PECULIARITIES OF NEUTRON FIELDS FORMATION IN THE SYSTEMS “NEUTRON PRODUCING TARGET – MODERATOR” IRRADIATED BY HIGH ENERGY PARTICLES

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The theoretical and experimental evidence of similarity of neutron spectra formed in sub-critical systems driven by external proton and neutron beams

PACS: 21.60.Ka, 25.10.+s, 25.45.-s, 25.85.Ec, 28.20.-v, 28.50.Qd, 28.52.Av, 29.85.+c

1. INTRODUCTION

The investigations of high energy particles interaction with nuclei in spite of a great deal of experimental and theoretical works are of great importance for study of peculiarities of nuclear reactions mechanism, atomic nucleus structure and physics of elementary particles. Further research in the field of nuclear physics fundamentals is still being stimulated by necessity of the solution of a wide range of applied problems, in particular the application of charged particle accelerators for energy production, transmutation of long-lived waste of fuel cycle of nuclear power engineering, tritium production, production of isotopes for industry, agriculture, medicine etc.

The problem of management of radioactive waste of nuclear power engineering became recently especially urgent due to further extension of nuclear energy contribution to world energy production and outstanding problems of open nuclear fuel cycle.

One of the most prospective trends in solving the problem of amount reduction of long-lived radioactive fission products (^{137}Cs, ^{90}Sr, ^{129}I, ^{126}Sn,…) and minor-actinides (Np, Pu, Cm,…) is transmutation – that is it’s conversion into stable or short-lived nuclei in sub-critical (target / blanket) systems driven by accelerators of high energy charged particles (ADS-technology) [1–4]. The main advantage of ADS-technology is stable system operation in a sub-critical mode.

Despite the considerable amount of theoretical researches the problem of choice of optimal neutron spectrum for transmutation of long-lived fission products and minor-actinides remains by now one of the most important. It is connected first of all with lack of valid evaluated nuclear data on interactions of neutrons with radioactive nuclei in wide energy range from some eV up to tens of GeV. For some nuclei even integral cross sections averaged over appropriate energy distributions are not available.

The principal aspects of ADS concept were widely discussed in theoretical papers but the experimental research on development of such systems is rather scarce. In this regard the experimental research of various aspects of ADS on the basis of low energy accelerators – cyclotrons, microtrons, as well as deuterium or tritium ions accelerators – neutron generators of high intensity is of great importance.

The application of such accelerators integrated with sub-critical multiplying systems gives the opportunity to carry out the experimental research of various aspects of ADS-technologies and to outline future investigations at high-energy particle accelerators. Similar situation took place in nuclear power engineering when many peculiarities of neutron-physical characteristics of nuclear reactors, first of all of nuclear power plants cores intended for special purposes, were investigated at critical benchmarks.

2. DESCRIPTION OF “YALINA” FACILITY DESIGN AND EXPERIMENT PROCEDURE

First experimental investigations of ADS with thermal neutron spectrum at the National Academy of Sciences of Belarus were started in 1999 at the “YALINA” facility – sub-critical assembly with polyethylene moderator and uranium dioxide fuel of 10% enrichment by ^{235}U driven by neutron generator operating both in continuous and pulse modes. The obtained results have shown that further investigations would be very prospective. The experiments at JINR (Russia, Dubna) accelerators performed in the framework of topical plan on electronuclear plants research are the continuation of this investigation program.

The interaction of high energy particles in energy range of some MeV up to thousands MeV is very complicated process involving participation of large number of strongly interacting particles (n, p, π-mesons) in which electromagnetic interactions, nuclear reactions, formation and development of nuclear cascade are taken into account.

An opportunity of investigation of various ADS characteristics at sub-critical target / blanket systems driven by neutron generator of high intensity has been shown for the first time in Ref. [5]. The similarity of $d^2\sigma/d\Omega dE$ distributions in the energy range $E_n \leq (15\ldots20)$ MeV [6,7] confirms a principal possibility of application of proton accelerators $E_p \leq 100\ldots150$ MeV for investigations in the field of ADS-technology.

The results of experimental investigations of ^{129}I, ^{237}Np transmutation by relativistic protons ($0.5 < E_p < 7.4$ GeV) are one more evidence of independence of the energy distribution of neutrons generated in spallation reactions in extended targets of heavy elements Pb, Bi, Th, U upon energy of primary proton beam [8]. It has been determined that transmutation rates of ^{129}I (n,γ) ^{130}I and ^{237}Np (n,γ) ^{238}Np related to one neutron generated in neutron-producing lead target do not depend upon energy of protons.

Just these considerations became a basic argument for setting up the nuclear sub-critical facility “YALINA” consisting of sub-critical assembly (Fig.1) driven by a neutron generator [9] operating both in continuous and pulse modes. The facility is intended for carrying out the experimental investigation of physics of sub-critical systems with external neutron sources.

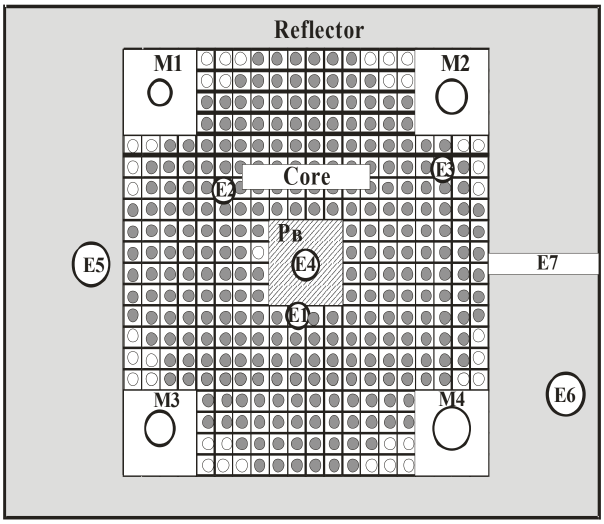

Fig. 1. Vertical cross section of the sub-critical assembly: E1-E3 – experimental channels located in the core; M1-M4 - channels for neutron flux monitoring; E5-E7 - experimental channels located in the reflector

The sub-critical assembly of “YALINA” facility is uranium-polyethylene multiplying system with $k_{max} < 0.98$ located inside graphite column of parallelepiped configuration with side dimension 100 and 120 cm that is arranged of “reactor graphite” blocks with side dimension 20×20×50 cm^3. The core of the assembly is of parallelepiped configuration with side dimension 40×40×60 cm^3 and consists of “bare” polyethylene sub-assemblies where fuel pins of EK-10 type (UO_2 of 10% enrichment by ^{235}U) are located.

At the core center a neutron-producing lead target is located that is arranged of 12 blocks (in height) with side dimension 8×8×5 cm^3 that reminds fuel subassembly by shape and size. The core is surrounded by 50 cm thick graphite reflector and by 1mm cadmium layer. At the distances 5, 11, 18 cm from the core center three experimental channels E1-E3 with diameters D = 2.5 cm are situated for location of samples of radioactive targets or detectors for measurement of neutron flux functionals. For the same purpose one radial channel E7 with diameter 2.5 cm is located in graphite reflector (Fig. 1).

The purposes of the experiments at the LHE of JINR at the sub-critical assembly “YALINA” (without nuclear fuel load) were: 1) investigation of thermal and fast neutron fields characteristics in experimental channels of the assembly by various energies of proton beam; 2) calculation of neutron spectra with application of Monte-Carlo codes, comparison of calculated and experimentally measured functionals of neutron flux; 3) comparison of above mentioned characteristics for sub-critical assembly “YALINA” driven by neutron generator with E_n=14.5 MeV with those for identical assembly driven by proton accelerator with various beam energies.

To obtain proton beam with energies 420 and 300 MeV a graphite moderator with side dimensions 20 ×20×60 cm^3 and 20×20×85 cm^3, respectively, was located in front of the sub-critical assembly. The setup of the experimental installation with graphite moderator of proton beam is presented in Fig. 2.

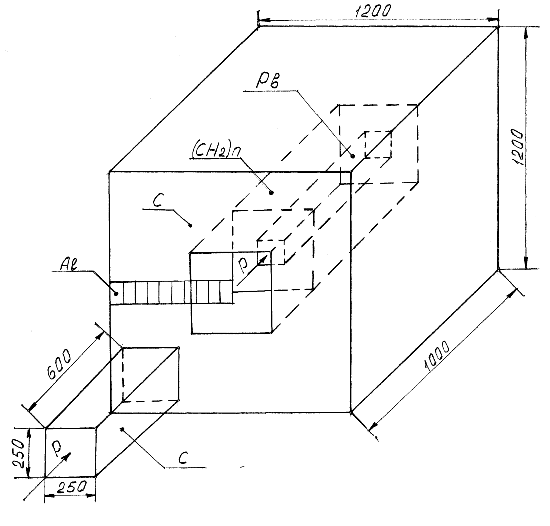

Fig. 2. Setup for the experiment on irradiation of sub-critical assembly “YALINA” by proton beam with energy 420 MeV

For estimation of proton beam divergence after passing the graphite moderator the aluminum foil in the shape of band with 9 cm in width and 60 cm in length was located at front wall of the assembly (Fig.2).

The experimental results and calculated ones obtained with application of codes based on statistical (Monte-Carlo) methods of nucleon-meson cascade calculations [10,11] have shown that after passing the moderator main part of protons gets to the central part of neutron producing lead target. Monitoring of the intensity of proton beam incident to the target was performed by measurement of ^{27}Al (p, 3p3n) ^{22}Na reaction rate [12]. For this purpose the aluminum foil with dimension 10×10 cm^2 was located at the proton accelerator profilometer in front of lead target.

For each of pointed values of proton energy two experiments have been carried out. In the course of first experiment the activation detectors with Indium foil were placed inside three experimental channels located along OZ axis at distances R = 5, 11, 18 cm from the target center at step of 5 cm. Forth experimental channel is perpendicular to OZ axis and passes through a point with coordinate Z = 25 cm. The rate of the reaction ^{115}In (n_{th},γ) ^{116}In was measured.

In the course of second experiment there were measured the rates of the reactions ^{27}Al (n,p) ^{27}Mg (E_n=2.5 MeV), ^{47}Ti (n,p) ^{47}Sc (E_n=3 MeV), ^{46}Ti (n,p) ^{46}Sc (E_n= 4 MeV), ^{48}Ti (n,p) ^{48}Sc (E_n=5 MeV), ^{65}Cu (n,2n) ^{64}Cu (E_n=11 MeV), ^{209}Bi (n,xn) $^{210-x}$Bi (x = 4…10) (E_n= 20…70 MeV) having different thresholds.

Calculated energy distributions (spectra) of neutrons generated in neutron-producing lead target located at the core center and irradiated by proton beam with energies 300, 420 and 660 MeV are presented in the Fig. 3.

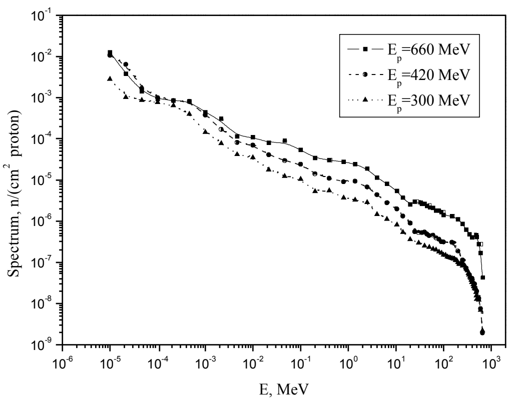

***Fig. 3**. Calculated spectra of neutrons from lead target by 660, 420 and 300 MeV protons irradiation*

It is seen from Fig. 3 that spatial distributions of particles′ flux inside polyethylene moderator will be the same differing by absolute value only. That it is really so is seen from Fig. 4 where experimentally measured dependence of ^{115}In (n_{th},γ) ^{116}In reaction rate upon distance *r* at central plane of the assembly (Z = 0 cm) is presented.

It is seen that radial distribution of thermal neutron flux looks similar for various energies of protons and neutrons. Neutron flux density is ten times lower at the border of core as compared with that at the center.

The measurements of (n, xnyp)-type threshold reactions rates are of special interest from the point of view of spatial and energy distribution of neutron flux density measurements in multiplying media.

The reaction rate *R* (proton^{-1}·atom^{-1}) is related to the neutron flux as follows [13]:

$$R \equiv \int_{Eth}^{\infty} \sigma(E)\varphi(E)dE.$$

Here, φ(E) is neutron flux (n/(cm^2· MeV · proton), E_{th} is threshold neutron energy for the observed reaction.

The results of measurements of threshold reaction rates ^{48}Ti (n, p) ^{48}Sc, ^{209}Bi (n, xn) $^{210-x}$Bi for primary protons with energies 660, 420 and 300 MeV and comparison with results of calculation are presented in Fig. 5 and in the table.

As it follows from presented results the threshold reaction rates decrease towards periphery of the core decreasing to be more significant than that of radiation capture reactions. Such reaction rates behavior is a consequence of reduction of high-energy neutron number due to both elastic and inelastic interactions with medium nuclei.

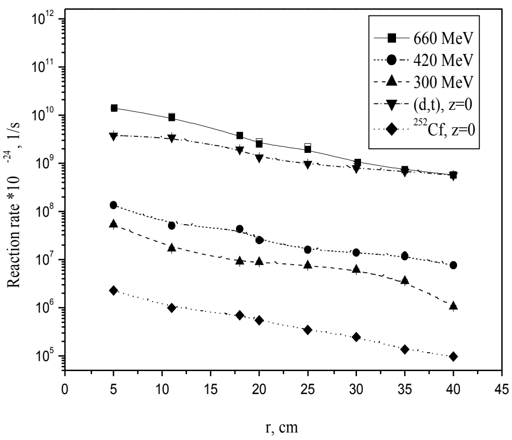

***Fig. 4**. Dependence of ^{115}In (n_{th},γ) ^{116}In reaction rate upon distance from the assembly center (Z=0 cm) for process with lead target irradiated by protons of 660, 420 and 300 MeV, neutrons from (D,T) reaction and neutrons from ^{252}Cf fission spectrum (statistical uncertainty of measurements is less than 5 %)*

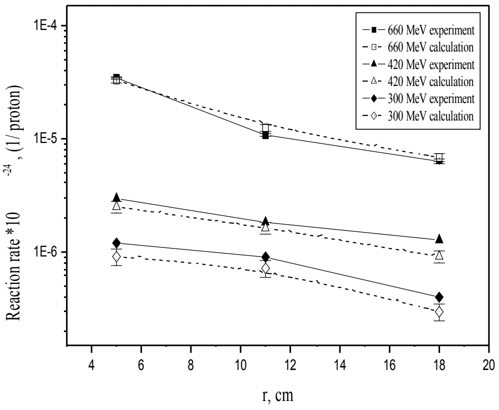

Fig. 5. *Comparison of experimentally measured and calculated rates of the reaction* ^{48}Ti *(n, p)* ^{48}Sc

Comparison of experimentally measured and calculated rates of the threshold reactions (in brackets - absolute values of measurement uncertainty)

Reaction	r, cm	E, MeV	Reaction rate 10^{-24}, 1/proton	
			Experiment	Calculation
$(n,7n)^{203}Bi$	5	660	$3.48\cdot10^{-4}$ $(2.09\cdot10^{-5})$	$1.01\cdot10^{-4}$ $(5.05\cdot10^{-6})$
		420	$5.11\cdot10^{-5}$ $(1.59\cdot10^{-6})$	$2.44\cdot10^{-5}$ $(2.44\cdot10^{-6})$
		300	$3.25\cdot10^{-5}$ $(2.71\cdot10^{-6})$	$1.03\cdot10^{-5}$ $(1.55\cdot10^{-6})$
	11	660	$5.71\cdot10^{-5}$ $(3.99\cdot10^{-6})$	$4.40\cdot10^{-5}$ $(3.52\cdot10^{-6})$
		420	$1.74\cdot10^{-5}$ $(1.19\cdot10^{-6})$	$1.82\cdot10^{-5}$ $(2.18\cdot10^{-6})$
		300	$1.62\cdot10^{-5}$ $(1.08\cdot10^{-6})$	$9.26\cdot10^{-6}$ $(1.57\cdot10^{-6})$
	18	660	$2.90\cdot10^{-5}$ $(2.03\cdot10^{-6})$	$2.58\cdot10^{-5}$ $(2.58\cdot10^{-6})$
		420	$8.48\cdot10^{-6}$ $(1.19\cdot10^{-6})$	$1.15\cdot10^{-4}$ $(1.61\cdot10^{-5})$
		300	$7.22\cdot10^{-6}$ $(9.02\cdot10^{-7})$	$6.67\cdot10^{-6}$ $(1.33\cdot10^{-6})$
$(n,6n)^{204}Bi$	5	660	$2.92\cdot10^{-4}$ $(2.62\cdot10^{-5})$	$1.30\cdot10^{-4}$ $(6.50\cdot10^{-6})$
		420	$5.43\cdot10^{-5}$ $(1.06\cdot10^{-6})$	$3.10\cdot10^{-5}$ $(3.10\cdot10^{-6})$
		300	$2.24\cdot10^{-5}$ $(2.59\cdot10^{-6})$	$1.25\cdot10^{-5}$ $(1.88\cdot10^{-6})$
	11	660	$7.29\cdot10^{-5}$ $(7.29\cdot10^{-6})$	$5.54\cdot10^{-5}$ $(4.43\cdot10^{-6})$
		420	$2.35\cdot10^{-5}$ $(4.68\cdot10^{-7})$	$2.24\cdot10^{-5}$ $(2.69\cdot10^{-6})$
		300	$1.73\cdot10^{-5}$ $(1.73\cdot10^{-6})$	$1.11\cdot10^{-5}$ $(1.89\cdot10^{-6})$
	18	660	$4.33\cdot10^{-5}$ $(4.33\cdot10^{-6})$	$3.29\cdot10^{-5}$ $(3.29\cdot10^{-6})$
		420	$1.29\cdot10^{-5}$ $(2.98\cdot10^{-7})$	$1.50\cdot10^{-5}$ $(2.10\cdot10^{-6})$
		300	$1.04\cdot10^{-5}$ $(1.73\cdot10^{-6})$	$8.72\cdot10^{-6}$ $(1.74\cdot10^{-6})$

3. CONCLUSION

Comparison of calculated and experimentally measured threshold reactions rates gives the opportunity to verify nuclear data used in calculations (first of all cross sections of the threshold reactions). The experimental data on (n, xnyp) reactions rates are of special importance for evaluation of nuclear data, further development of models and codes intended for the calculation of charged particles transport and for investigations in the field of hybrid electronuclear systems aimed for energy production and long-lived fission products and minor-actinides transmutation. It allows to avoid in the future the expensive and time consuming experiments with application of accelerators, generators and other installations for simulation of various parameters of subcritical systems. Experimentally measured reaction rates demonstrate the independence of neutron flux radial distribution in system "neutron producing target – moderator" upon energy of primary proton beam and type of external neutron source.

Moreover the investigation of energy spectrum of neutrons in experimental channels of sub-critical assembly is necessary for determination of optimum conditions for transmutation of long-lived radioactive isotopes (for example, minor-actinides) [14].

REFERENCES

1. C.D. Bowman, *Accelerator Driven Systems in Nuclear Energy. Role and Technical Approach.* Report ADNA/97-013, Los Alamos: ADNA Corporation, 1997.
2. V.I. Subbotin. *Accelerators Promise to Make Nuclear Energy Safer*: Report at 85-th Session of JINR Scientific Council, 15 January 1999,– Dubna, Preprint JINR, P1-99-97, 1999, p. 24 (in Russian).
3. R.G. Vasilkov, V.I. Goldanskiy, V.L. Gelepov, V.P. Dmitriyevskiy. Electronuclear Method of Neutron Generation // *Atomic Energy*. 1970, v. 29, № 3, p. 151-158 (in Russian).
4. C. Rubbia, J.O. Rubio, S. Buono et al. *CERN – Group Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier / Accelerator Driven Systems: Energy Generation and Transmutation of Nuclear Waste*, IAEA-TECDOC-985, Vienna, 1997, p. 187-312.
5. S.E. Chigrinov, H.I. Kiyavitskaya, A.M. Khilmanovi ch et al. *Experimental Research of the Transmutation of Long - Lived Fission Products and Minor – Actinides in a Subcritical Assembly Driven by a Neutron Generator.* Proc. of the ADTTA'96-Conf. Kalmar, Sweden, 1996, p. 737-744.
6. R.R. Fullwood, J.A. Cramer, R.A. Haarman et al. *Neutron Production by Medium Energy Protons on Heavy Metal Targets*: Report LA-4789 UC-34, Los Alamos, New Mexico, 1972.
7. H. Takada, S. Meigo, T. Sasa et al. *Present Status of Integral Spallation Experiments in JAERI / Accelerator Driven Systems: Energy Generation and Transmutation of Nuclear Waste,* IAEA-TECDOC-985, Vienna, 1997, p. 187312.

8. D. Chultem, Ts. Damdinger, V.M. Dyachenko, L. Enkhligin, L.A. Lomova, V.P. Perelygin, K.D. Tolstov. *Measurement of the Neutron Component in a Shower Generated in a Lead Target by Relativistic Nuclear Beam:* Preprint JINR E1-94-0407, Dubna, 1994
9. S.F. Boulyga, V.G. Goulo, I.V. Zhouk et al. *Neutron Generator NG-12-1 as a Basic Installation to Perform Researches at Neutron Center of the National Academy of Sciences of Belarus:* Preprint IRPCP of NAS of Belarus, 21, Minsk: 1998, 36 p. (in Russian).
10. J.F. Briesmeister. MCNP – *A General Purpose N-Particle Transport Code, Version 4B*: Report LA-12625-M, Los Alamos National Laboratory, 1997, 736 p.
11. R.E. Prael, H. Lichtenstein. *User Guide to LSC: the LAHET Code System:* Report LAUR-89-3014, Los Alamos National Laboratory, 1989.
12. J.-S. Wan, M. Ochs, P. Vater et al. Monitor Reaction in Al-Foils for High Energy Proton Beams Bombarding a Thick Target // *Nucl. Instr. and Meth.* B. 1999, v. 155, p. 110-115.
13. E. Kim, T. Nakamura, A. Konno et al. Measurements of neutron spallation cross-section of 12C and 209Bi in the 20- to 150 MeV energy range // *Nucl. Sci. and Engineering.* 1998, v. 129, p. 209-223.
14. J. Adam, A. Balabekyan, R. Brandt et al. *Investigation of the Formation of Residual Nuclei from the Radioactive* ^{237}*Np and* ^{241}*Am Targets in the Reaction with 660 MeV Protons:* Preprint. Dubna: JINR E15-2000-256, 2000, 18 p.

ОСОБЕННОСТИ ФОРМИРОВАНИЯ НЕЙТРОННЫХ ПОЛЕЙ В СИСТЕМАХ «НЕЙТРОНОПРОИЗВОДЯЩАЯ МИШЕНЬ – ЗАМЕДЛИТЕЛЬ», ОБЛУЧАЕМЫХ ЧАСТИЦАМИ ВЫСОКИХ ЭНЕРГИЙ

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Представлены теоретические и экспериментальные доказательства подобия спектров нейтронов, образующихся в подкритических системах, управляемых внешними протонным и нейтронным пучками.

ОСОБЛИВОСТІ ФОРМУВАННЯ НЕЙТРОННИХ ПОЛІВ В СИСТЕМАХ «НЕЙТРОНОУТВОРЮЮЧА МІШЕНЬ – СПОВІЛЬНЮВАЧ», ОПРОМІНЕНИХ ЧАСТИНКАМИ ВИСОКИХ ЕНЕРГІЙ

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Представлено теоретичні та експериментальні докази подібності спектрів нейтронів, що утворюються в підкритичних системах, керованих зовнішніми протонним та нейтронним пучками.