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THORIUM AS A FUEL FOR ACCELERATOR DRIVEN SUBCRITICAL ELECTRONUCLEAR SYSTEMS

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1. Introduction

It is known that Intra-Nuclear Cascade(INC) is realized at energies higher than several tens MeV. The inelastic hadron-nucleus interaction includes three stages - firstly, an Intra-Nuclear Cascade(INC)is evolved which is accompanied by the emission of fast (shower) nucleons and pions, secondly, the highly excited after-cascade nucleus relaxes into a stationary state sometimes with the emission of one or several nuclons and in the the final stage a highly excited residual nucleus decays by successive evaporation, fission and emission of γ-quanta. Upto now all details of such a complicated process have not been investigated comprehensibly. For example, in some cases the fission occurs during the relaxation stage, before the formation of a stationary state. Sometimes, it turns out that in case of light nuclei excitation energy is so large that the model of successive evaporation becomes unapplicable and the decay process must be considered as an explosion. At present, we have no single satisfactory theory for the complete description of such a complicated phenomenon .

Secondary charged particles created in nuclear collisions lose their energy little by little by way of ionization processes and may come to the rest. Several charged π -mesons produced in a high energy collision decay into μ-mesons, electron and neutrino possessing yet a large energy. All π^{o}-mesons decay into γ-quanta at the point of their creation. On the other side, created fast cascade and decay neutrons are moderated by numerous elastic nuclear collisions up to a very low energy. At the same time due to fission, number of low-energy neutrons increases, especially when the medium contains fissile nuclei U^{233}, U^{235}, Pu^{239} etc. Finally, the low-energy neutrons are captured by way of (n,γ) reactions producing Pu^{239} from U^{238} and U^{233} from Th^{232} target. The produced energy is taken away by a hard γ-quanta.

An experimental study of different types of Accelerator Driven Sub-Critical Systems with different kinds of particle / ion beam , nuclear fuel and coolant etc. is complicated and rather expensive. Therefore, the most conclusions about properties of electro-nuclear set-ups are obtained presently by means of Mathematical Modelling using Monte Carlo Codes for the sampling of intra-and inter-nuclear cascades (see refs. [1-7] where one can find out a detailed bibliography).

2.Monte-Carlo Modelling

The Monte Carlo method allows one to consider a very complicated geometry of ADSS and to take into account other conditions of the supporting experimental data. As described earlier [1-3] by our Casacde- Code we can estimate collision probabilities of different types of collisions, characteristics of the produced particles / radiations and on their propagation through the complicated medium, generation of various cascade tree etc. From all these basic informations one can estimate the required physical quantity such as neutron multiplicity, heat generation at the required position of the reactor and various transmutation probabilities.

Our computer realization of such a dynamical model includes three special features:

1. In the calculation of the passage of the particle (hadron or ion) through the medium we account for the energy-losses of a charged particle due to electro-magnetic processes taking place in the medium in between two consecutive nuclear interactions. This is very important since in many cases, particularly, at low energies and for the heavy ions, the particle energy at the end point is vey small and it loses energy by ionization than nuclear interaction. Secondly, at high energies of several GeV (for ions even at 1 GeV) one must take into account a decrease of the intra-nuclear density due to the knock-out of nucleons by the proceeding echelons of cascade particles.

2. It accounts for the possibility of decay of a cascade π-meson or even subsequent secondary and tertiary particle decay between two consecutive nuclear interactions of the primary particle. Such decays become important at $E \cong 1$ GeV compared to smaller energies where pion production becomes significant.

3. In an inelastic interaction a primary particle may be accompanied with the secondary particle(s) and similarly in case of a nuclear disintegration or fission like processes there are more than one particles which become part of the simulation programme. Thus, one has to simulate the three-stage interaction of a cascade particle which moves ahead by encountering nuclei along its path.

Ionization losses of charged hadrons are calculated with the help of the Sternheimer's method[8,9]. For ions a more complicated method [4,10] is used.

The angular distributions of elastically scattered high-energy particles are sampled by means of a plain-cloths-man formulae. The properties of the particles created in inelastic high energy hadron-nucleus collisions are calculated by means of the intranuclear cascade - evaporation model [1-3]. The non-stationary pre-compound processes in aftercascade residual nuclei are also taken into account. The calculations at energies higher than 10.5 MeV are based on the library of the hadron-nucleus cross-sections[11,12]. In our recent works we have used a new, more correct version of this library [13]. For the low-energy calculations we have used 26-group system of constants [14]. In this model we follow a neutron down up to energies 3.10^{-8} eV.

For all the calculations presented in this paper we have used the Monte Carlo method described as above. We should mention that details of such a complicated process have not been investigated comprehensibly. This physical model needs some basic improvements. Nevertheless, the parameters essential for the calculation of Electro-Nuclear systems are described by the existing theory quite accurately. For example, the precision of the calculated particle multiplicities, their average energies and emission angles is about 10 % in case of nucleon- and π-nucleus interactions and is approximately two times worse for nucleus-nucleus collisions. The errors of angular and momentum distributions are half as much again. The distributions of the residual nuclei are calculated worst of all, because in some cases the theoretical values deviate from the experimental ones by a factor of 2 - 3 and more. [15].

3. Inter- and Intra-nuclear Cascade

in a Fissionable Medium: The primary particle with an energy of several tens MeV and higher can create an intensive inter-nuclear cascade shower in the irradiated matter, especcially if the matter contains fissionable nuclei. For example, a proton with energy E = 1 GeV initiates about 2100 x 10^3 nuclear inreractions i.e. branches of "cascade tree" (see Table I) in a large Thorium block. In a similarly large large block of Uranium the number of interactions is 1.5-2 times higher. It may be pointed out that the number of the Cascade branches increases with the increase of primary energy.

Table I.

Average number(x10^3) of diverse types of nuclear interactions generated in a very large Thorium (Uranium) block because of the primary Proton of energy, E.

Type of Inter-ion	Elastic (x,x')	Inelastic (x,y) etc.	Capture (n,γ)	Fiss.
E= 1 GeV	1810 (4231)	241 (303)	62 (87)	1.64 (12.1)
E= 2 GeV	3370 (9158)	510 (658)	133 (187)	3.60 (5.8)

So far as the parameters of Uranium and Thorium nuclei and accordingly, of the produced excited after-cascade nuclei are close to one another the multiplicity and the properties of the secondary particles in hadron-Thorium and hadron-Uranium collision are also very much similar. At the same time in the "reactor region", at energies E < 10 - 15 MeV, the fission cross-sections for Thorium are smaller than for Uranium, so we expect a significant decrease of the neutron multiplicity in the thick Thorium target compared to the Uranium.

a) **Neutron Yield in an Elementary p+A Interaction:** Such an yield is a smooth function of both energy and the

b) target. In table II, average multiplicities of all secondary particles and the neutrons is given for the p-A interaction.

Table II

Calculated average particle multiplicity in inelastic p+Th^{232}and p+U^{238} interactions at energy E. Here $<N_{tot}>$ is the average multiplicity of all neutral + charged secondary particles & $<N_n>$ is the average multiplicity of created neutrons.

	E, GeV	0.2	0.5	0.7	1.0	1.5	2.0
$<N_{tot}>$	**U^{238}**	**15**	**18**	**23**	**26**	**33**	**39**
	Th^{232}	**14**	**17**	**22**	**24**	**31**	**37**
$<N_n>$	**U^{238}**	**12**	**16**	**19**	**21**	**24**	**27**
	Th^{232}	**11**	**14**	**17**	**20**	**23**	**26**

In table III, percentage contribution of various nuclear channels such as INC, evaporation, fission for neutron yield is given along with percentage yield of charged particles.

Table III

The percentage break-up ($\langle N \rangle / \langle N_n \rangle$%) of various channels into the total neutron yield $\langle N_n \rangle$ (first 3 rows) and the relative yield of charged particles $\langle N_{ch} \rangle / \langle N_n \rangle$% (last row) in p+A collision at E=1 GeV.

Target(A)= **(Channel)**	**U^{233}**	**U^{235}**	**Th^{232}**	**Pb^{207}**
I N C	18	18	18	22
Decay with the evaporation	22	22	34	63
Dcay with the fission	60	60	48	15
Yield of charged Particles	30	23	30	35

b) Neutron Yield in a thin Target: If we consider a thin system filled with the fuel and estimate the neutron yield as a result of development of a Cascade shower right from the point of entry (Z=0, where the beam moves along the Z-direction) then from the Cascade- data given in table IV we find that neutron multiplicity is lower by a few percent at low energies < 500 MeV than in the corresponding elementary collision and it is higher upto about 50% at 1 GeV energy. This may be because of very high ionization-losses of primary beam energy at smaller energies.

Also, it can be seen from the comparison of the data in table IV that the neutron yield from the Thorium fuel is worse than Uranium . Though the number of neutrons created in an elementary collision of proton with a Thorium and Uranium nuclei is almost same but the multiplication of neutrons in voluminous Thorium target is significantly less than in Uranium. This may be because of the fact that in the 'reactor region' at energies E < 10-15 MeV fission cross-section for the Thorium is smaller than for Uranium .

Table IV

The calculated yield of neutrons $<N_n>$ per one bombarding proton with the energy, E in the thin Uranium (natural composition of isotopes) and Thorium targets. The target diameters D=10 cm, the length L=60 cm.Point of entry of beam is at Z=0 cm.

E Gev	**0.3**	**0.4**	**0.5**	**0.7**	**1.0**
U	6	12	19	28	39
Th	4.5	9	14	22	33

c)Neutron Yield and Energy Gain in a large Uranium and Thorium target: **I**n the following analysis we restrict ourselves to the case of a very large (practically without any neutron leakage) blocks of natural Uranium and Thorium. Analysis based on such target-blocks provide informations about the qualitative processes and the main features of ADSS which may be treated as the limiting case of a real Electro-Nuclear set-up. We consider a cylindrical Uranium block with the length L=200 cm and the radius R=100 cm and two times larger Thorium block (L=400 cm, R=200 cm) since the density of Thorium is ~ 1.7 times less than that of Uranium. In both cases we suppose that the primary proton beam is introduced inside the target through an axial needle-shaped slit of several tens of centimeter length (L=30 and 60 cm for the Uranium and Thorium blocks

Values of major processes contributing towards the total heat are given in table VII.

Table V

Neutron yield <N> and energy gain, G in the very large natural Uranium amd thorium blocks (per one primary proton with energy E) .

E,GeV	Nucl.	<N>	G	G_{tot}
0.1	U	1.4	0.71	3.46
	Th	0.8	0.01	1.59
0.2	U	5.5	1.41	6.96
	Th	3.9	0.25	3.98
0.35	U	18.2	2.69	13.1
	Th	11.6	0.39	6.72
0.65	U	54.7	4.75	21.7
	Th	33.4	0.85	10.7
0.8	U	75.0	5.29	24.1
	Th	46.7	0.95	12.1
1.0	U	100	5.51	25.6
	Th	62.4	1.03	12.9
1.5	U	161	5.80	27.4
	Th	99.5	1.16	113.8
2	U	216	6.00	27,7
	Th	133	1.23	13.9

We see that at the energies smaller than several hundreds MeV in both, Uranium and Thorium, blocks the main contribution towards Q is expected to be from the ionization processes. The relative contribution of this channel, Q_{ion} / E (%) is around 50% at E > 0.5 GeV and increases fast to 89% at smaller energies (see Table VIII). This is respectively) so that a significant part of the created neutrons leaving the target in backward direction (at angles $\theta > 90^\circ$ also participate in the process of inter-nuclear cascade.

In Table V we show the dependence of neutron yield on the type of the target and the primary proton energy for the said large target volumes. The yield is very small at $E \cong 0.1$ GeV, however, it increases faster at energies ≥ 0.35 . In the next Table VI the numbers of high- ($E_n > 10.5$ MeV) and low-energy ($E_n < 10.5$ MeV) fissions generated in the two kinds of fuel blocks are presented for only three primary proton energies. Comparing the data in table V and VI for the corresponding primary energies it may be concluded that a significant part of the neutron flow in Uranium and the main part of the flow in Thorium are produced in high-energy interactions and not from the fission like processes. As we understand that the low-energy neutron multiplication is larger in the targets containing fissile fuel (or easy fission nuclei)and natural Uranium contains contains ~0.7% of isotope U^{235} therefore, a significant excessive neutron yield in Uranium over the Thorium target is because of the fissile U^{235} .

Energy gain may be defined as ,

$$G(E) = [Q(E) - E]/E$$

where the heat produced in the target, Q due to ionisation loses + stopping of γ's and other particles + the fission-fragments in the medium. Estimates of the energy gain , G(E) are given in table V for the two fuels and different primary proton energies.

the main reason why very low-energy proton beams, although much economic, are not applicable for ADSS. However. this conclusion is true only for ADSS with coefficient of neutron multiplucation $K_{eff} << 1$ (for the considered Uranium and Thorium blocks K_{eff} is around 0.4 and 0.06 respectively). In ADSS with $K_{eff} =$ 0.95-0.99 even the small remaining part of the energy $\Delta E = E - Q_{ion}$ is enough for sufficiently large amplification[16-19].

Table VI

Numbers of high-and low-energy fissions generated in the Uranium amd Thorium blocks by a single proton of energy E.

E, GeV		0.1	0.65	2.0
>10.5 MeV	U	0.1	3.3	13.3
	Th	0.09	2.9	11.3
<10.5 MeV	U	0.27	11.0	43.5
	Th	0.02	0.9	3.6

Table VII

The main contributions towards the heat Q (GeV) produced by a proton with the energy E in the natural Uranium and Thorium blocks.

E, GeV		0.1	0.65	2.0
Ionization, losses	U	0.089	0.307	1.02
	Th	0.081	0.230	0.856
Fission,	U	0.061	2.40	9.39
	Th	0.019	0.614	2.37
γ-rays from (n,γ)-reac-	U	0.022	1.03	3.51
tions	Th	0.001	0.346	1.18

It is clear from the data given in table VIII that at energies E > 0.35 GeV fission becomes the important sources of heat as the ratio, $Q_{ion}/E\%$ becomes less than 50% and in case of Thorium it is better even at E=0.35 GeV . It may also be pointed out that the raio, $Q_{ion}/ E\ \%$ is smaller in case of Thorium than Uranium at all the energies.

Table VIII

The relative energy losses in ionization processes.

E,GeV		0.1	0.2	0.35	0.65	1.0
$Q_{ion}/E\%$	U	89	75	57	47	47
	Th	81	62	44	37	41

One must take into account that the energy produced in (n,γ) reactions is taken away by the weakly interacting γ-quanta which is absorbed at large distances. In small size targets this part of the produced energy does not give a remarkable contribution towards heat production.

It may be made clear from table V that the energy gain, G is strongly dependent on E at small proton energies and becomes rather constant at E ≥ 1 GeV in both cases of Uranium and Thorium targets. The same is true for the total energy gain, in the situation of total burn-up of the fuel. Total energy gain may be defined as follows,

$$G_{tot}=G+N\ Q_f/E$$

where Q_f=201 MeV for Pu^{239} and Q_f= 191 MeV for U^{233} is the energy produced by burning in ADSS or in a fission reactor burning of nuclei which are created in the fuel-block. The gain G_{tot} exoceeds unity significantly even at E = 0.1-0.2 GeV. It may also be pointed out that although the neutron yield in Thorium target is only 30-40% less yet the G_{tot} is approximately two times smaller in comparison to Uranium target . This is because of the fact that a sizeable number of 'fissile' nuclei for example Pu^{239} is produced in the Uranium block and U^{233} is produced in Thorium block. This significant effect of 'fissile' nuclei may be seen from the computation of N,G and G_{tot} for the pure U^{238} nucleus than Natural Uranium. Data of these calculations is given in table IX along with the data for the natural Uranium (in bracket).

Table IX

. Neutron yield, N and the energy gain, G and G_{tot} in the block of pure U^{238} (all parameters of the block are the same as in Table V) . Values in the bracket are for Natural Uranium.

E,GeV	0.1	0.65	1.0
N	1.2(1.4)	47.7(54.7)	87.7(100)
G	0.44(0.71)	3.09(4.75)	3.66(5.51)
G_{tot}	2.85(3.46)	17.9(21.7)	21.3(25.6)

It is clear from the table that at the three energies N, G and G_{tot} assume higher values in case of natural Uranium than pure U^{238} .

Space distributions of the heat in the longitudinal(along the beam, Z- direction)and transverse directions may be defined by the relations (3) and (4) respectively,

$$dQ(z)/dz=\int Q(z,r)\ dr/\int Q(z,r)\ dzdr$$

and

$$dQ(r)/dr=\int Q(z,r)\ dz/\int Q(z,r)\ dzdr$$

where Q is the heat production without the energy contribution of γ -quanta. In fig.1 longitudinal heat distributions are given for E=0.1 GeV and 1.0 GeV energies for the Uranium and Thorium blocks. Similarly, in figure 2 radial heat distribution is given.

One can see from fig.1 that the longitudinal distribution has a maximum close to the proton beam entry points e.g. 30 cm in Uranium and 60 cm for Thorium. This is particularly noticeable at small energies where the primary protons loses their energy in a thin layer of matter. Second important feature which may be pointe out that because of the smaller density of matter heat generation in Thorium block occurs in a more extended region than in Uranium.

From the raw data as well as data displayed in fig.2 for the radial distribution of heat it may be pointed out that the main part of the heat is produced in a narrow central stem. For example, at E= 100 MeV 90% of the heat in Thorium and 50% in Uranium is generated in the cylinder with the radius r=4 cm. In layers larger r where the main contribution to Q is due to fission the distribution dQ/dr in Thorium is much narrower than in Uranium. However, at higher energies where ionization losses are decreased and charge particles pass larger distances the radial heat distribution widens significantly and in contrast to low energies becomes broader in Thorium than in more dense Uranium.

In Fig. 3, normalized neutron spectra,

$$dN(E_n)/dE_n=\int N(E_n,r,z)\,drdz/\int(dN/dE_n)\,dE_n$$

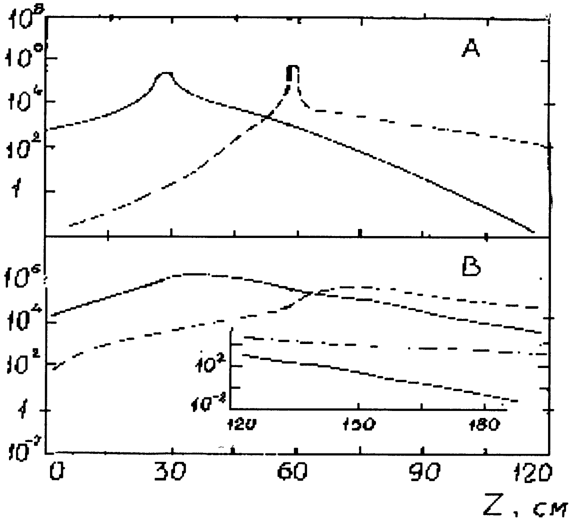

Fig. 1. *Longitudinal distribution of the produced heat. The primary proton beam is introduced in the target through the axial dip at the point r=0, z=30 cm in Uranium and z=60 cm in Thorium. Solid lines - Uranium, dashed lines - Thorium. A - for E=0.1, B - for E=1 GeV.*

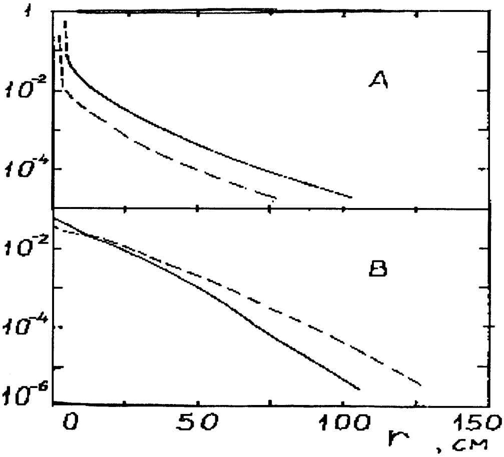

Fig 2. *Transversal dustribution of the produced heat. The proton beam is introduced through the dip with the same parameters as in Fig. 1. All designations are also the same as in Fig. 1.*

in case of Uranium and Thorium are compared for small (E=0.1 GeV) and large(E=1.0 GeV) proton energies. The spectra have a sharp maximum at $E_n \cong$ 0.1 MeV weakly sensitive to the proton energy and to the type of the target. The spectra in Thorium are a little gentler. This is stipulated by a relative smaller fission cross-section and accordingly because of large contribution of elastic collisions at low-energies and a neutron generation in high-energy region.
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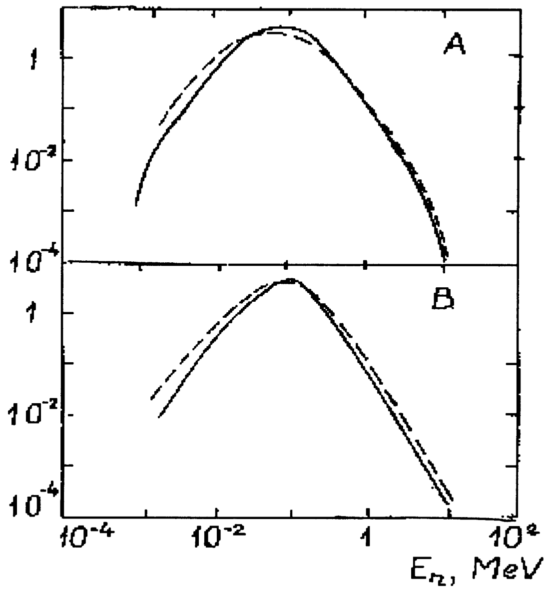

Fig. 3. *The normalized neutron spectra. All designations are the same as in Fig, 1 and Fig. 2.*

4. **Conclusions**

From the energy gain point of view the Thorium fuel for ADSS is somewhat worse than Uranium . Nevertheless, the neutron yield and energy gain are still rather significant and the ADSS with Thorium are economically profitable, especially if one takes into account an admixture of easy fission isotopes increases essentially the energy amplification of the system. For example, in an accelerator driven system a mixture of approximately 3.8% U^{233} amplifies neutron generation to about 8 times and energy gain, G to 35 times at primary Proton energy 500 MeV. Similarly, for E=1 GeV total neutron yield jumps to 20 times and energy gain G to 42 times. This conclusion is particularly important for India which is rich of Thorium reserves.

It is important to remark that due to the practically complete burning of fuel in such sub-critical and safe set-ups there is no need of technology of conversion of the exhausted fuel which is a very difficult and unsolved problem for the fission reactors and specially for Thorium reactors where separation of U^{233} is very difficult. In addition, one may point out that there is another very important circumstance, although Thorium electro-nuclear systems are weak systems but attract special attention from the point of the nuclear stability and with respect to the non-proliferation of nuclear weapons. The share of easy fission ("used in weapons") nuclei(U^{233}) among all light Uranium isotopes created in the Thorium system is less than a half and it is very difficult to separate the dangerous U^{233} from other isotopes.

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References

1. V, S. Barashenkov, V. D. Toneev. Interactions of high-energy particles and atomic nuclei with nuclei. Atomizdat, Moscow, 1972. (In Russian).

2. V. S. Barashenkov et al. Usp. Fiz. Nauk. 1073 v.109, p.91. [Sov. Phys. Usp. 1974, v.16, p. 31].

3. V. S. Barashenkov, B. F. Kostenko, A. M. Zadorogny. Nucl.Phys. 1980, v. A338, p. 413 and

J. J. Musulmanbekov, B. Khurelbaatar. Modified model of hadron-nucleus and nucleus-nucleus collisions. JINR P2-99-59, Dubna. 1999. (In Russian).

4. V. S. Barashenkov at al. Phys. Part. Nucl. 1983, v. 24, p. 107.

5. N. M. Sobolevsky, A. V. Dementyev. SHIELD - Monte Carlo hadron transport code. INR 0874/94, Moscow, 1994.

6. S. Chigrinov, A. Kievitskaia, K. Koutkovskaia. Proc. ICENES'93, p. 434. Makuhari chiba, Japan, 1993.

7. S. G. Mashnik. Physics of the CEM92M code. JINR E2-94-352, Dubna, 1994.

8. R. Sternheimer. Phys. Rev. 1966, v. 145, p. 247.

9. R. Sternheimer. Phys. Rev. 1971, v. 3B, p. 3681.

10. L. Lindhard, M. Scharf, H. E. Schiott. K. Dan. Vidensk. Selsk. Nat.-Fys. Medd. 1963, v. 33, No 14.

11. V. S. Barashenkov, A. Polanski. Electronic Guide for nuclear cross-sections. JINR E2-94-17, Dubna, 1994.

12. V. S. Barashenkov. Cross-sections of the interactions of the particles and nuclei. JINR, Dubna, 1993.

13.V. S. Barashenkov, W. Gudowski, A. Polanski.Integral high-energy nuclon-nucleus

cross-sections for mathematical experiments with electronuclear facilities. JINR E2-99-206,Dubna,1999.
14. L. P. Abagian et al: Group constants for reactor and shielding calculations. Energoatomizdat, Moscow, 1981 (In Russian).
15. V. G. Batjaev. Proc. of 3rd Intern. Conf. on Accelerator Driven Transmutation Technology. Prague, June 1999.
16. V. S. Barashenkov, A. Polanski A. N. Sosnin. Kerntechnik, 1998, v. 63, p.197.

17. V. S. Barashenkov, I. A. Shelaev. Atomnaja Energija. 1998, v. 95, p.409. (In Russian).
18. V. S. Barashenkov, I. A. Shelaev.Electronuclear amplifiers with low-energy proton beams, JINR E2-98-137. Dubna, 1998.
19. V. S. Barashenkov, A. Polanski, I. V. Puzynin, A. N. Sissakian. An experimental accelerator driven system based on plutonium subcritical assambly and 660 MeV proton accelerator. JINR E2-99-206, Dubna, 1999.

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Торий как топливо для управляемых ускорителями подкритических электроядерных систем

Путем монте-карловского моделирования изучаются выход нейтронов, тепловыделение и другие особенности взаимодействия пучков протонов с энергиями в диапазоне 0,1–2 ГэВ с очень большими, практически бесконечными блоками урана и тория. Сравнение полученных результатов показывает, что выход нейтронов в тории меньше на 30–40 % и выигрыш в энергии приблизительно вдвое меньше, чем в уране. Тем не менее, в области энергий бомбардирующих протонов, больших нескольких сотен МэВ, управляемые ускорителями подкритические электроядерные системы (ADS) с ториевым горючим представляются весьма перспективными, особенно для стран, которые, подобно Индии, богаты торием. Добавка в облучаемый блок легкоделящихся изотопов U^{233}, U^{235}, Pu^{239} может увеличить мультипликацию нейтронов и, соответственно, выход энергии. Подчеркивается, что благодаря практически полному выжиганию топлива такие системы не нуждаются в дорогостоящей технологии регенерации отработанного топлива.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

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Thorium as a Fuel for Accelerator Driven Subcritical Electronuclear Systems

Neutron yield and energy production in a very large, practically infinite, uranium and thorium target-blocks irradiated by protons with energies in the range 0.1–2 GeV are studied by Monte Carlo method. Though the comparison of uranium and thorium targets shows that the neutron yield in the latter is 30–40 % less and the energy gain is approximatelly two times smaller, accelerator Driven subcritical Systems (ADS) with thorium fuel are very perspective at the bombarding energies higher than several hundreds MeV. An admixture of fissile elements U^{233}, U^{235}, Pu^{239} in the set-up gives larger neutron multiplication which in turn shows better energy amplification. It is argued that due to the practically complete burning of the fuel in such set-up there is no need of technology of conversion of the exhaust fuel.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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