous work [1]. This model was upgrades and optimized for the calculation of the neutronics of subcritical system using the Geant4 code. Different materials of an insertion were investigated as a spallation neutron sources in the ADS irradiated with 2-GeV proton beam.

3. PHYSICAL MODELS ANALYSIS

The simulation was carried out using Geant4 10.5 code version, one IntelCore i7-6700 processor with 3.4 GHz CPU and 8 Gb RAM in multithreading mode. Three standard physics lists were used for calculations performing: Intra-Nuclear Cascade Liège (QGSP_INCLXX_HP), Bertini Cascade (QGSP_BERT_HP) and Binary Intranuclear Cascade (QGSP_BIC_HP), with default evaporation model G4ExcitationHandler and alternative model ABLA [2].

The comparison of the integral data of the neuron yield from lead and tungsten spallation targets is presented in Table 1. The good agreement between-Geant4 simulation with QGSP_BIC_HP physics list, experimental data and calculations using other MMC codes was obtained for both target materials.

Despite of less volume and atomic number of tungsten spallation target, it shows about 5–10% more neutron production rate in comparison with lead. Furthermore, the cross sections of high energy fission and (p, xn) reactions are less for tungsten. The reason

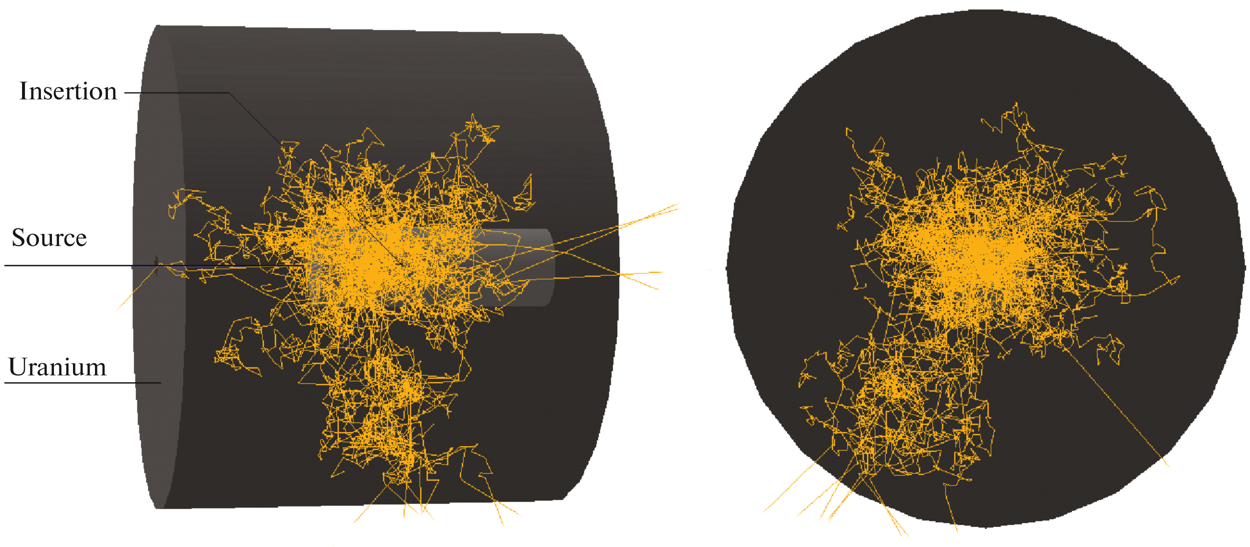

Fig. 1. Model of the big uranium target.

for this difference is about 70% higher density of tungsten compared to lead.

Integral data of the neutron yield calculated using various Geant4 physics lists are presented in Table 2. Standard error of simulation results is less than 1%. The BERT model shows the significantly less real time of simulation than the other ones (see Table 3). However, it demonstrates 15–25% overestimation of the neutron yield, especially in the low-energy range. The same result was obtained in the previous research [7].

Table 1. Neutron yield from the heavy targets

Target	Proton energy, GeV	Experiment, BNL [3]	Geant4, BIC [1]	SONET [4]	MCNPX [5]	LAHET [6]
Pb, $D = 10.2$ cm, $H = 61$ cm	0.8	13.60 ± 0.20	14.430 ± 0.008	15.00 ± 0.35	14.45 ± 0.2	14.96
	1.0	17.38 ± 0.20	18.440 ± 0.009	16.90 ± 0.35	18.64 ± 0.2	19.82
	1.2	22.31 ± 0.30	21.742 ± 0.009	23.30 ± 0.40	23.20 ± 0.2	24.25
	1.4	26.21 ± 0.45	24.903 ± 0.010	26.10 ± 0.30	27.09 ± 0.3	28.26
W, $D = 10.2$ cm, $H = 40$ cm	0.8	15.11 ± 0.11	15.341 ± 0.008	16.60 ± 0.90	17.25 ± 1.0	17.47
	1.0	20.40 ± 0.15	19.691 ± 0.009	21.70 ± 0.80	22.58 ± 1.0	23.22
	1.2	–	23.606 ± 0.010	26.90 ± 1.40	28.54 ± 1.0	28.81
	1.4	28.46 ± 0.20	27.286 ± 0.010	31.60 ± 1.60	31.85 ± 1.2	33.67

Table 2. Neutron yield from the heavy targets for different Geant4 physics lists

Target	Proton energy, GeV	Experiment, BNL [3]	BIC	BERT	INCL	INCL/ABLA
Pb, $D = 10.2$ cm, $H = 61$ cm	0.8	13.60 ± 0.20	14.678	16.673	13.551	15.607
	1.0	17.38 ± 0.20	18.484	21.762	17.361	20.112
	1.2	22.31 ± 0.30	21.890	26.148	20.648	24.064
	1.4	26.21 ± 0.45	25.012	30.068	23.561	27.574
W, $D = 10.2$ cm, H =40 cm	0.8	15.11 ± 0.11	15.306	17.337	13.771	15.797
	1.0	20.40 ± 0.15	19.621	22.983	17.869	20.600
	1.2	–	23.646	28.087	21.587	24.996
	1.4	28.46 ± 0.20	27.300	32.667	24.954	28.950

Table 3. Real time of 10^6 events simulation of the tungsten target in minutes

Proton energy, GeV	BIC	BERT	INCL	INCL/ABLA
0.8	73.06	17.08	43.70	42.33
1.0	104.85	23.12	58.18	55.62
1.2	131.11	29.28	71.42	68.41
1.4	155.52	34.40	83.00	79.45

The BIC and INCL (with standard or ABLA evaporation) models well reproduce experimental data.

It's important to mention that real time of simulation with INCL/ABLA model is about 50% less than the BIC one. Moreover, according to [8], simulation of ADS with uranium fuel using the INCL/ABLA physics list provides the best agreement with experimental data of the fission fragments production.

Figure 2 demonstrates that the shape of energy spectra of the particles emitted from the lead spallation target are pretty the same for different proton energies. The proton beam energy has an impact on the rate of hadron-nucleus interactions and total yield of the secondaries only.

The comparison of the neutron spectra simulated using different physics lists is shown in Figs. 3, 4. For the INCL and BIC models, the spectral characteristics of spallation neutrons vary within 25% over all energy range. A significant deviation of the BERT model from other is observed in low energy, especially

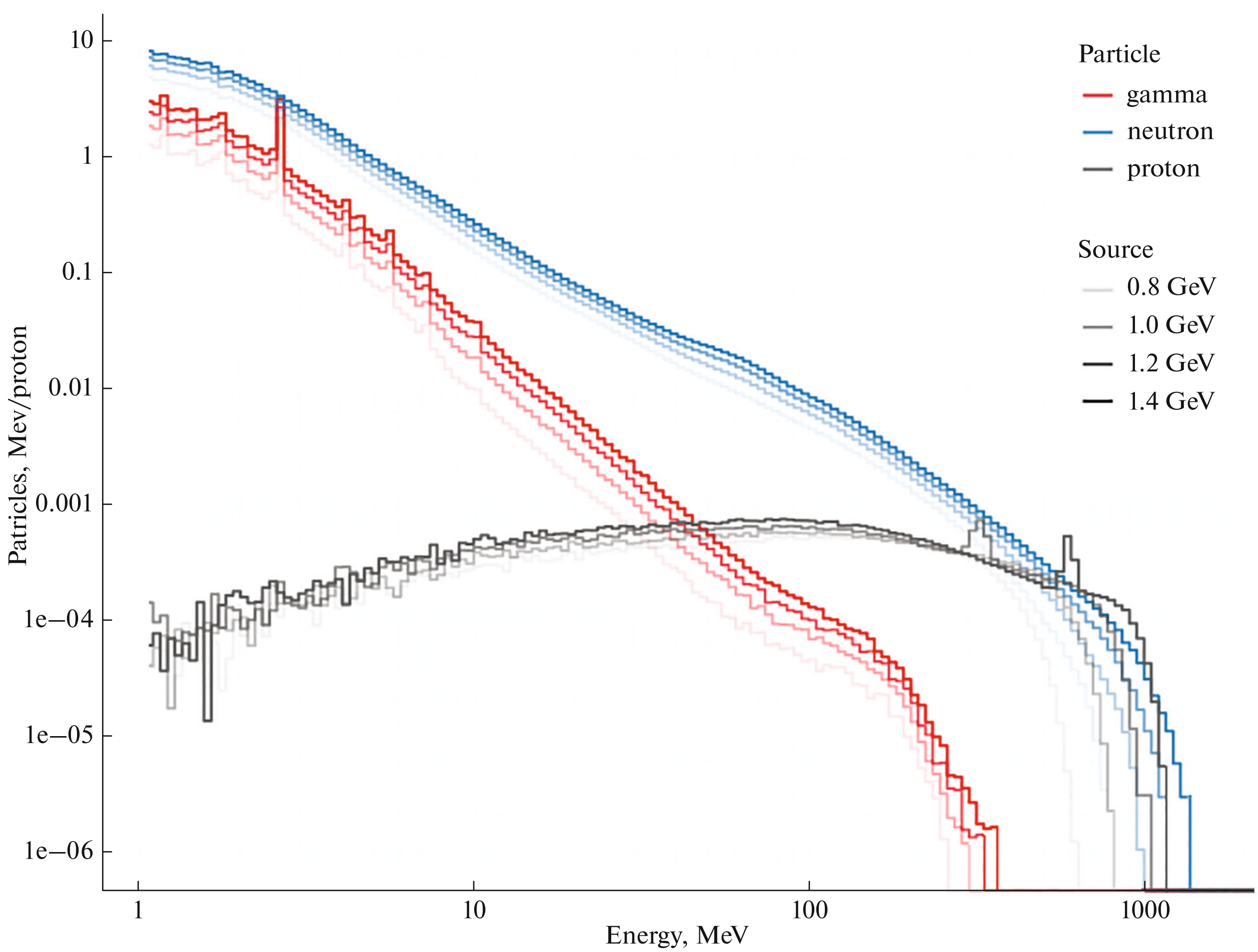

Fig. 2. Energy spectra of particles emitted from the lead target (using the BIC physics list).

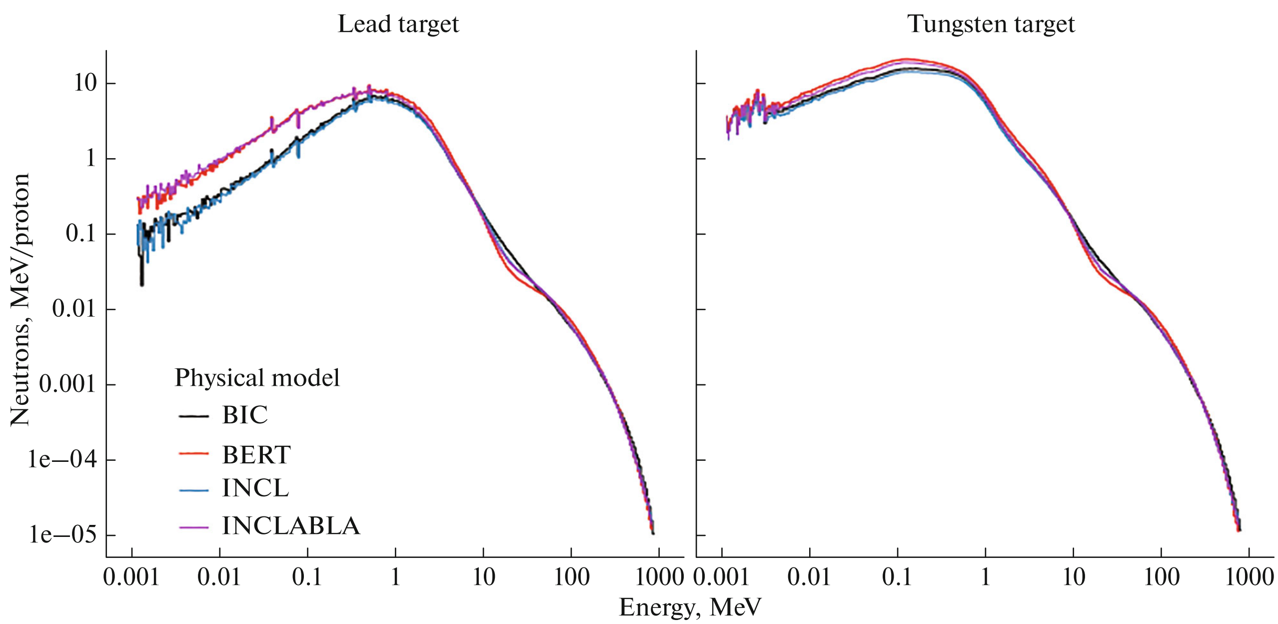

Fig. 3. Energy spectra of neutrons emitted from lead and tungsten spallation targets.

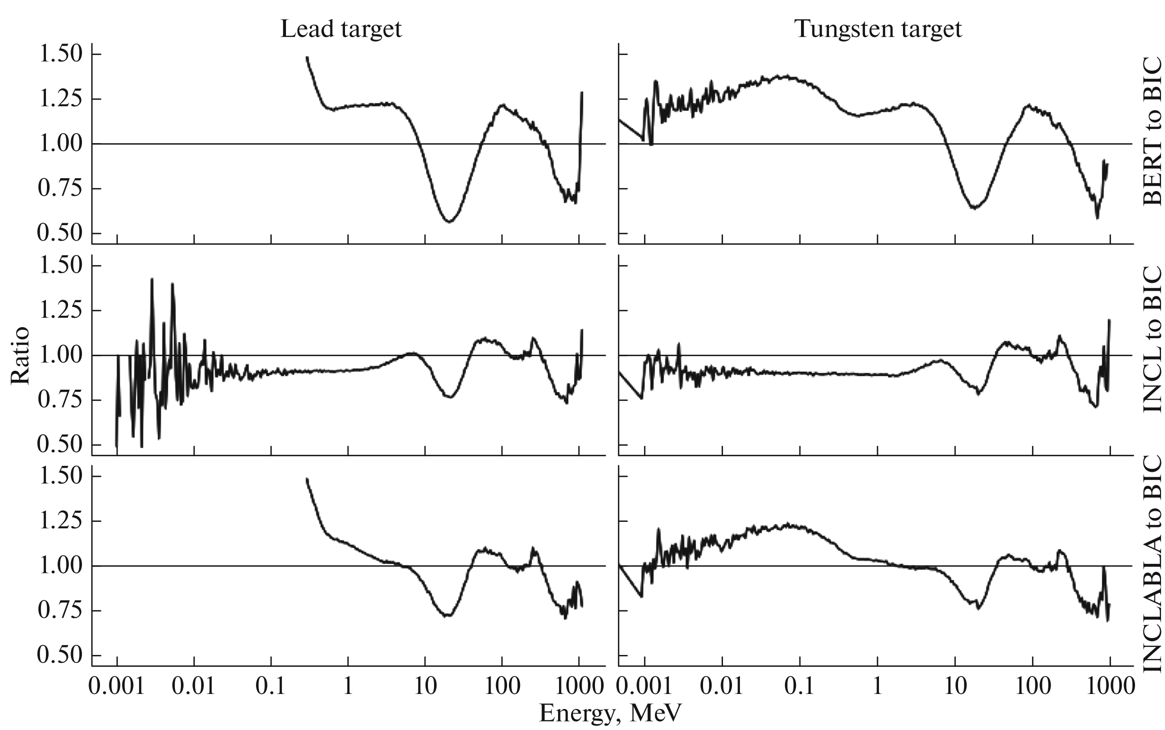

Fig. 4. Ratio of the neutron spectra obtained using different physics lists.

in the case of lead target. It seems like it's related to the differences in the equilibrium (evaporation) stage of interactions. If replace default evaporation model by ABLA in the INCL physics list it will predict the low-energy part of the spectrum almost equally as the BERT model.

Today, coupling the ABLA nuclear de-excitation model to the INCL only has been tested [2]. For BIC and BERT physics lists, replacing the standard evaporation model with ABLA does not affect the neutron yield or energy or simulation time.

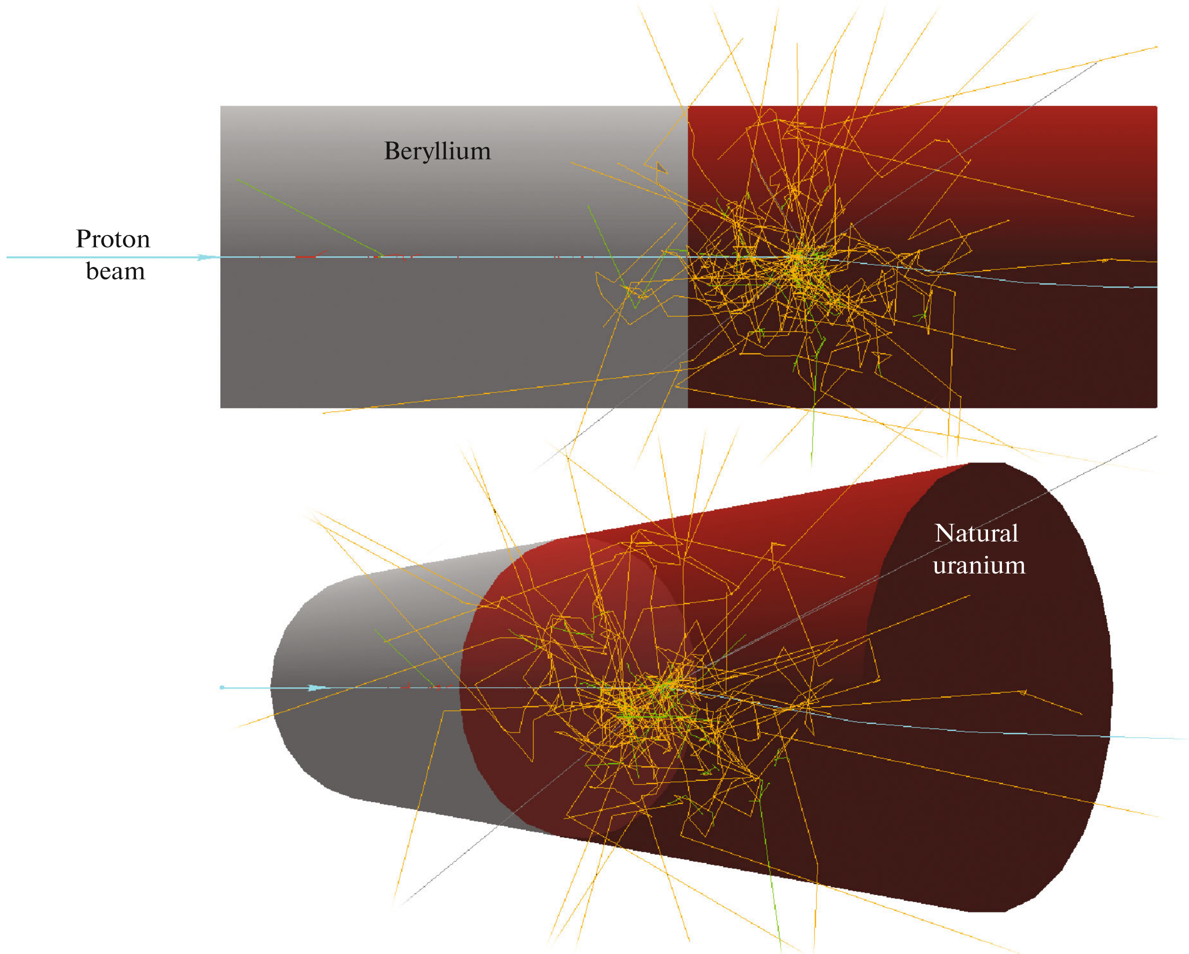

Fig. 5. Model of combined uranium-beryllium insertion.

Based on the foregoing and due the lack of experimental data to reasonable and definitely choose the best physics list the simulations were performed using both INCL/ABLA and BIC models.

4. CALCULATION OF THE CHARACTERISTICS OF COMBINED INSERTION

For the purpose of the nuclear waste transmutation the problem of choosing the optimal neutron energy spectrum is still opened. Therefore, beside the homogeneous spallation targets the combined one are also of interest. Figure 5 shows the model of a uranium-beryllium target, the result of hadron-nucleus interactions induced by a single proton with energy 2 GeV.

Figure 6 shows energy spectra of neutrons emitted from the cylindrical 20 × 30 cm beryllium and uranium targets and from their coaxial combinations irradiated with 2-GeV proton beam (INCL/ABLA model). For the targets contains uranium part of the spectrum has some increase in a low-energy range due to fission neutrons. The beryllium part of target leads to growing of high- and thermal energy ranges. This effect is enhanced when beryllium is first by the beam direction, but then neutron yield is about 30% less.

The energy deposition in a homogeneous beryllium target varies between 10–1000 MeV (see Fig. 7). There is a single peak about 90 MeV corresponds to the energy released by the proton passed over the entire length of the target. The position of the peak shifts toward higher energy with decreasing the target length or increasing its density and/or atomic number. Also, it's important to note that beam energy does not affect to the peak position. The increasing of the source energy leads to the growing of the peak area only, because the angles of proton scattering become smaller. The part of the spectrum from the right side of the peak is corresponds to the addition of energy deposition from the secondary particles. A decrease of the target diameter allows proton to exit through the side surface of the target. It leads to growing of left part of

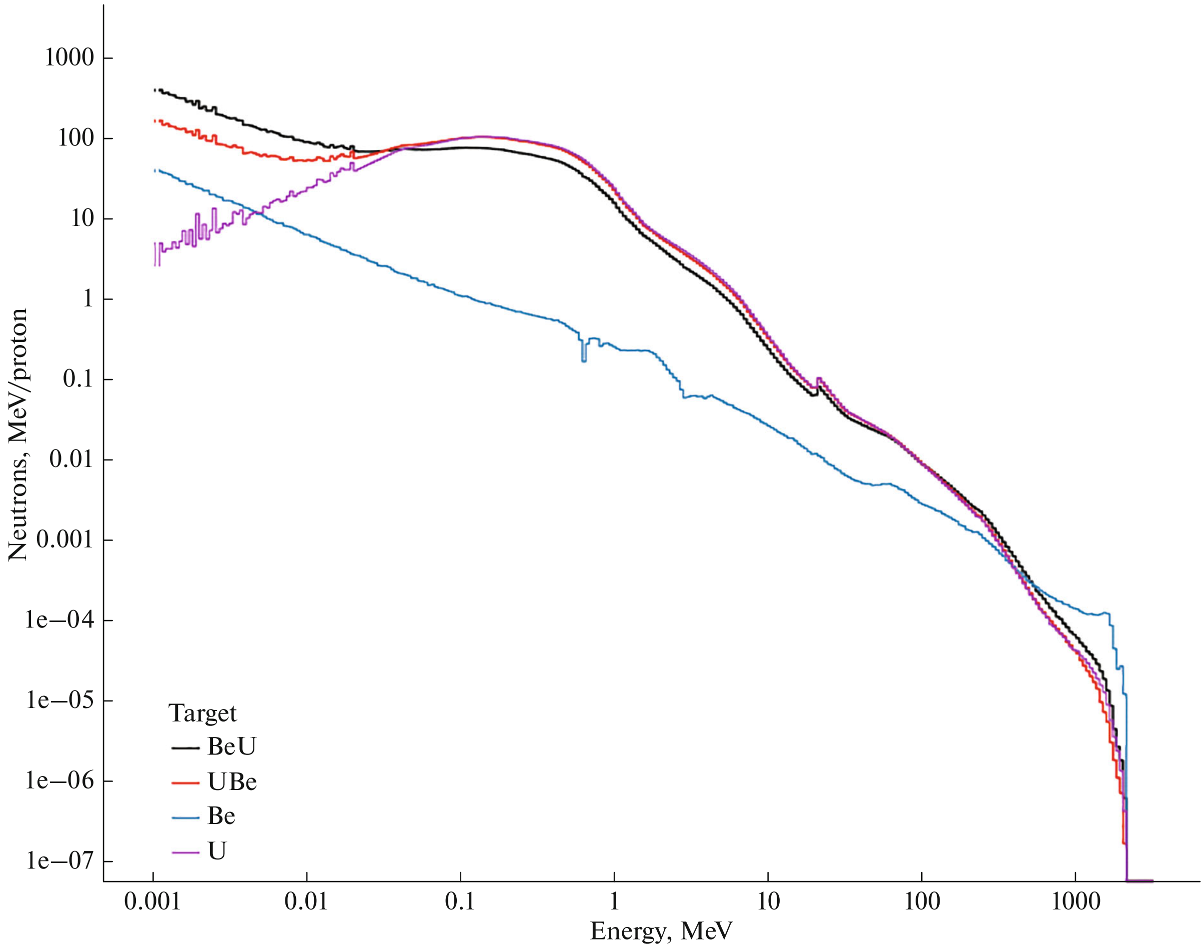

Fig. 6. Energy spectra of neutrons emitted from uranium, beryllium and combined targets.

the spectrum relative to the peak. When proton comes out from the side surface of the target total energy deposition does not exceed the value of the peak position.

The energy deposition in the simple uranium target is about 10 times more than in beryllium one. The position of the main peak is approximately 600 MeV. Also there are smaller peaks with discreteness of 180–200 MeV (energy of uranium fission) which correspond to the single, double, triple fissions and etc. Obviously, the probability of events with more than four fissions of uranium is too low. The same shape of the distribution of energy deposited in the uranium spallation target was already obtained in previous research [8].

Regarding the combined uranium-beryllium target it should be noted that for any combination of its components the energy deposition varies over a wide energy range. Depending on the sequence of hadron-nuclear interactions total deposited energy may be from the MeV up to several GeV. And of course, the front part of the target is dominant. Therefore, on average, when beryllium is first by the beam direction, the energy deposition is less than opposite combination.

5. CALCULATION OF THE NEUTRONICS OF THE BIG URANIUM TARGET

Figure 8 shows that the shape of the neutron spectra is the same for all insertion materials. The same result was already obtained in previous research [9–11]. Generally, the more atomic number of the insertion material, the higher nuclear reaction rates and the neutron yield. And of course, the rates of neutron-induced reactions are the highest for thorium and uranium due addition fissions inside the insertion. It is demonstrated in Table 4. Standard error of simulation results does not exceed 2%.

In comparison with bismuth the lead spallation target has a 17% higher atomic density but about 50% less cross section of high energy fission reaction. However, the neutron yield from the Pb-insertion (without the blanket) is still about 10% higher. The reason is the high-energy fission in heavy targets does not significantly affect the total neutron flux in subcritical system. It is generally forming by hadron-nuclear interac-

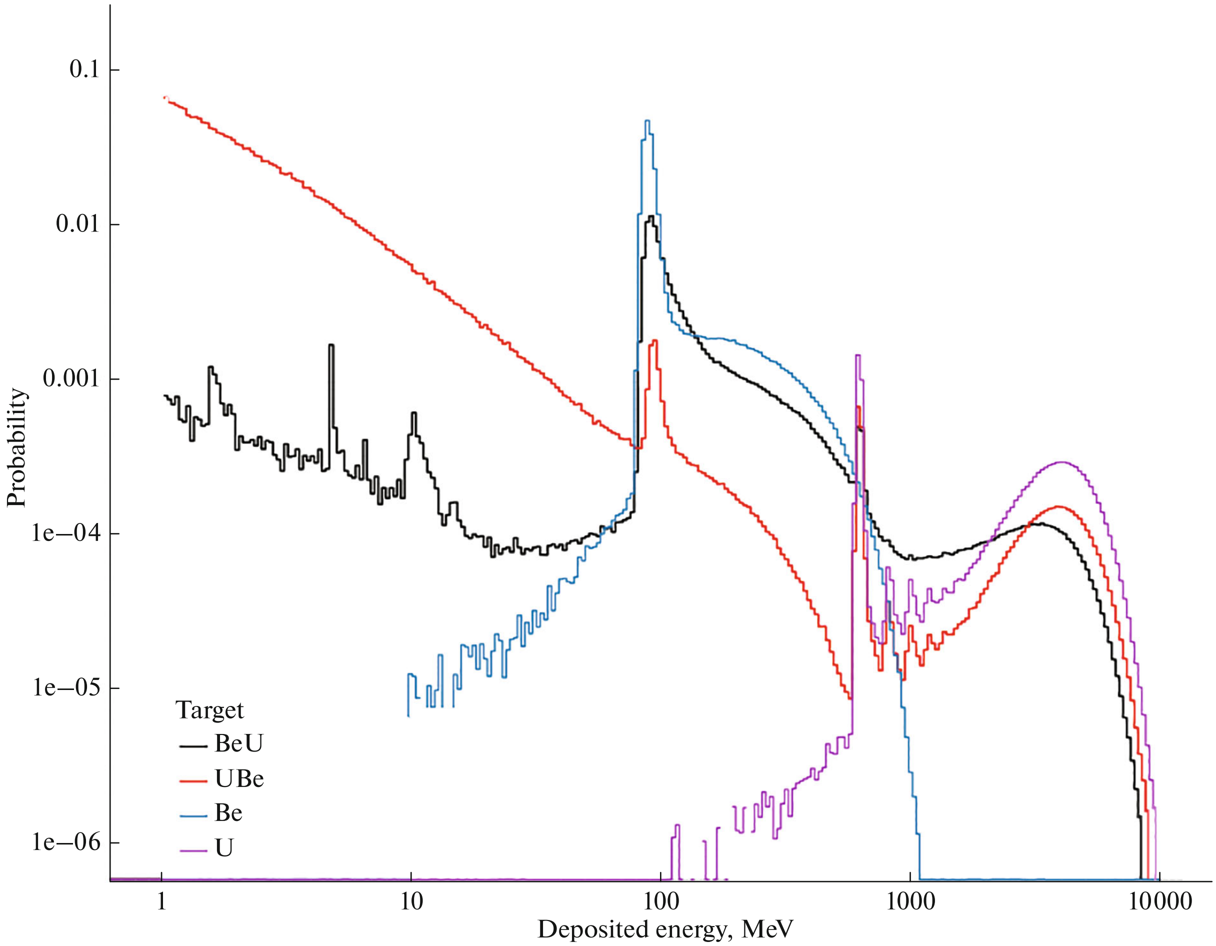

Fig. 7. Energy deposition inside uranium, beryllium and combined targets.

tions in the insertion and especially by the chain fission reaction in the blanket. Therefore, the energy spectra of neutrons emitted in the big uranium target with Pb- and Bi-insertions are pretty the same.

To calculate the neutronics of the big uranium target 10^4 events were simulated using both physical models. The results show that ionizing processes and elastic interactions quantitatively prevail in the system.

Table 4. Neutron yield and a list of the processes occurring in the big uranium target with different insertions

Insertion		Be	Al	Fe	Pb	Bi	Th	U	BeU	UBe
Atomic number, Z		4	13	26	82	83	90	92	–	–
Density, g/cm^3		1.848	2.699	7.874	11.35	9.747	11.72	18.95	–	–
Neutron yield, n/p	INCLABLA	29.659	29.577	37.961	76.764	75.859	91.975	136.19	99.384	127.32
	BIC	35.491	33.458	41.263	76.353	75.680	92.596	144.82	114.10	137.14
Neutron capture	INCLABLA	32.770	33.579	49.653	95.368	91.533	118.47	159.85	105.34	148.29
	BIC	36.925	35.743	51.768	94.322	90.501	117.98	167.15	116.74	157.91
Neutron-incident fission	INCLABLA	7.416	6.779	8.652	16.135	16.065	18.592	32.414	23.863	30.259
	BIC	9.001	7.955	10.040	17.106	17.043	19.760	35.822	28.478	34.164
Neutron inelastic collision	INCLABLA	160.04	192.84	291.04	550.17	532.98	662.93	903.64	564.50	801.27
	BIC	183.37	208.95	308.36	555.60	536.05	670.65	954.06	635.07	862.76
Proton inelastic collision	INCLABLA	1.568	1.601	2.176	1.774	1.727	1.728	1.798	2.061	1.768
	BIC	1.567	1.629	2.225	1.758	1.713	1.716	1.774	2.052	1.726
Simulation time, min	INCLABLA	11.15	8.70	13.43	23.977	22.61	25.07	37.99	40.62	32.50

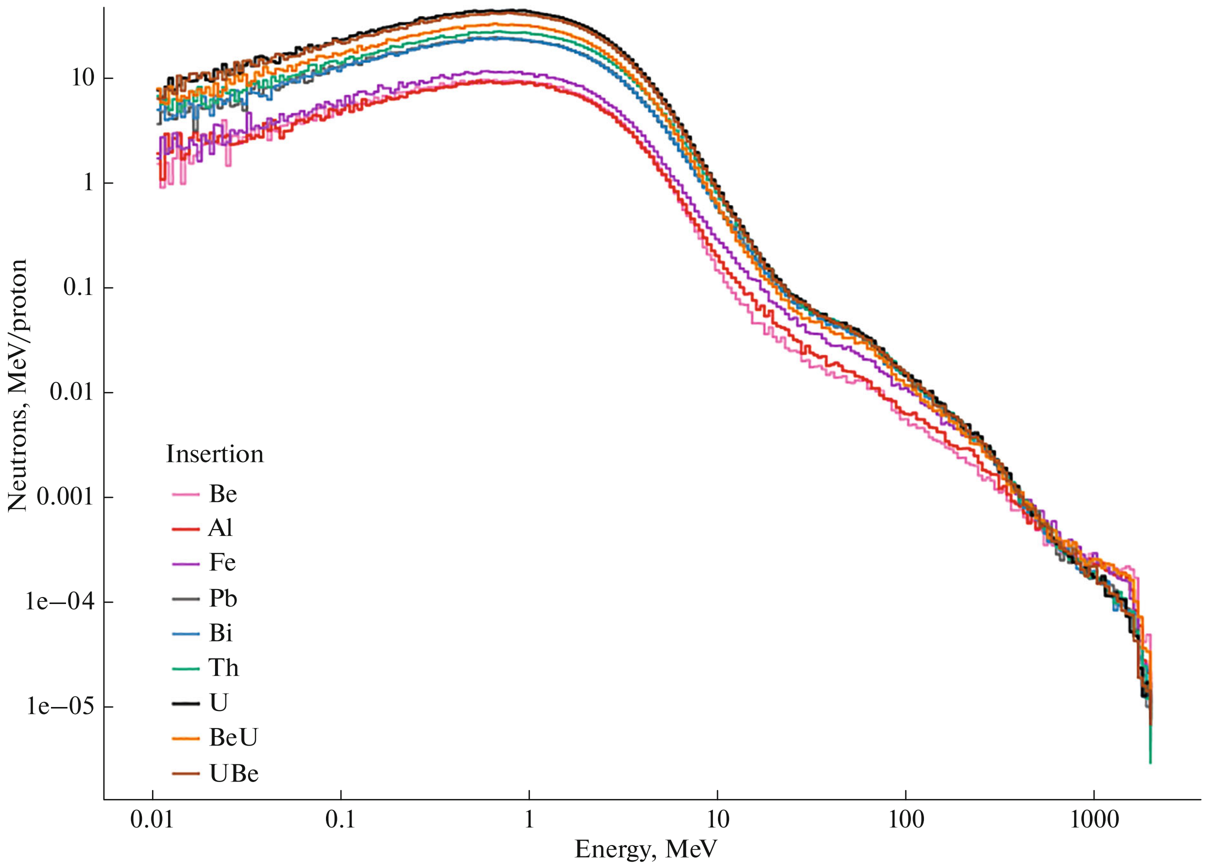

Fig. 8. Energy spectra of neutrons emitted inside the big uranium target with different insertions.

However, the discrete processes listed in Table 4 are much more interesting.

Both physics lists used for simulation are in a good agreement for inelastic proton collisions. But for neutron-induced processes the BIC model systematically provides a 10–20% higher reaction rates compared to INCL/ABLA for fissile and light insertions.

The rate of the proton inelastic scattering is almost equal for all homogeneous insertions except the iron one. This process is about 25–40% more intense for the blanket with iron spallation target possibly due to ^{56}Fe(p, xp) and ^{56}Fe(n, xp) reactions.

It's important to note also that beryllium has lower density and atomic number compared to aluminum. Nevertheless, the blanket with Be-insertion gives a 6% more neutron flux due to ^{9}Be(n, 2n) reaction and less neutron capture cross section. More efficient thermalization of the secondary neutrons in beryllium leads to higher thermal fission reaction rate than aluminum one.

In comparison with Be–U the blanket with the U–Be insertion has a 27–42% higher neutron yield and neutron-induced interaction rates while inelastic proton scattering is about 17% less.

6. CONCLUSIONS

The previous investigation of neutronics of a subcritical system irradiated by high-energy proton beam was continued. Simplified model of the JNIR big uranium target was upgraded and optimized for simulation performing.

The integral data of neutron yield for different spallation targets was calculated and compared with corresponding experimental data. Several standard physics lists were used to obtain a good agreement between measured and simulated data.

Kinetic and deposited energy spectra were simulated and analyzed for several materials of spallation target including combined uranium-beryllium insertion.

The calculations of the neutronics of the big uranium target with number of insertions were performed using the Geant4 code with different physical models.

The results will be used for justification and planning of an experimental investigation on the accelerator-driven subcritical system in JINR (Dubna, Russia).

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