

Main results on the topic:  
Theoretical and Experimental Investigations of the Electronuclear Method of  
Energy Production and Radioactive Waste Transmutation  
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Main results of the investigations performed have been published in the journals, proceedings of the scientific conferences and preprints. About 100 scientific publications, reports of conferences and JINR preprints were published and presented.

Transmutation of nuclear waste means conversion of highly radioactive and toxic wastes containing long-lived radionuclides to low-level and short-lived nuclear wastes by means of nuclear technologies.

Experimental investigations were carried out on the 660 MeV proton beam of a phasotron of the Laboratory of Nuclear Problems. In 2000-2001 experiments were carried out on VI channel, (176 hours of proton beam) and since December 2003 on specially modernized IX channel (105 hours of proton beam).

The specialized experimental IX channel for investigation of transmutation was rebuild with financial support Polish, Czech and Rumanian grants.

Theoretical investigation, simulation and data processing have been carrying out in Department of Computational Physics Laboratory of Information Technologies. In the frame of this topic the methods for Monte Carlo modeling and experimental data processing have been developed.

A confirmation of high level of this investigation and an interest of the world scientific community the international workshop in the fields of ADTT by the Joint Institute for Nuclear Research was organized.

The International Workshop on Nuclear Methods for Transmutation of Nuclear Waste: Problems, Perspectives, Cooperative Research (NMTW'96) was held at the Joint Institute for Nuclear Research (JINR), Dubna, Russia from May 29<sup>th</sup> to 31<sup>st</sup>, 1996. Of the 80 participants, 64 were from Russia, including JINR, and 16 from abroad (Czech Republic, Finland, France, Germany, Peoples Republic of China, Poland, Sweden, and the USA). Fifteen Russian nuclear research centers and institutions were represented.

This workshop concerned itself primarily with accelerator-driven transmutation methods and technologies (ADTT). The basic principles of ADTT, the current status of development as well as the problems and perspectives of this method were presented and discussed. One emphasized current problems in computer modeling, data basis accumulation and experimental work, the other future perspectives and cooperative research possibilities in the above areas and in accelerator, target and blanket design for ADTT demonstration experiments and prototype development, using facilities of nuclear research institutions in Russia and European Countries.

From 25 to 30 April 2000, the *International Meeting on ADTT demonstration experiments* was held at the Laboratory of Information Technologies

Western European collaborators decided to support the idea to build a Subcritical Assembly in Dubna (SAD) driven by 660 MeV proton beam of a phasotron of the Laboratory of Nuclear Problems JINR. The project was funded by ISTC.

The last *International Meeting on SAD/YALINA demonstration experiments* took place in Minsk on 23-25 January 2005. In the meeting it was decided to include SAD/YALINA project to six framework programs of the Europe Union.

## Experimental and Scientific Program:

1. Obtaining new experimental data about the neutrons and protons escaping from lead, tungsten and uranium targets under interaction of protons with energy 0,66 - 3,5 GeV/nucleon.
2. Obtaining experimental data about cross sections of the nuclear reactions necessary for a study of efficiency of transmutation processes.
3. Development of alternative projects of high current accelerating complex for electronuclear installations.
4. Study of kinetic properties of multiplication coefficient fluctuation of subcritical electronuclear systems.
5. Creation of the software necessary for designing of various types of electronuclear systems and mathematical modeling of nuclear-physical processes occurring in them.
6. Study of nuclear physical aspects of sub-critical assembly in Dubna (SAD).

### 1. Obtain of new experimental data about the neutrons and protons escaping from lead, tungsten and uranium targets under interaction of protons with energy 0,66 - 3,5 GeV/nucleon.

A series of experiments have been performed in Dubna using a phasotron proton beam [1-6]. The proton beam intensity and proton distribution on the targets front surface has been monitored with the use of ionization chamber. All activation detectors, matrix of thermoluminescent detectors and profilometer were used. The scheme of the measured average proton beam profile is presented on Fig.1.

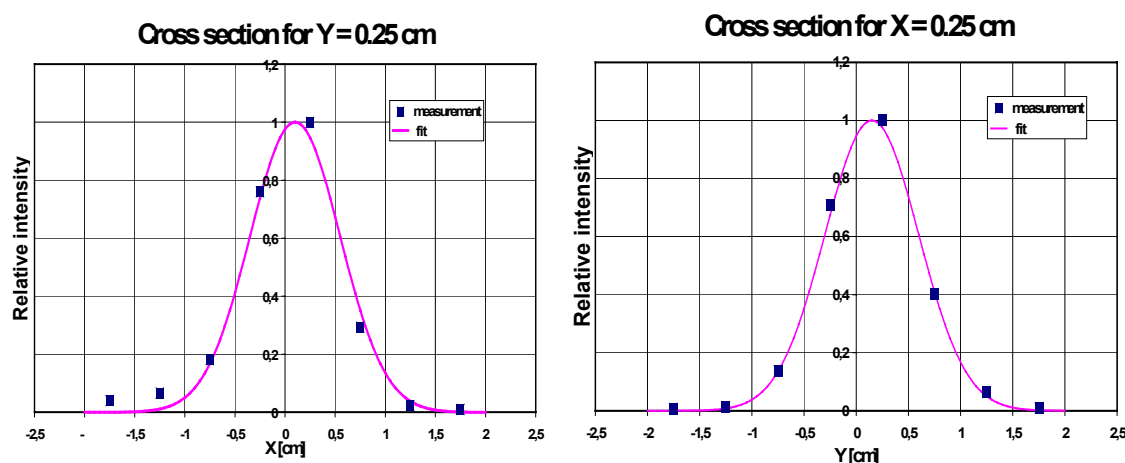


Fig.1. Average Proton Beam Profile.

The experimental investigation of the integral and differential characteristics of the hadron field around the thick cylindrical target of natural lead (50 cm long and 8.2 cm in diameter) irradiated by protons with energy 650 MeV has been done at the JINR phasotron. Neutron spectra have been measured at angles  $45^\circ$ ,  $75^\circ$  and  $105^\circ$  to the beam direction by a multisphere Bonner spectrometer (BSS) with LiI detector Fig. 2 [2]. The angular distribution of specific activities of threshold activation detectors arranged around the target as well as spatial distribution of the same values on the target surface have been evaluated experimentally [3]. The numerical evaluations of neutron spectra from the target taking into account the detailed experimental conditions have been presented in [4].

The experimental target was assembled from four equal cylinders of natural lead. Each cylinder was of 12.5 cm length and 8.2 cm in diameter. The target was enclosed in a 1,5 mm thick stainless steel cylinder. The proton beam extracted from the phasotron with timing stretching passed through the narrow collimator of a carbon absorber in order to reduce the original proton current of  $\sim 0.2 \mu\text{A}$  down to intensity of  $10^{10} \text{ s}^{-1}$ .

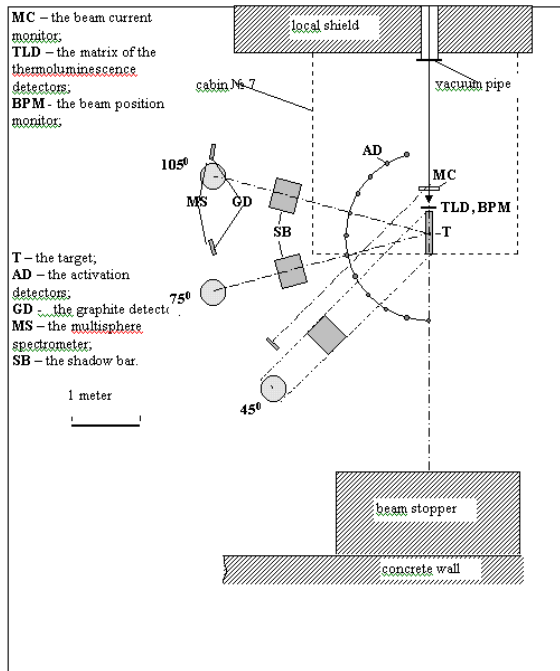


Fig.2. Geometry of measurement of neutron spectrum around the lead target.

The measurements [2] were performed using a multi-sphere neutron spectrometer with a LiI (Eu) crystal (4 mm of height and 4.3 mm of diameter) enriched up to 90% with  $^6\text{Li}$ . The spectrometer was coupled with the spectrometric photo-multiplier. A set of polyethylene spherical moderators of 2, 3, 5, 7, 8, 10 and 12 inches in diameter was used. The results of measurements and calculations is presented on Fig.3. [4].

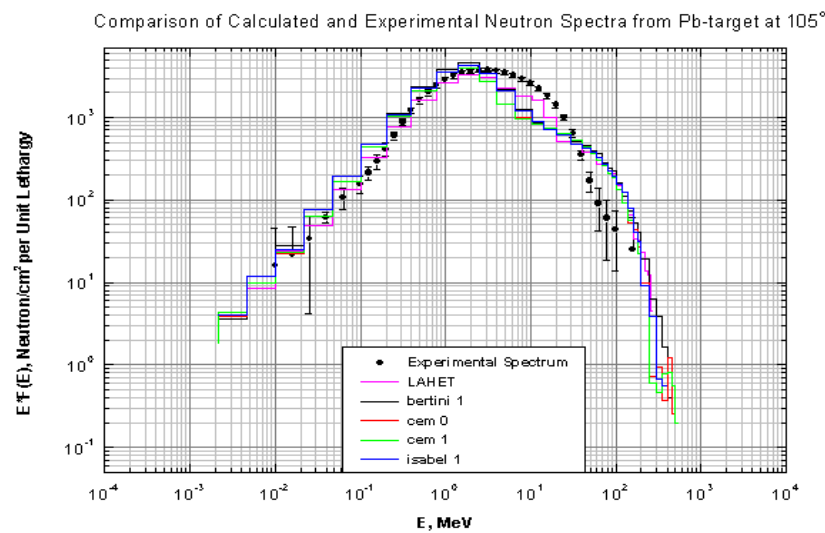


Fig. 3 Comparison of experimental results of the neutron spectra measurements at different angles with computer simulations of LAHET and MCNPX.

The differences between various high-energy transport models used in LAHET and MCNPX codes seem to be very small for this type of experiments, and much more precise and refined measurements and better statistics in simulations are needed to make any conclusions concerning the performance of the specific models. This is, in principle, a good message for those who simulate accelerator - driven systems i.e. - neutron yields and their spectra in high-energy region are not very sensitive on different models used for high-energy transport simulations.

Activation measurements of angular and surface distributions of hadrons around the target are presented in paper [3]. In the measurement the longitudinal distribution of hadron yields was assessed. For this the lead target was wrapped with layers of activation detectors (AD) i.e. aluminum and polyethylene foils Activation detectors (AD) positioned on the side-surface along and at the ends of the lead target. The results of measurements compared with calculations are presented in Fig. 4 [4].

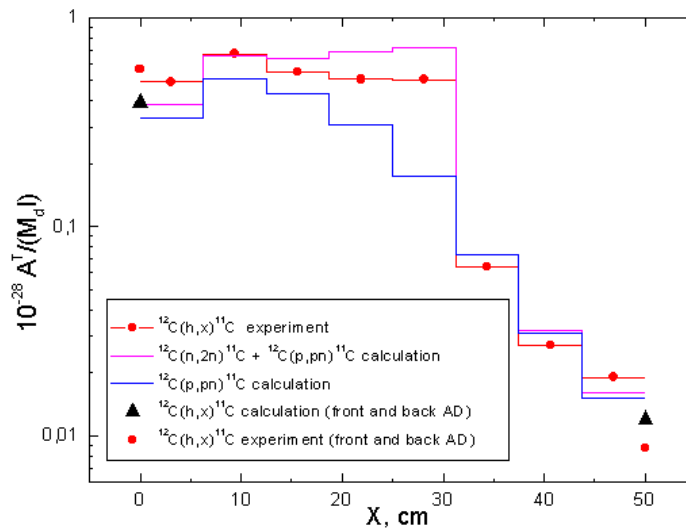


Fig. 4. The distribution of specific activity of the C detectors positioned on the surface of a Pb target

The respective experimental errors were estimated to remain between 6 and 15 % for different parts of the distributions. Generally, the calculated and experimental angular distributions show fair agreement with the exception of the back angle ( $105^\circ$ ) where the low energy protons scattered from the target front may be underestimated in calculations [4]. Also for the longitudinal distribution of activity the calculation results are similar to the experimental ones. The differences remain within the limits of total uncertainty of the results.

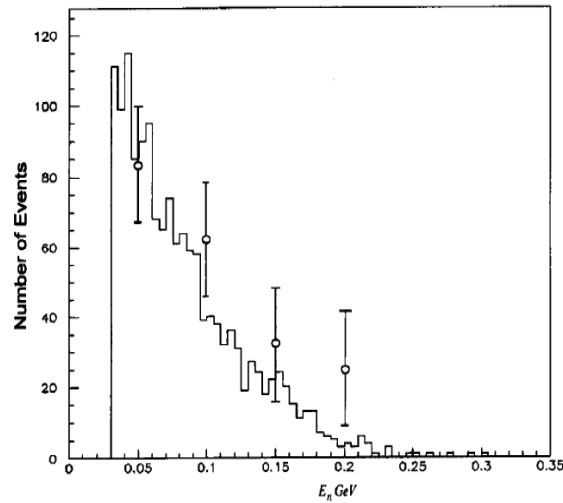


Fig. 5 Energy spectrum of fast neutrons emitted at 60 deg. from a lead extended target. Open circles- experiment results, histogram-GEANT simulation.

Preliminary experimental result of the study on the distribution of neutrons emitted at 60 deg. from a lead target exposed to a 660 MeV proton beam is presented on Fig.5 [1].

The results of the neutron spectrum measurement are shown in Fig. 5 by open circles.

One can see a qualitative agreement between experimental data and those calculated with the GEANT code (solid line). However, the experimental errors are large. We expect to continue our measurement and to reduce the experimental errors in the future experiments.

A method for measuring neutron flux produced in the interaction of protons (660 MeV) with an extended lead target – the sodium tank method – is described [6]. Subjects related to optimisation of the tank size and minimization of induced radioactivity in the contained sodium is considered. The method and procedure of measuring within the sodium tank are much simpler in comparison with other methods applied. The relative error of measurements does not exceed 10%.

The first experiment using a large U/Pb assembly (lead target plus 103.2 kg natural uranium blanket) exposed to 1.5 GeV proton beams was carried out in November 1999[7,8]. It is a start towards the construction of a full scale setup to study two aspects of accelerator driven systems (ADS) at the Synchrophasotron/Nuclotron complex at the Laboratory of High Energies, Joint Institute for Nuclear Research (JINR), Dubna, Russia: the energy production and transmutation of radioactive waste using relativistic protons. The Dubna Cascade Model in its DCM-CEM version was employed to calculate the neutron spectrum at different positions of the target system Fig.6. Three geometrical positions along the beam direction were chosen for this calculation at a circle of 7.5 cm distance from the central axis. The dependence of the neutron spectra on the length in the upstream position of the first section of the blanket was calculated for three values of the traversed distance. The calculated neutron spectra are shown in the figure in absolute terms of n/cm /proton. One observes in this set-up an exceedingly hard neutron spectrum as practically no low-Z moderating materials have been included, and cadmium shield protects the assembly from reflected thermal neutrons.

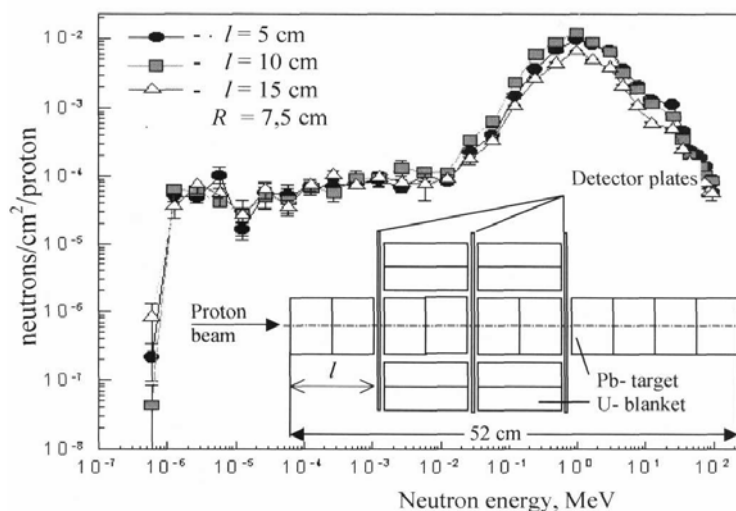


Fig. 6 Calculated neutron spectrum for the U/Pb assembly in the plane of the central detector plates. The positions of the Pb target, the U blanket and the three detector plates are shown in the lower part of this figure.

Neutron fields generated in extended heavy ( $Z \geq 82$ ) targets under irradiation with proton beams at energies in the range of 1 GeV are investigated [9]. Influence of different moderator on the spectra and multiplicities of neutrons escaping the surface of the assembly consisting of a lead target ( $\varnothing 8 \text{ cm} \times 20 \text{ cm}$  or  $\varnothing 8 \text{ cm} \times 50 \text{ cm}$ ) screened by variable thickness of polyethylene or graphite, respectively, was compared in the present work. It is shown that the effectiveness of graphite as a material used in such assemblies to moderate spallation neutrons down to thermal energies is significantly lower than that of paraffin.

1. D.A. Arkhipkin, V.S. Buttsev, S.A. Gustov, R.Kh. Kutuev, I.B., Mirokhin, A.G. Molokanov, A. Polanski, I.V. Puzynin, A.N., Sissakian, R.Ya. Zulkarneev, Yu.R. Zulkarneeva. // Neutron spectra emitted from the lead target irradiated by 660 MeV protons. // Nuclear Instruments and Methods in Physics Research A 505(2003) 397-398.
2. V.P. Bamblevski, Gudowski W., Krylov A.R., Polanski A., Timoshenko G.N., Shvetsov V.N. // The Investigation of the Radiation Field Around the Thick Lead Target Irradiated by the 650 MeV Protons. Part 1 // JINR Report E1- 2000 - 307, Dubna, 2000.
3. Bamblevski V.P., Krylov A.R., Polanski A., Timoshenko G.N., Shvetsov V.N. // The Investigation of the Radiation Field Around the Thick Lead Target Irradiated by the 650 MeV Protons. Part 2. The Measurement of the Angular and Spatial Distributions of the Hadron's Yield from the Target. // Preprint JINR E1-2000-308, Dubna, 2000.
4. V.P. Bamblevski, Gudowski W., Krylov A.R., Polanski A., Timoshenko G.N., Shvetsov V.N., Janczyszyn J. // Comparison of Evaluation and Experiment for Nuclear Cascade Induced by 650 MeV protons in Thick Lead Target of a Subcritical Assembly. // JINR Report E3- 2002 - 237, Dubna, 2002.
5. Bamblevski V.P., Krylov A.R., Polanski A., Timoshenko G.N., Shvetsov V.N. // The measurement of the differential and integral characteristics of the radiation field around the lead core of the subcritical assembly irradiated with 650 MeV protons. // Proc. of the XIII Conference on charged particle accelerators (RUPAC-2002), Obninsk, 2004, v. 1, pp. 286-294.
6. Марцынкевич Б. А., Хильманович А. М., Бутцев В. С., Густов С. А., Мирохин, И. В., Молоканов А. Г., Чултэм Д., Корнеев С. В., Чигринов С. Е. // Метод натриевого бака для измерения потока нейтронов, испускаемых в результате взаимодействия протонов с протяженной свинцовой мишенью. // Приборы и техника эксперимента. - 2004. - N 4. - С. 14-19
7. M.I. Krivopustov, D.Chultem, J.Adam, V.P.Bamblevski, A.V.Pavlyuk, V.P.Perelygin, A.Polanski, A.N.Sosnin, Ts.Tumendelger, R.Odoj, R.Brandt, W.Westmeier, E.-J.Langrock, S.P.Kaznovski, A.Kugler, R.S.Hashemi-Nezhad, A.Zamani, J.Adlo, M.Bielevicz, K.K.Dwiwedi, J.-S.Wan. // Experimental studies of electronuclear method of energy production and transmutation of radioactive wastes using relativistic beams from JINR synchrotron/nuclotron. // XV International Seminar on High Energy Physics Problems, Relativistic Nuclear Physics and Quantum Chromodynamics. Dubna, Russia, September 25-29, 2000. p.48..

8. *M.I. Krivopustov, A.Polanski et al.* // First Experiments With a Large Uranium Blanket Within the Installation "Energy plus Transmutation" Exposed to 1.5 GeV Protons. *Kerntechnik*, vol.68 No. 1-2, 2003.
9. *A.N.Sosnin, A. Polanski, S.A. Petrochenkov, V.M. Golovatyuk, M.I. Krivopustov,, V.P.Bamblevski, W. Westmeier, R.Odoj, R.Brandt, H.Robotham, R.S.Hashemi-Nezhad, M. Zamani-Valasiadou.* // Influence of Different Moderator Materials on Characteristics of Neutron Fluxes Generated under Irradiation of Lead target with Proton Beams. // Preprint JINR E2-2002-258, Dubna, 2002.

## 2. Obtaining experimental data on cross-sections of the nuclear reactions required for an estimate of the transmutation efficiency.

### Measurement of specific activities of threshold activation detectors in front and behind the target.

In this initial experiment [15], [16] the samples of different metals were placed directly in the proton beam of 650 MeV in front of the target, and in the neutron field behind the target. One measurement was devoted to testing of the applied irradiation and counting procedure. The samples of Al, Fe, Cu, Nb and Pb were irradiated directly in the proton beam without the lead target. Aluminum foils were applied for monitoring the absolute number of protons both for the whole beam and for each irradiated sample. Gamma spectra of irradiated samples were counted with the use of semiconductor detectors and analyzed to identify radionuclides and determine their activities. The samples and individual Al monitors (99.99 %) were mounted in a special sample holder suitable for fitting either to the front or to the end of the target. The holder with samples is presented in Fig. 7.

Based on the irradiation of Fe sample the cross sections for the proton induced production of some residue radionuclides in natural Fe were determined and compared with other results Table 1. The obtained values agree within experimental errors with the results of earlier experiments for such nuclides as:  $^{41}\text{Ar}$ , K,  $^{46}\text{Sc}$ ,  $^{48}\text{V}$ ,  $^{51}\text{Cr}$  and  $^{52}\text{Mn}$ . For  $^{24}\text{Na}$ . The evaluated average relative determination error amounted to  $\sim 5\%$ . However, the accuracy can be still improved, mainly by better monitoring of the number of protons. More detailed discussion of this cross section measurement will be presented in the paper being prepared for publication. Still more values of cross section are foreseen to be calculated from our measurements, for other irradiated target elements.

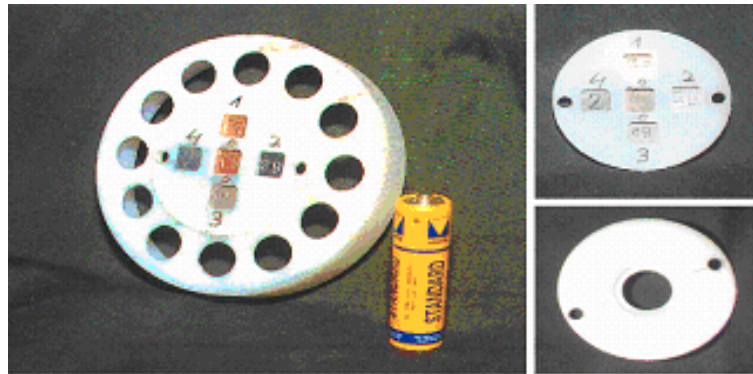


Fig. 7. The polyethylene sample holder with mounted samples (numbered). Behind each sample is placed an individual Al monitor

Table 1. Comparison of cross section results for some reactions on Fe.

Product	T1/2	Cross section (uncertainty) [mb]		
		650 MeV	660 MeV	600 MeV
		This experiment	Experimental values	
$^{24}\text{Na}$	15.02	0.71(0.05)	1.2(0.2)	0.47(0.05)
$^{41}\text{Ar}$	1.82	0.55(0.04)		0.62(0.07)
$^{42}\text{K}$	12.36	3.96(0.19)	2.6(0.23)	4.82(0.75)
$^{43}\text{K}$	22.30	1.17(0.05)	0.95(0.05)	0.87(0.07)
$^{46}\text{Sc}$	2011	9.70(0.42)	9.44(0.37)	9.55(0.18)
$^{48}\text{V}$	383.364	21.7(1.2)	22.7(0.8)	22.71 (0.28)
$^{48}\text{Cr}$	21.56	1.08(0.05)	0.62(0.10)	0.61(0.12)
$^{49}\text{Cr}$	0.705	6.07(0.28)	7.3(0.5)	19.4(2)
$^{51}\text{Cr}$	664.86	44.8(2.0)	46.3(1.7)	44.3(0.4)
$^{52}\text{Mn}$	134.2	11.9(0.6)	11.5(0.6)	
$^{52}\text{Fe}$	8.275	0.52(0.03)	1.8(0.3)	1.34(0.25)

## Measurement of axial and radial distributions of the radionuclides activity induced in the target.

For assessing the axial distribution the spallation target was built of several pieces of 5 cm and 1 cm thick cylindrical parts and of 31 pieces of 1mm thick lead samples all 80 mm in diameter Fig. 8. The Pb samples were placed along the target in such a way that to best reproduce the characteristic distribution of proton induced activity of Bi radionuclides (evaluated earlier with the use of LAHET code).

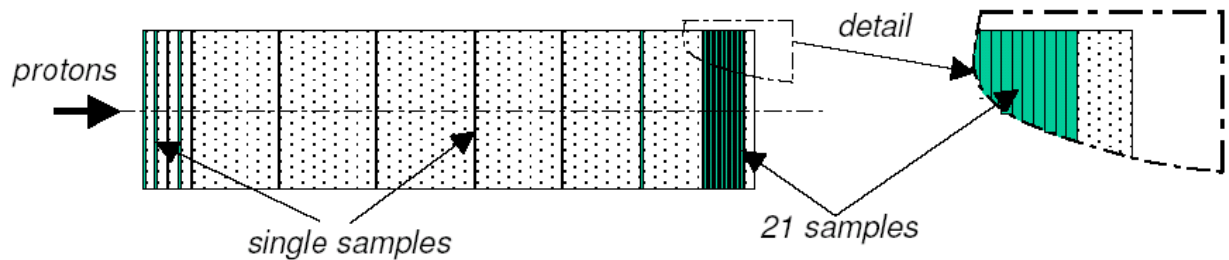


Fig.8. Structure of the lead target (diameter 80 mm, length 308 mm).

All parts of the target plus samples together with proton monitors were irradiated and then the samples and monitors were counted with the use of HPGe coaxial detector. For quantitative evaluation some nuclides were selected from the ones with the identified lines in the measured y-spectra and for which axial distributions inside the Pb target were obtained. Examples of the results are presented in the Figure 9. Majority of calculations simulating the experiment was done with the code MCNPX (versions 2.5b and 2.5d). Different model options were applied in calculations of the induced activity. For the sake of example, the following representatives of nuclides:  $^{83}\text{Rb}$  (fission),  $^{185}\text{Os}$  (spallation) and  $^{207}\text{Bi}$  (p,xn), resulting from different types of reactions, were selected for comparison of the experiment and calculations. This comparison is presented in Fig. 10. One can observe LAHET calculation results in better agreement with the experiment. Comparisons for other nuclides have been presented in reports from our investigations as well as results of our calculations [17-29].

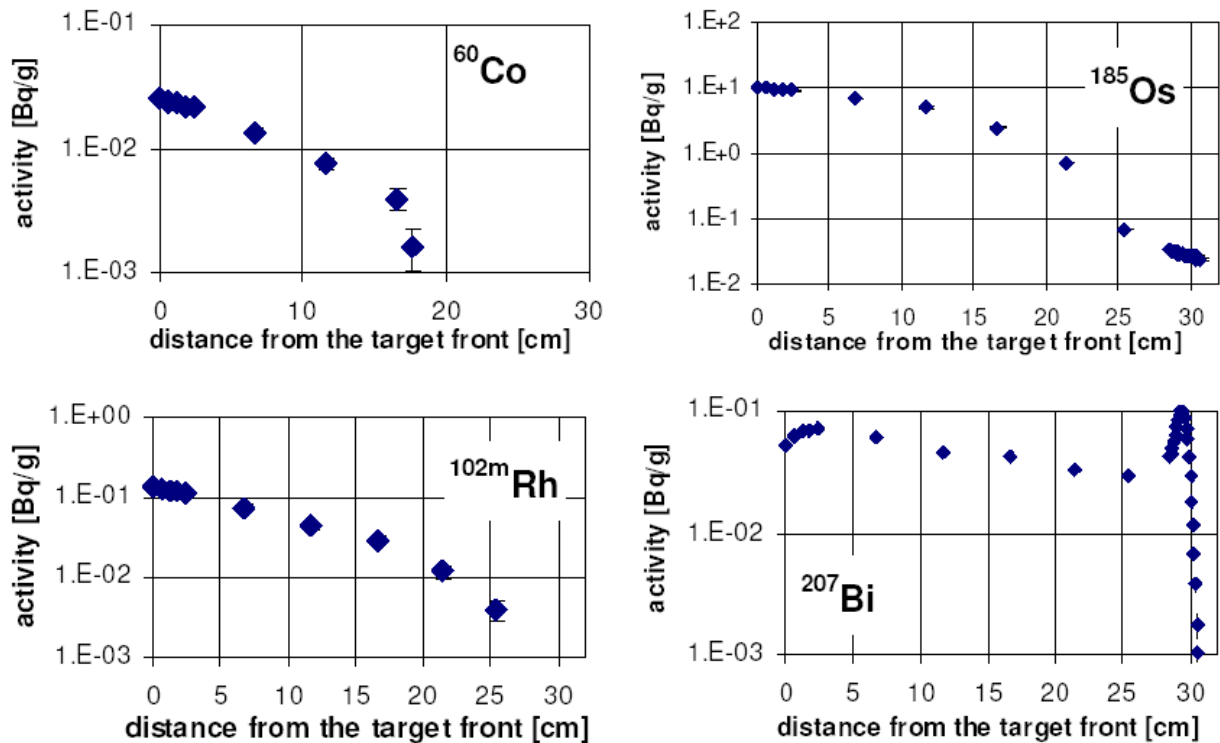


Fig. 9. Distributions of the specific activity of radionuclides along the Pb target irradiated with 660 MeV protons.

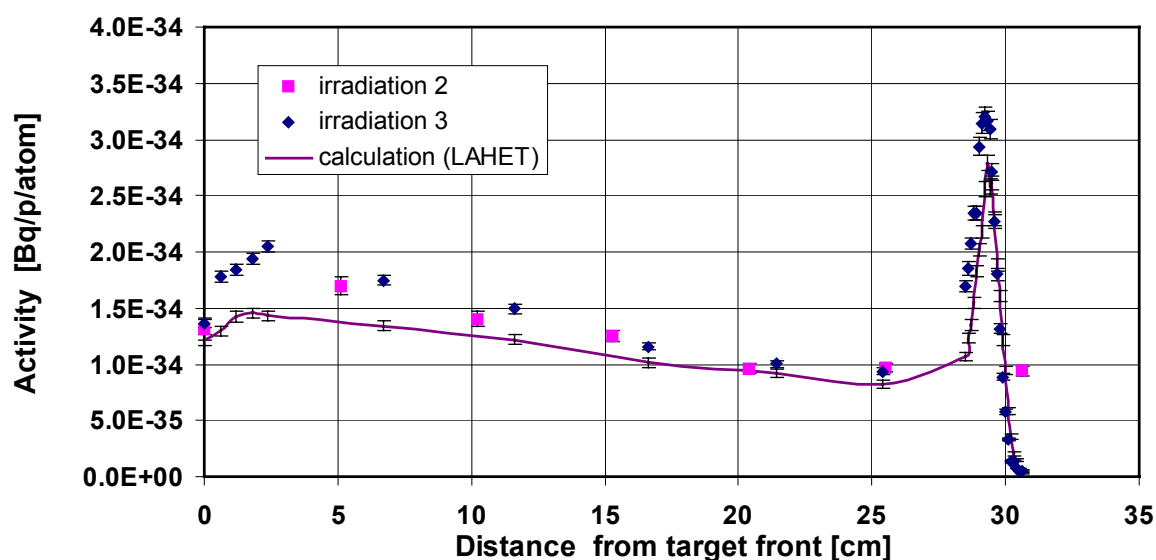


Fig. 10. Distributions of the Bi-207 activity of radionuclides along the Pb target irradiated with 660 MeV protons.

The research [30] is aimed at studying processes taking place in a multisection electronuclear lead target (diameter 10 cm, length 50 cm) irradiated with a proton beam at 1.5 GeV. Space and mass distribution of nuclear fragments as well as the level of heat generated in the target are studied by means of activation-track tomography and highly sensitive thermometry.

#### Investigation of the formation of residual nuclei from the radioactive $^{237}\text{Np}$ and $^{241}\text{Am}$ and $^{129}\text{I}$ targets.

Radioactive  $^{237}\text{Np}$  and  $^{241}\text{Am}$  targets were irradiated by proton beams with energy 660 MeV [10, 13]. The cross-sections of formation of 80 and 60 residual nuclei from  $^{241}\text{Am}$  and  $^{237}\text{Np}$  are determined. The experimental results are compared with the theoretical cross-sections calculated by the cascade-evaporation model.

Small samples of  $^{129}\text{I}$  and  $^{237}\text{Np}$  and  $^{241}\text{Am}$ , were exposed to spallation neutron fluencies from relatively small metal targets of lead [10,11]. The  $(n,\gamma)$  transmutation rates were determined for these nuclides. Compared with results from calculations with well-known cascade codes (LAHET from Los Alamos and DCM/CEM from Dubna), the observed secondary neutron fluencies are larger.

10. J.Adam, A.Balabekyan, R.Brandt, V.P.Dzheleпов, S.A.Gustov, V.G.Kalinnikov, I.V.Mirokhin, J.Mrazek, R.Odoj, V.S.Pronskikh, O.V.Savchenko, A.N.Sosnin, A.A.Solnyshkin, V.I.Stegailov, V.M.Tsouпоkо-Sitnikov // Investigation of the formation of residual nuclei from the radioactive  $^{237}\text{Np}$  and  $^{241}\text{Am}$  targets in the reaction with 660 MeV protons. // JINR preprint E15-2000-256, Ядерная Физика, 2002, т. 65, № 5, стр. 797-809.
11. И.Адам, А.Балабекян, В.С.Барашенков, В.П.Джелепов, С.А.Густов, В.П.Филинова, В.Г.Калинников, М.И.Кривоустов, И.В.Мирохин, В.С.Пронских, А.А.Солнышкин, В.И.Стегайлов, В.М.Цупко-Ситников, Я.Мразек, Р.Брандт, В.Вестмайер, Р.Одой, С.Г.Машиник, Р.Е.Праел, К.К.Гудима, М.И.Базнат // Исследование образования продуктов протон-ядерных реакций в мишени  $^{129}\text{I}$  при энергии протонов 660 МэВ. // Письма в ЭЧАЯ, 2004, т.1, №4(121), с.53-64.
12. J.Adam, A.Balabekyan, R.Brandt, V.S.Barashenkov, V.P.Dzheleпов, V.P.Filinova, S.A.Gustov, V.G.Kalinnikov, M.I.Krivopustov, I.V.Mirokhin, J.Mrazek, R.Odoj, V.S.Pronskikh, O.V.Savchenko, A.N.Sosnin, A.A.Solnyshkin, V.I.Stegailov, V.M.Tsouпоkо-Sitnikov // Investigation of the formation of residual nuclei in reactions induced by 660 MeV protons interacting with the radioactive  $^{237}\text{Np}$ ,  $^{241}\text{Am}$  and  $^{129}\text{I}$  targets. // Journal of Nuclear Science and Technology, Supplement 2, p.272-275, August 2002.

13. И.Адам, А.Балабекян, В.С.Баращенко, В.П.Джелепов, С.А.Густов, В.П.Филинова, В.Г.Калинников, М.И.Кривопустов, И.В.Мирохин, В.С.Пронских, А.А.Солнышкин, В.И.Стегайлов, В.М.Цупко-Ситников, Я.Мразек, Р.Брандт, В.Вестмайер, Р.Одой, С.Г.Машиник, Р.Е.Праел, К.К.Гудима, М.И.Базнат. // Сравнение сечений образования остаточных ядер в мишенях  $^{237}\text{Np}$  и  $^{241}\text{Am}$  при энергии протонов 660 МэВ с модельными расчетами, направлено в Письма в ЭЧАЯ, 2004.
14. J. Adam, A. R. Balabekyan, V. S. Barashenkov, R. Brandt, V. M. Golovatiouk, V. G. Kalinnikov, K. Katovsky, M. I. Krivopustov, V. Kumar, H. Kumawat, R. Odoj, V. S. Pronskikh, A. A. Solnyshkin. // Spallation neutron spectrum on a massive lead/paraffin target irradiated with one GeV protons. // JINR E1-2004-16, Dubna, 2004. E. J. Phys 2004 (in press)
15. J. Janczyszyn, W. Pohorecki, S. Taczanowski, V. Shvetsov, G. Domańska, G. Gerbysh. // Production of radionuclides in the vicinity of Pb target irradiated with 650 MeV protons from the Dubna Phasotron// Semi-annual topical MUSE Meeting, 5<sup>th</sup> Framework Programme MUSE, ENEA Headquarter Rome, 29-30.03.2001, CD-ROM (Ed. M. Carta) p.154
16. J. Janczyszyn, W. Pohorecki, S. Taczanowski, V. Shvetsov, O. Kaczmarek.// Measurement of cross section for (p,x) reactions on natural Fe for 650 MeV protons Semi-annual topical MUSE Meeting, 5<sup>th</sup> Framework Programme MUSE, ISN Grenoble, 18-19.10.2001, CD-ROM (2002)
17. W. Pohorecki, J. Janczyszyn, S. Taczanowski, A. Polański // Measurements of production and distribution of radionuclides in the spallation target.// PHYSOR 2002 Int. Conference on the New Frontiers of Nuclear Technology: Reactor Physics, Safety and High-Performance Computing, Seoul, Korea, October 7-10, 2002, CD-ROM
18. W. Pohorecki, Horwacik T., Janczyszyn J., Taczanowski S., Bamblevski V.P., Gustov S.A., Mirokhin I.V., Molokanov A.G., Polanski A. // Spatial Distributions of Residuals Production Inside a Spallation Target, // Proceedings of the Conference ICRS-10 - RPS 2004. Madeira Island (Portugal) from 9-14 May 2004, J. Radiation Protection in press.
19. W. Pohorecki, J. Janczyszyn, S. Taczanowski, A. Polanski. // Measurements of production and distribution of radionuclides in the spallation target PHYSOR 2002 Int. Conference on the New Frontiers of Nuclear Technology: Reactor Physics, Safety and High-Performance Computing, Seoul, Korea, October 7-10, 2002.
20. W. Pohorecki, T. Horwacik, J. Janczyszyn, S. Taczanowski, I. V. Mirokhin, A. G. Molokanov, A. Polanski // Spatial distributions of reaction rates inside and next the spallation neutron source // Proceedings of the International Workshop on PT AND ADS DEVELOPMENT 2003 W. Haeck, G. Van den Eynde, Th. Aoust, H. Adt Abderrahim, P. D'hondt (Editors), SCK CEN Club-House, Belgium, CD-ROM, ISBN 9076971072, BLG- 959, October 6-8, 2003
21. W. Pohorecki, T. Horwacik, J. Janczyszyn, S. Taczanowski, I.V. Mirokhin, A.G. Molokanov, A. Polanski // Spatial distributions of reaction rates inside and next the spallation neutron source // Neutron Spectroscopy, Nuclear Structure, Related Topics. // Proceedings of the XI International Seminar on Interaction of Neutrons with Nuclei, Dubna, Russia, May 28-31 2003, ISBN 5-9530-0043-x, JINR Dubna 2004, s. 220-227
22. W. Pohorecki, T. Horwacik, J. Janczyszyn, S. Taczanowski, I.V. Mirokhin, A.G. Molokanov, A. Polanski // Spatial distributions of reaction rates inside and next the spallation neutron source // 5th MUSE Progress Meeting, Madrid 26-27 May 2003
23. W. Pohorecki, J. Janczyszyn, S. Taczanowski, I.V. Mirokhin, A.G. Molokanov, T. Horwacik, A. Polanski // Investigations of Radionuclide Production in a Spallation Target carried out in the Frame of MUSE and SAD Projects Euradwaste '04. // 6th European Commission Conference on the Management and Disposal of Radioactive Waste; 29 Mar 2004 to 31 Mar 2004, Luxembourg
24. W. Pohorecki, T. Horwacik, J. Janczyszyn, S. Taczanowski, V. P. Bamblevski, S. A. Gustov, I. V. Mirokhin, A. G. Molokanov, A. Polanski // Spatial Distributions of Residuals Production Inside a Spallation Target ICRS 10, 21st Century Challenges in Radiation Protection and Shielding, Madeira, 9-14 May 2004
25. W. Pohorecki, T. Horwacik, J. Janczyszyn, S. Taczanowski, I. V. Mirokhin, A. G. Molokanov, A. Polanski // Spatial distributions of reaction rates inside and next the spallation neutron source. // Ibid.

26. *W. Pohorecki, T. Horwacik, J. Janczyszyn, S. Taczanowski, V. P. Bamblevski, S. A. Gustov, I. V. Mirokhin, A. G. Molokanov, A. Polanski // Spatial Distributions of Residuals Production Inside a Spallation Target // ICRS 10, 21<sup>st</sup> Century Challenges in Radiation Protection and Shielding, Madeira, 9-14 May 2004*
27. *S. Taczanowski, W. Pohorecki, J. Janczyszyn, G. Domańska, P. Gronek, M. Kopeć, V. Mirokhin, A. G. Molokanov, V. N. Shvetsov, A. Polanski, T. Horwacik Experimental program with spallation sources (WP4) // MUSE Meeting Cracow 2004, 15-16 March 2004, CD-ROM*
28. *S. Taczanowski, W. Pohorecki, J. Janczyszyn, G. Domańska, I. V. Mirokhin, A. G. Molokanov, V. N. Shvetsov, A. Polanski, T. Horwacik // Measurement and analysis of the spallation products inside a target bombarded by a high energy proton beam. // MUSE International Workshop, October 21-22, 2004, Rome, CD-ROM, ENEA 2004*
29. *S. Taczanowski, W. Pohorecki, J. Janczyszyn, M. Kopeć, G. Domanska, I. V. Mirokhin, A. G. Molokanov, V. N. Shvetsov, A. Polanski, T. Horwacik // Experimental program with spallation sources (WP4) 6th MUSE Progress Meeting, Brussels 3-4 November 2003 1st Technical Information Exchange Meeting on IP EUROTRANS, Karlsruhe, November 6, 2003*
30. *T.S. Tumendelger, A. Polanski et al. // Calorimetric of an Electronuclear Target for Uranium-Lead Assembly at Proton energy 1.5 GeV. // Preprint JINR P1-99-247(1999)*

### **3. Development of alternative projects of high current accelerating complex for electronuclear installations.**

A power system including a subcritical nuclear reactor with a heat power 3 GW and a proton accelerator (1 GeV, 120 mA), producing a dense stream of primary neutrons, stimulates control reaction of fission, is considered [30]. It is shown that the most suitable accelerator for this purpose is the separated orbit cyclotron with the magnet system composed out of miniature superconducting magnets with iron yokes. It is possible with its help to place economically in one facility simultaneously several (up to 10) beam channels. Such multi channel system eliminates the restrictions of the beam intensity in the accelerator due to the space charge of the beam and permits to get more uniform neutron yield in the reactor. The main project parameters of the considered accelerating facility are given and it is shown that overall efficiency of the network beam of the rapid proton is 60-65%. The investigation has been performed at the Laboratory of High Energies, JINR.

30. *A. Shelaev, A. M. Baldin, A. I. Malakhov, E.-I. Langrok. // Accelerator and Reactor.// PEPAN, 6[103]-2000, p.70-85.*

### **4. Study of kinetic properties of multiplication coefficient of subcritical electronuclear systems.**

A result of study of kinetic properties of subcritical assembly is presented in papers [31-33]. Properties of the Feynman-a method applied to Accelerator-Driven Subcritical Systems (ADSS) were studied [31].

The main general question is what conditions should be fulfilled that this technique is correct. Let us look at the excess of variance over the Poisson one for infinite measurement time [1]:

$$Y = (f - \bar{f})/i - 1 = \xi - D_v/p_p^2, \quad (1)$$

where:  $T$  - mean number of registered events;  $\xi$  - detector efficiency;  $D_v$  - Diven factor;  $p_p$  - prompt reactivity.

There are also further factors affecting the result of real experiments. The instruments are in principle nonlinear e.g. as a result of the dead time effect. In the source-driven neutron field the harmonics accompany the fundamental mode, i.e. the  $k$  proves generation dependent or  $k_j \neq k_{eff}$ , the Diven factor for the source (spallation) neutrons is different than in fission. Therefore, seeing difficulties in analytical expressing of the influence of such effects they have been numerically tested.

For the above purpose a simple FORTRAN code simulating the multiplication chain, confined to pertinent time-dependent phenomena has been written. In all the calculations discussed here  $K_{eff} = 0.95$ .

Some simulations, e.g. those modeling pulsed 5-source (Fig.11.1) have been a certain check of correctness of this code. Then, the independence of the Feynman-a method of the reflector/shield influence has been demonstrated (Fig.11.2)

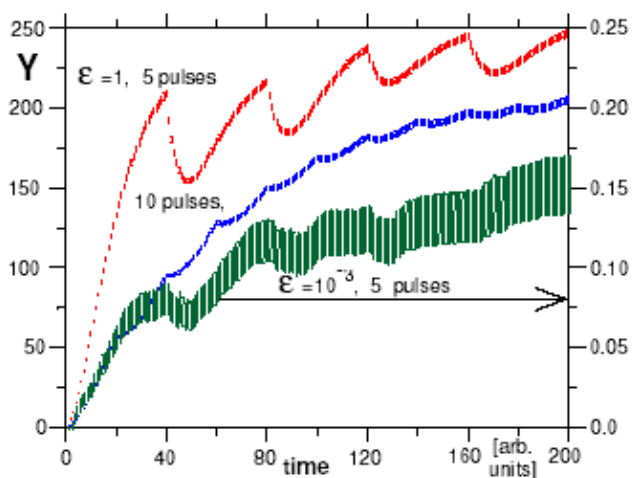


Fig. 11.1. Multi-pulse simulation

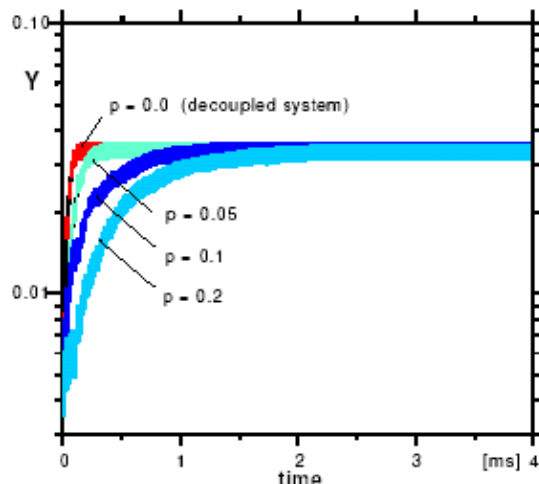


Fig. 11.2. The effect of reflected system

It is assumed in this case, as usual, that the neutron source driving the subcritical system is a pulsed source with the period long as compared with decay of the prompt neutron chain but short, as compared with that of delayed neutrons. The "excursions" of neutrons to the zone surrounding the core, with probabilities  $p = 0.05, 0.1, 0.2$  have been simulated with randomized neutron lifetime being there 100 times longer than in the core. The evident identity of the values of  $Y$  for sufficiently long times of collecting events confirm the insensitivity of the Feynman-a technique to the influence of the second region.

The next investigated effect has been the influence on the Feynman  $Y$  of harmonics in the neutron pulse making the effective multiplication of neutrons not to correspond to the sole  $K_{eff}$  but to another value named  $k$ -source i.e.  $K_s$ . These changes stem in general from two factors generation dependent: the number of neutrons per fission and the probability of fissioning, which both depend e.g. on the neutron energy. The formulae used for simulation of the dependency of multiplication factor on the generation number are:

$$K_i = 0.95(1 + \exp(-2i)) \quad (2)$$

$$K_i = 0.95(1 + 1.5(1 - \exp(-2i))) / 2.5 \quad (3)$$

The results of calculations obtained by distorting the multiplication factor in initial neutron generations according to the formula (2) for detector with efficiency  $\epsilon$  are shown in the Table 2.

Table 2. Effect of the discrepancy  $K_s \neq K_{eff}$  on the detector response for  $(1 - K_s) \approx 0.5(1 - K_{eff})$

	$\epsilon$		
	1E-2	1E-4	1E-5
$Y(K_s \neq \text{eff}) / Y(K_s = K_{eff})$	$1.23 \pm 0.03$	$1.13 \pm 0.06$	$1.21 \pm 0.1$

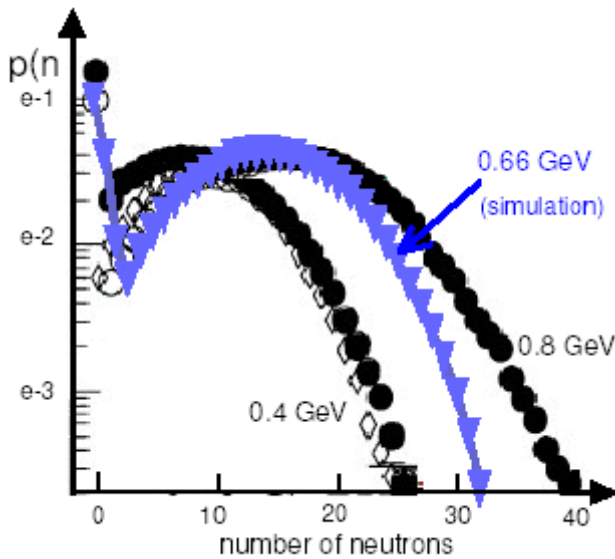
It can be seen that the significance of the  $k$ -source though not particularly strong, cannot be neglected: for the case when the number of neutrons i.e. power of the system is doubled the  $Y$  is changed by about 20% on the average. The next tested effect was the fluctuation of the number  $n_{sp}$  of spallation neutrons. The neutron multiplicity modeled in simulations is shown in the Fig. 12 together with the experimental distributions. The spectrum of  $n_{sp}$  was obtained for fixed number of spallation neutrons  $V_{sp0} = V_{sp}$  with the use of standard random generator of uniform distribution,  $\text{rand} \in (0, 1)$  as follows:

$$V_{sp} = \text{int}(0.995 * V_{sp0} * (\text{rand} + \text{rand} * \text{rand} + \text{rand}) + 0.5),$$

for  $\text{rand} > 0.2$  or else

$$V_{sp} = \text{int}(V_{sp0} * \text{rand} * \text{rand} * 2).$$

The spallation Diven factor, for such neutron multiplicity, amounts to 1.32.



Its role has been checked by comparison of the respective  $Y$  value with that one obtained for a fixed number  $V_{sp} = V_{sp0} = 12$  of spallation neutrons. i.e. the ratios of  $Y(V_{sp \text{ rand}})/Y(V_{sp0} \text{ const})$  have been calculated. The obtained results confirm a certain influence of source neutron multiplicity. Generally, the ratio  $Y(V_{sp})/Y(V_{spc})$  is  $> 1$ . However, since the observed increase in this ratio with decrease in the detection efficiency has not been satisfactorily proven (due to insufficient calculation statistics) further studies in this respect are required.

Fig. 12. Spallation neutrons multiplicities  $V_{sp}$

One of the gravest distortions of measurements seems to be caused by the detector dead time. This effect has been simulated by registration of only one event of any if closer to each other than say, 100 ns. The Table 3 contains the results regarding small number of neutrons per burst, while the cases of large numbers are shown in the Fig. 13.

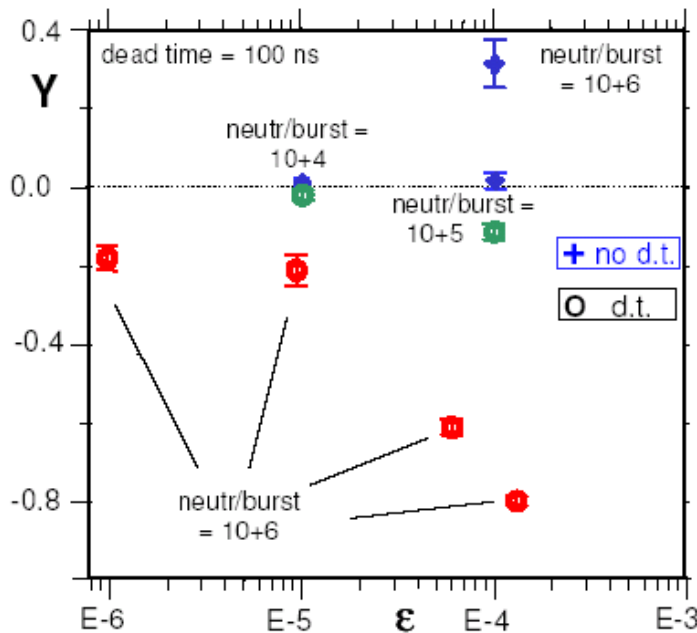


Fig. 13. Effect of the fission detection dead-time

Table 3. Effect of the detection dead time

neutrons/ burst	$\epsilon$	$Y_d/Y$
1	1E-4	1.0
1	1E-3	0.992±0.01
1	1E-2	0.992±0.01
12	1E-5	1.0
12	1E-4	0.83±0.04

In the Table 3, one can see that solely in cases of mere few neutrons per burst and the low detector efficiencies  $\epsilon$  the influence of the detector dead time has proven negligible. To the contrary, for strong neutron pulses, even at relatively low  $\epsilon$  the dead time effect can extremely bias the results (Fig.13). Meanwhile, in exception of rare cases of extremely weak sources driving the system, usually the number of initial neutrons in a pulse is very high and the measurement results are distorted in dependence on the number of source neutrons per burst.

Then one may ask whether the common dead-time correction techniques can be a remedy in this case. It seems, however, that a mere correction of the expected number of events (the first moment) is useless without knowledge of its variance. For adequate correction one would have to know the true

number of events lost due to temporary detector overload in each neutron burst, that seems to be a problem. Finally, it can be of interest to know what numbers of fission events are needed in a real measurement or in its computer simulations that they are statistically reliable. It should be reminded here that the neutron chains stemming from different source neutrons are physically i.e. causally independent of each other in a similar way as are independent e.g. cascades of gammas originated from different nuclei though simultaneously decaying. Only the detector counts are not quite independent events, since due to the dead-time effect they can hinder each other registration. As it was mentioned in [3] for realistic detection efficiencies - about  $10^{-5}$  to  $10^{-6}$  the variance excess  $Y$  is very small and can drop to very minute values even  $<10^{-3}$ . In such conditions the Poisson distribution of numbers of registered events can be regarded as good approximation. With this assumption have been calculated the required numbers of fission events in the system that assure the desired precision of evaluation of  $Y$  for given detector efficiencies, keffs and numbers of neutrons in the burst. On this basis several observations have been done. Highest numbers of fission events are required (worst estimation of  $Y$ ) when the numerator ( $\bar{I}^2 - \bar{I}^2$ ) and denominator  $\bar{I}$  in the formula (1) are statistically independent. Meanwhile, one might note that sometimes the required number of fission events can be reduced by 3 orders of magnitude. Yet, the above numerator and denominator are estimated on the basis of the same sets of events, thus are correlated and lower dispersion (numerator) draws behind a lower mean (denominator), as well as higher mean values allow for higher dispersions. Moreover, a significant fraction of events detected in one burst is constituted by those belonging to the same chain, i.e. source neutron, since quite numerous chains are not rare. Due to this correlation the fluctuations of the above ratio are “damped” and the obtained precision proves much better than might be anticipated. It occurs, however, solely for bursts of very few neutrons whereas for more realistic strong bursts of  $10^5$ - $10^6$  the above correlation disappears (dominates detection of events from different chains) together with all the gains. It is interesting and also advantageous that the savings are greater for lower keffs, e.g. 0.9, than for higher ones, about 0.975. Nevertheless, in any case the required numbers of events are large. E.g. for Keff equal to 0.95, relative standard deviation amounting to 10% and detection efficiency of  $10^{-5}$  they would approach  $3 \cdot 10^9$  - at the best case, whereas for realistic bursts would exceed a number 1000 times larger i.e.  $3 \cdot 10^{12}$ . This hinders direct applications of the MCNP code for simulation of detector counts statistics since the runs with mere hundreds of millions of fissions can last a day. At the same time no variance reduction technique seems applicable since this is just the true variance, what one needs to study. Also in this work, the very unsatisfying statistics of present simulations, in spite of their length /calculations of ca.  $10^{12}$  neutrons lasted 6 weeks/ have been a serious problem. Instead, a respective physical measurement corresponding to the above numbers of fissions appears quite realistic.

31. *S.Taczanowski et al.* // Properties of the Feynman-a method applied to Accelerator-Driven Subcritical Systems, // Proc. of the ICRS -10, 9-14.05. 2004, Madeira, (in the press in Radiation Protection Dosimetry)
32. *S. Taczanowski, M. Kopec and J. Janczyszyn.* // Simulation of Time-dependent Processes of Subcritical Systems with the MCNP Code.// Proceedings of the ANS Topical Meeting on Accelerator Applications/Accelerator Transmutation Technology and Applications - AccApp/ADTTA'01 - Reno November 11-15, 2001, CD-ROM, ISBN: 0-89448-666-7, 2002
33. *S. Taczanowski, G. Domanska, M. Kopec, J. Janczyszyn.* // Contribution to the design and experimental program of the SAD\* accelerator-driven system \*/Subcritical Assembly in Dubna// Proceedings of the International Workshop on P&T AND ADS DEVELOPMENT 2003. W. Haeck, G. Van den Eynde, Th. Aoust, H. Ad't Abderrahim, P. D'hondt (Editors), SCK CEN Club-House, Belgium, October 6-8, 2003, CD-ROM, ISBN 9076971072, BLG-959, 2003

## **5. Creation of the software necessary for designing of various types of electronuclear systems and mathematical modeling of nuclear-physical processes occurring in them.**

In frames of this topic the methods for mathematical simulation of physics processes and analysis of data for theoretical and experimental research were developed.

Computer simulation methods and software for data processing were developed on the basis of new methods of information filtering, compression and visualization and image recognition [34].

34. *Ososkov G.A., Polanski A., Puzynin I.V.*// PEPAN. 2002. V.33. Issue 3. P. 676-745.

A parametrization of the integral cross sections  $\sigma_{\text{none}}, \sigma_{\text{el}}, \sigma_{\text{tot}}$  for elastic, nonelastic and total proton- and neutron-nucleus interactions is considered at medium and high energies. On the basis of the

parameterization a code is created for the interpolational calculations of the integral cross sections for arbitrary target nuclei at proton energies  $E = 1\text{MeV} \text{ -- } 1\text{TeV}$  and neutron energies  $E = 12.5\text{MeV} \text{ -- } 1\text{TeV}$  [35-36].

The neutron cross-section obtained by the interpolation procedure are in the limits of the best experimental data and are close to the values presented in the figures of the atlas [37]. As an example, in Fig. 14 the cross-section for lead are shown. It should be noted that our interpolated curves are smoothly sewed together with data taken from the compilation EB6.

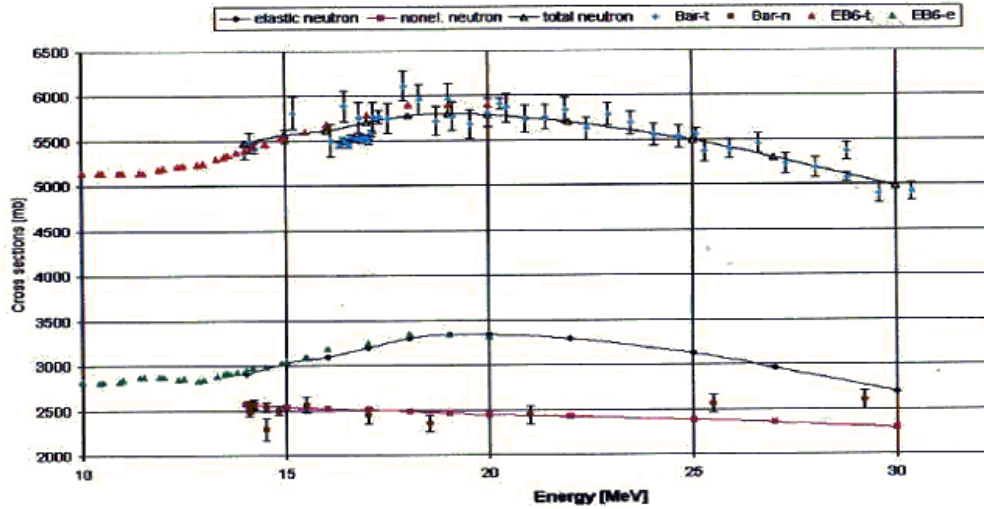


Fig.14. Cross-section for  $n+^{207.2}\text{Pb}$ . The upper, intermediate and low curves are the calculated  $\sigma_{\text{nonel}}$ ,  $\sigma_{\text{el}}$ ,  $\sigma_{\text{tot}}$ . The triangles at low energies are the data EB6. The other marks are the experimental points.

RANGE				DGM		FLUKA		B&P		NASA		W&A	
$Z_{\min}$	$Z_{\max}$	$E_{\min}$	$E_{\max}$	n	$\chi^2$	n	$\chi^2$	n	$\chi^2$	n	$\chi^2$	n	$\chi^2$
2	100	0.0	20T $\approx$ B	128	5.04	1598	8.43	1429	8.07	1602	15.82	1602	14.42
6	82	0.0	20M $\approx$ B	0		194	18.64	55	6.80	194	43.51	194	27.66
6	82	20M $\approx$ B	50 M $\approx$ B	0		374	4.77	374	7.94	374	3.70	374	6.99
6	82	50M $\approx$ B	400M $\approx$ B	128	5.04	128	7.54	128	6.57	128	10.04	128	6.15
6	82	400M $\approx$ B	10T $\approx$ B	0	0	449	6.41	449	10.81	449	21.34	449	8.45

Table 4. Proton reaction cross-section comparison to experimental data: reduced  $\gamma^2$ . B&P (Barashenkov and Polanski) calculation above 14 MeV.

Compilations of neutron and proton reaction and elastic scattering cross sections were extracted from the files of reference [37]. The graphical comparison of the model calculations with experimental data is shown in the rather large plot files available for download [36]. These plots, although qualitative, are the more important part of the comparison. They may be examined for discontinuities, interpolation artifacts and other undesirable features. (Such characteristics may be observed in the 150 MeV evaluated data libraries, as well.)

The extracted experimental data were also used for a statistical comparison with the models, with the optical model calculation (“DGM”) discussed above applied as an interpolation table for  $12 \leq A \leq 208$  and  $50 \text{ MeV} \leq E \leq 400 \text{ MeV}$ . The proton reaction cross-section comparison is shown in table 4 for reduced  $\chi^2$ .

35. *V.S. Barashenkov, W.Gudowski, A.Polanski. //Integral High-Energy Nucleon-Nucleus Cross Sections for Mathematical Experiments with Electronuclear Facilities.// Preprint JINR E2-99-*

207. Proc. of 3-rd International Conference on Accelerator Driven Transmutation Technologies and Applications, June 7-11,1999, Praha, Czech Republic.
36. R.E. Prael, A.Polanski et al. // Comparison of Nucleon Cross- Sections Parameteriation Methods for Medium and High Energies. // Rep. Los Alamos National Laboratory LA-UR-98-58-13,1998. Plots Supplement to Comparison of Nucleon Cross Sections Parameterization Methods for Medium and High Energies". Rep. Los Alamos National Laboratory LA-UR-98-58-43,1998.
37. V.S. Barashenkov. // Cross section of interactions of particle with nuclei. JINR (1989)

The QMD model [38] for description of the nucleon spectra and the residual nuclei mass distribution at low and intermediate energy hadrons-nucleus interactions was development. We included the evaporation model for calculations of the second stage of nuclear interaction [39], [40]. The results of calculations of nuclear interactions using QMD with evaporation and Cascade Evaporation Model are presented on Fig.15. QMD model + evaporation model allows to describe p+A reactions at energy about 250 MeV and quite good agreement with cascade-evaporation model and with experimental data is indicated. However at high energies it is needed to take into account generation of pions. The modified QMD model can be useful for calculations of neutron and proton spectra and the residual nuclei mass distribution at low and intermediate energy hadrons-nucleus interactions.

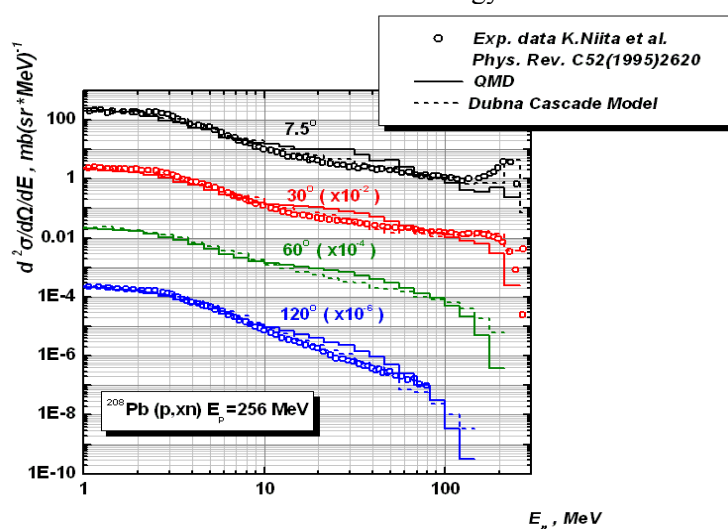


Fig. 15: Comparison of experimental data on cross sections for neutron production with calculations using QMD model and Dubna Cascade Model.

38. A. Polanski, V.V. Uzhinsky. // Monte Carlo simulation of hadron-nucleus interactions within the QMD. // Proceedings of The 6th World Multiconference on Systemics, Cybernetics and Informatics, July 14-18,2002, Orlando, Floryda, USA, P. 79-89.
39. A. Polanski, I. Amirkhanov, T. Puzynina, V. Uzhinsky, E. Zemlyanaya. // Simulation of nuclear reactions within the framework of QMD model. // Congress on Mathematical Modeling, Dubna, September 30 – October 6, 2002.
40. A. Polanski, V. Uzhinski. // Development of QMD models for Mathematical Modelling of Electro-Nuclear Processes. // Workshop: "Review of ADS R&D Activities" 26-29 May 2003, Minsk.

The QMD model by a new evaporation-fission model, the generalized evaporation model (GEM2) is developed [41], [42]. The spectrum of particles and residual nuclide mass and charge distributions in the reactions of protons and neutrons with heavy targets (238U, 208Pb, 207Pb, 206Pb) has been calculated using QMD+GEM2 model [43].

It is known that the Quantum Molecular Dynamic model (QMD) supplemented by the statistical decay model allows one to reproduce quite satisfactory spectra of protons and neutrons produced in nuclear targets at intermediate energies. In [42] we present the spectra of neutrons and residual nuclide mass and charge distributions in proton and neutron reactions with U-238, calculated using QMD+GEM2 model Fig. 16.

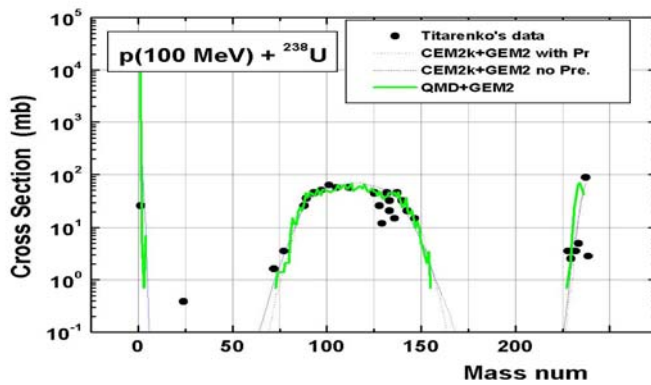


Fig. 16: Comparison of the experimental mass distribution of the nuclides produced in the reaction p (100 MeV) +<sup>238</sup>U(circles) with calculations by the QMD+GEM2 model.

As we can see the reaction cross sections calculated in QMD+GEM2 model agree quite well with the experimental data. Merging QMD with GEM allows us to describe many fission and fragmentation reactions. Production of fission fragments is weakly dependent on energy of interacting particles. Production of light fragments and heavy nuclei essentially depends on energy of interaction neutrons.

41. A.Polanski, V. Uzhinsky, M. Baznat // Residual nuclide production induced by neutrons and protons between 20 and 200 MeV in framework of the QMD model. // Workshop on Nuclear Data for the Transmutation of Nuclear Waste GSI-Darmstadt, September 1-5, 2003.
42. A.Polanski, S. Petrochenkov, V. Uzhinsky, N.I. Baznat. // Development of Quantum Molecular Dynamic (QMD) Model to Describe Fission and Fragment Production. // Proceedings of the Conference ICRS-10 – RPS 2004. Madeira Island (Portugal) from 9-14 May 2004. Radiation Protection in press.
43. V. Amirkhanov, A.S. Galoyan, E.V. Zemlyanaya, A. Polanski, T.P. Puzynina, V.V. Uzhinsky.B. // Use of quantum molecular dynamics models for analysis of particle – nuclei interactions, // JINR Preprint (in press).

The process of nuclear multifragmentation has been implemented, together with evaporation and fission channels of the disintegration of excited remnants in nucleus-nucleus collisions using percolation theory and the intranuclear cascade model [44]. Colliding nuclei were treated as face centred cubic lattices with nucleons occupying the nodes of the lattice. The site – bond percolation model was used. An algorithm of calculation of the number of percolation clusters inside nuclei was developed. The code can be applied to calculation of the fragmentation of nuclei in spallation and multifragmentation reactions.

44. G. Musulmanbekov, A. al-Heydari. // Phys. Atom. Nucl. Vol. 66, No. 9, 2003, P. 1671 – 1679.

Simulation of processes of multifragmentation and spallation in reactions of separated Sn isotopes with proton and deuteron beams at the energies 0.6, 3.5 and 8.1 GeV/nucleon has been performed [45]. Cross sections of products yield are analyzed in connection with the number of accompanying neutrons. Results of simulation are compared with experimental data obtained at LHE synchrotron [46], [47].

45. V. E. Aleksandryan, G. Musulmanbeko. // Isomeric ratios of the cross sections for Sn(p, xpyn)X reactions, // Phys. Atom. Nucl. Vol. 65, No. 5, 2002, P. 776 – 784.
46. A.R. Balabekyan, G. Musulmanbekov. // Isotopic effects of fragment – yields in proton induced reactions on Sn isotopes, // Nucl. Phys. A 735, 2004, P. 267 – 276.
47. A.R. Balabekyan, ...G. Musulmanbekov. // Analysis of fragmentation of <sup>120</sup>Sn and channels (d,xn), (d,pxn), (p,xn) and (p,pxn) on enriched isotopes of Sn. // Submitted to Yad. Fiz.

Designing an accelerator driven system needs a thorough evaluation of the build-up of long-lived radioactivity and changes in elemental composition in construction materials. This data can be calculated with the use of experimentally verified computer codes and data libraries. In the experiment performed in DLNP the activation detectors and track detectors with heavy metal radiators - Bi, Pb, Au, W, Ta were irradiated inside and/or on the surface of a cylindrical Pb targets irradiated with 660 MeV protons [48]. Activities of several radionuclides in Pb and Bi samples were determined and compared with the values obtained from LAHET, MCNPX [48, 49] calculations.

48. *Pohorecki W., Horwacik T., Janczyszyn J., Taczanowski S., Mirokhin I.V., Molokanov A.G., Polanski A.* // Spatial distributions of reaction rates inside and next the spallation neutron source. // The XI International Seminar on Interaction of Neutrons with Nuclei. Dubna, 28-31 May, 2003.
49. *W. Pohorecki, Tomasz Horwacik, Jerzy Janczyszyn, Stefan Taczanowski, Valentin P. Bamblevskii, Sergey A. Gustov, Igor V. Mirokhin, Aleksander G. Molokanov, Aleksander Polanski.* // Spatial Distributions of Residuals Production Inside a Spallation Target, // Proceedings of the Conference ICRS-10 – RPS 2004. Madeira Island (Portugal) from 9-14 May 2004.

The improved model of decaying very excited post-cascade nuclei has been included into the program complex CASCADE [50], thus increasing drastically its accuracy, especially when computing isotope yield. Based on the complex, a mathematical model of the U-Pu assembly "Energy + Transmutation" has been designed, and detailed analysis of its modes and neutron and gamma-quanta yields has been performed [51]. It was shown that the radiation shielding used did not stop the neutrons but only converted them into the low-energy ones.

We proposed a cheap modernization of the installation [52] that improves its features essentially. Calculations were performed on particles yield and heat release in bismuth, leaden and tungsten targets of various configurations in a 660 MeV proton beam. A method of calculating the neutron spectra generating in splitting reactions inside various targets has been elaborated [53].

50. *V.S. Barashenkov, H. Kumawat.* // JINR P2-2003-207, // Kerntechnik 2004, V.69, P. 112.
51. *J. Adam, A. R. Balabekyan, V. S. Barashenkov, R. Brandt, V. M. Golovatiouk, V. G. Kalinnikov, K. Katovsky, M. I. Krivopustov, V. Kumar, H. Kumawat, R. Odoj, V. S. Pronskikh, A. A. Solnyshkin.* // Spallation neutron spectrum on a massive lead/paraffin target irradiated with one GeV protons. // JINR E1-2004-16, Dubna, 2004. Evr. J. Phys 2004 (in press)
52. *V.S. Barashenkov, Ch. Kumavat, S.G. Stetsenko.* // On possible reconstruction of the electronuclear U-Pu installation on the JINR Nuclotron beam. // JINR P2-2003-241.
53. *V.S. Barashenkov, Ch. Kumavat, V.A. Lobanova, S.G. Stetsenko.* // Targets of electronuclear set-ups. // Part. Nucl. Letters (in press)

An improved model of decaying very excited nuclei remaining after the intranuclear cascade has been developed [54], [55]. The results of the computations are in a better agreement with experimental.

54. *V.S. Barashenkov, H. Kumawat.* // Development of Monte Carlo model of high-energy nuclear interactions. // JINR E11-2004-221, Nucl. Instr.& meth. (Submitted).
55. *Trebukhovskiy Y.V., Barashenkov V.S., Kumavat Ch. Et al.* // Double differential cross-sections of neutrons from Pb, W, Zr, Cu, Al and Na, bombarded by protons with energies of 0.8, 1.0 and 1.6 GeV. // Nucl. Physics. (in press).

Main components of ADS include a high-intensity accelerator delivering a proton beam of 5 to 20 MW power, a sub-critical reactor core with a spallation target, and chemical reprocessing facilities. There are no such accelerators available, and no technologies of needed sub-critical reactors developed. Thus experimental ADS are projected at existing accelerators. The review [56, 57] is devoted to an actual problem of nuclear waste transmutation. Different approaches and methods to dispose the waste isotopes considered as harmful because of high radioactivity, migration in biosphere and level of their influence are discussed. Electronuclear installations (EI), which generate intense fluxes of neutrons in interactions of high-energy proton beams with subsequent multiplication in fissile medium, are considered as a safe method to transmute nuclear waste.

The accepted conceptual design of the experimental Subcritical Assembly in Dubna (SAD) is based on the core with the nominal unit capacity of 30 kW (thermal). This corresponds to the multiplication coefficient  $k_{\text{eff}}=0.95$  and accelerator beam power 1 kW. A sub-critical assembly driven with the existing 660 MeV proton accelerator at the Joint Institute for Nuclear Research (JINR) in Dubna has been modelled in order to make choice of optimal parameters for the experimental set-up. Different combinations of the target, fuel and reflector materials have been considered. Some of the calculation results are presented [58], [59].

56. *A. Polanski.* // Accelerator Driven Transmutation Systems. // The 4th Conference on Nuclear and Particle Physics, 11-15 Oct. 2003, Fayoum, Egypt.

57. *Bznuni S.A., Barashenkov V.S., Zhamkochyan V.M., Polanski A., Sosnin A.N., Khudaverdyan A.H.* // Perspectives of electronuclear systems. // Journal of Particle Physics and Nuclear Physics, V.34, № 4, 2003. Dubna.(In Russian).
58. *P. Selborg, A. Lopatkin, W. Gudowski, A. Polanski, V. Shvetsov.* // Investigation of Radiation Fields outside the Experimental Sub-critical Assembly in Dubna, // Proceedings of the Conference ICRS-10 – RPS 2004. Madeira Island (Portugal) from 9-14 May 2004.
59. *S. Petrochenkov, A. Polanski, I. Puzynin.* // Mathematical Modelling of Parameters of Subcritical Assembly in Dubna (SAD), preprint JINR (in press).

The Monte Carlo method was used to simulate a new full scale electronuclear system consisting of cascade sub-critical zones: fast reactor, which is used as a booster, and a thermal liquid-metal reactor, where most of the energy is released [60], [61], [62]. Reactors of the type MSBR-1000, and CANDU-6 are considered. The systems considered, functioning in the safe regime ( $k_{\text{eff}} = 0.94\text{--}0.98$ ), possess much higher maximum power in the entire range of  $k_{\text{eff}}$  than similar systems without an intermediate fast booster reactor. At the same time, for high neutron flux and with both fast and thermal zones present nuclear wastes can be efficiently transmuted in them, decreasing the required proton current in the beam by approximately a factor of 10. This is especially important when the molten salt thermal reactors are considered as the main power production zone.

60. *S. Bznuni, A. Polanski.* // Monte Carlo modelling of parameters of a sub critical cascade reactor based on molten salt and liquid metal technologies. // The International Workshop on P&T and ADS Development, Mol (Belgium) in October 6-8, 2003.
61. *Bznuni S.A., Barashenkov V.S., Zhamkochyan V.M., Polanski A., Sosnin A.N., Khudaverdyan A.H.* // Bireactor Electronuclear Systems with Liquid Cadmium Valve. // Atomnaya Energia, 2003, v.94, N 2 (in Russian).
62. *S. Bznuni, A. Polanski.* // Monte Carlo Modeling of Features of Advanced Reactor Systems, // Proceedings of the Conference ICRS-10 – RPS 2004. Madeira Island (Portugal) from 9-14 May 2004.

The electronuclear systems consisting of two “cascade” sub-critical assemblies were simulated by Monte-Carlo method. Reactors of VVER-1000, MSBR-1000, and CANDU-6 types are considered. The research results show that the two-reactor systems with an enriched uranium booster and a liquid cadmium valve are the most effective ones from the viewpoint of high output characteristics and safe functioning [63], [64], [65].

63. *Bznuni S.A. et al.* // Journal of Computational Methods in Sciences and Engineering. 2002. V.2. N. 1-2. P. 21-29.
64. *Bznuni S.A. et al.* // Atomic energy. 2002. V. 92. Issue 5. P. 344-351
65. *Bznuni S.A. et al.* // Atomic energy. 2002. V. 93.

The nucleus-nucleus eikonal phases were calculated in the Glauber approach using realistic Fermi type nuclear densities taken from electron scattering data [66]. Special method of solving the inversion problem was suggested for restoring the Woods-Saxon type optical potential. The problem of ambiguity in the parameters of the obtained potentials was discussed. Comparisons were carried out between both of the restored potentials, the fitted to the experimental data ones, and the respective elastic differential and total reaction cross sections.

66. *V.K. Lukyanov, E.V. Zemlyanaya, B. Slowinski, K.M. Hanna.* // Izv. RAN ser .fiz. V.67, № 1, 2003, P.55-61.

For the nucleus-nucleus scattering, the complex potentials obtained which corresponds to the eikonal phase of an optical limit of the Glauber-Sitenko high-energy approximation [67]. The potential does not include free parameters, its real and imaginary parts depend on energy and are determined by the reported data on the nuclear density distributions and nucleon-nucleon scattering amplitude. Alternatively, for the real part, the folding potential can be utilized which includes the effective NN-forces and the exchange term, as well. As a result, the microscopic optical potential is constructed where contributions of the calculated real and imaginary parts are formed by fitting the two respective factors. An efficient of the approach is confirmed by agreements of calculations with the experimental data on elastic scattering cross-sections.

67. *V.K. Lukyanov, E.V. Zemlyanaya, K.V. Lukyanov.* // Preprint JINR P4-2004-115, Submitted to Yad. Fiz.

Based on the thickness (profile) function, previously obtained for the realistic Fermi-type distribution of nucleons in nuclei, calculations are made of the microscope eikonal phases of the nucleus-nucleus scattering and the total reaction cross-sections. In so doing, the phase is deduced to the one-dimensional integral provided that the Gaussian density distribution for the projectile nucleus and the arbitrary shape of the thickness density for the target nucleus are used. The problems of obtaining parameters of the “point” nucleon density are considered. A possibility to approximate the realistic densities by the “surface-matched” Gaussian functions and dependence of cross-sections on the nucleon-nucleon radius are discussed. The in-medium effects and a role of the trajectory distortion are studied. Conclusions are made on physics of the process, and comparisons with experimental data are made with cross-sections calculated by using the developed method where no free parameters are introduced [68].

68. *V.K. Lukyanov, B. Slowinski, E.V. Zemlyanaya.* // Nucleus-Nucleus Reaction Cross-Sections Calculated for the Realistic Nuclear Matter Distributions within the Glauber-Sitenko Approach.// Preprint JINR P4-2003-80, Dubna, 2003.

An algorithm and a computer program to calculate a zone boundary crossing points of a particle trajectory in heterogeneous medium are discussed. Zone boundaries are described by surfaces with the order not higher than the second. Illustrations are presented in [69].

69. *V.S. Barashenkov, A.G. Solov'ev, A. N. Sosnin* // An Algorithm to Calculate Zone Boundaries Crossing Points by a Particle Trajectory in Heterogeneous Medium (Geometrical Modules of the Program to Simulate Internuclear Cascades). // Preprint JINR P2-1998-221, Dubna, 1999.

Results of Monte-Carlo mathematical experiments with various homo- and heterogeneous targets are discussed [70-74]. For equal projectile energy many average characteristic of an electro-nuclear process, in particular, its neutron yield, are weakly dependent on a type of the projectile, however, at fixed energy per nucleon the neutron yield is maximal for deuterons and decreases rapidly in the case of heavy projectiles [70]. The time dependent nonlinear effects stipulated by an accumulation of fissile nuclei are important in subcritical reactors with large values of  $K_{eff}$  [71].

70. *V.S. Barashenkov, A. Polanski, A. N. Sosnin and V.P. Filinova.* // Neutron production in fissile targets under ion beam irradiation// *Kerntechnik*, Vol. 61, No. 2-3, May 1996, p103.
71. *V.S. Barashenkov, A. Polanski, A.N. Sosnin.* // Monte Carlo Modeling of Electro-Nuclear Processes with Non-Linear Effects. // Proceeding of the International Workshop on Nuclear Methods for Transmutation of Nuclear Waste, May 29-31, 1996, Dubna, Russia.
72. *V.S. Barashenkov, A. Polanski, A.N. Sosnin.* // Interactions of Proton and Heavy Ion with Uranium and Thorium Targets // Proceeding of the Second International Conference on Accelerator-Driven Transmutation Technologies and Applications. // Kalmar, Sweden June 3-7, 1996, Editor Henri Conde, ISBN 91-506-1220-4 (2 volumes), p. 723-728.
73. *V.S. Barashenkov, A. Polanski, A.N. Sosnin., V.P. Filinova.* // Heavy-Ion-Driven Electronuclear Process.// Proc. The Eight International Conference on Emerging Nuclear Energy Systems, June 24-28, 1996, p.572 Obninsk, Russia.
74. *A. Polanski, A.S. Galoyan, and V.V. Uzhinskii.* // Simulation of nucleus-nucleus interactions in the framework of the FRITIOF model. // International Conference on Advanced Monte Carlo on Radiation Physics, Particle Transport Simulation and Applications. Lisbon, Portugal, 23-26 October 2000. p.382.

### Study of nuclear physical aspects sub critical assembly in Dubna (SAD).

As the first step in the studies of characteristics of ADS, combination of installations available at JINR – the plutonium reactor IBR-30 and the 660 MeV proton phasotron was proposed [75,76]. The next step the subcritical assembly with a metallic weapon grade plutonium fuel was proposed ("Pluton" project [77-80]). But, the results of calculations have shown that mix of oxides ( $\text{PuO}_2 + \text{UO}_2$ ) MOX fuel is better than metallic plutonium for this subcritical assembly [81].

The results of simulation of various type electronuclear systems and their components due to the preparation of the project SAD are presented in papers [81-91]

The papers [92, 93] present last results of Monte Carlo modeling of an Experimental Accelerator Driven System (ADS), which employs a subcritical assembly and a 660 MeV proton accelerator operating at the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research in Dubna. The mix of oxides  $\text{PuO}_2 + \text{UO}_2$  MOX fuel designed for the reactor will be adopted for the core of the assembly. The present conceptual design of the experimental subcritical assembly in Dubna (SAD) is based on the core with a nominal unit capacity of 30 kW – 100 kW (thermal). This corresponds to the multiplication coefficient  $K_{\text{eff}} = 0.952 - 0.972$  and the accelerator beam power of 1kW- 2 kW.

The proposed ADS facility consists of a 660 MeV proton accelerator, beam bending magnets, a spallation target with different materials, a subcritical core based on MOX fuel elements, reflectors, concrete shielding, control and auxiliary systems. The schematic layout of the subcritical assembly is presented on Fig. 17. Main parameters of the ADS facility are given in Table 5.

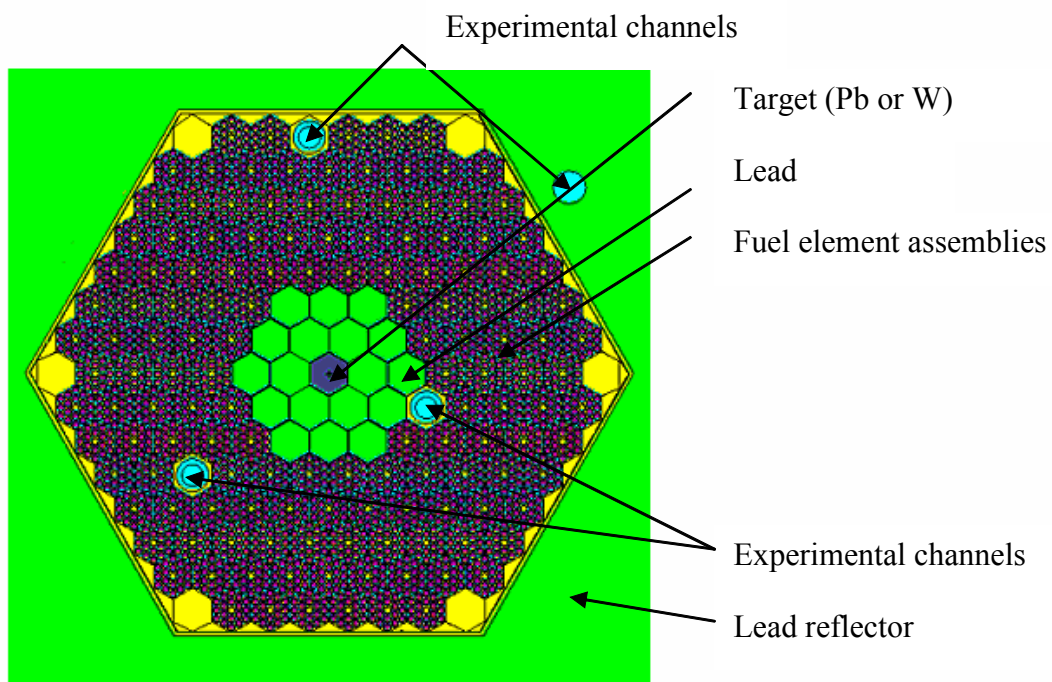


Fig. 17. The schematic layout of the subcritical assembly.

Main parameters of the facility	
Max. proton beam energy	660 MeV
Max. beam power	2 kW
Proton energy deviation	6 MeV
Max. beam intensity	2.E+13 p/s
Repetition rate	250 Hz
Pulse length (fwhm)	20 $\mu$ s
Set up parameters	
Beam power	1 - 2 kW
Keff	0.952 – 0.972
Energetic gain	30 -50
Max. neutron flux	2.26E+12 cm <sup>-2</sup> *s <sup>-1</sup> – 7.10E+12 cm <sup>-2</sup> *s <sup>-1</sup>
Max fission power	30 –100 kW
Density of fissile material	10.2 g/cm <sup>3</sup>
The full length of a fuel element	70 cm
Core length of a fuel element	58 cm
Fissile material	29.7% PuO <sub>2</sub> + 70.3% UO <sub>2</sub>
Fuel element assemblies	133 -141

Tab. 5. Main parameters of the ADS facility.

The proton beam is transported horizontally to the target through a vacuum track provided with a concrete shielding. The proton beam interacts with the lead or tungsten target. A blanket containing MOX fuel surrounds the target. The fuel is placed in a stainless steel vessel. A lead reflector and concrete shielding surround the core. The target and fuel elements are cooled by air.

The fuel designed for the fast breeder BN-600 reactor will be adopted for the core of the assembly. The fuel elements with external diameter equal to 6.9 mm are located in a hexagonal grid. The full length of a fuel element with its end details is about 70 cm, when the core length is 58 cm. The fuel element consists of a stainless steel tube 0.3 mm thick with the plutonium and uranium oxides mixture. The ADS facility will be placed in the special hall equipped with radiation shielding.

Properties of the experimental facility have been investigated by using the particle transport Dubna CASCADE code and MCNPX code.

The calculations have been done for: optimization of the structure and composition of SAD, numerical analysis of the SAD parameters, estimation of the parameters of targets-converters, spatial and energy distribution of neutron fields and energy deposition in SAD components.

Before the final design of SAD was chosen a series of studies had been performed to assess important physical parameters of different target-subcritical core arrangements. Special attention was focused on a removable target and subcritical core design for different Keff. Removable targets with different materials (Pb, W) and different position in the subcritical assembly need for studies of the coupling between a spallation target and a subcritical assembly.

Investigations of the spallation neutron source importance and the resulting consequence on the global energy gain of the ADS. All targets will be instrumented for monitoring neutron and proton fields and isotopes production. Different Keff give possibility to increase the energy gain of the system.

The calculated quantities were: a neutron multiplication coefficient, energetic gain, the neutron field distribution in experimental channels a neutron energy distribution for different places inside the subcritical assembly. The energetic gain G is a ratio of the heat produced in the device to the beam energy.

The dependence of the energetic gain per 1 kW beam power produced in the system with the lead target at various Keff is presented in Fig.18. Using the Fig.18. we can find the average gain G=32 for Keff=0.952 and G=50 for Keff=0.972. The results are the same for tungsten target.

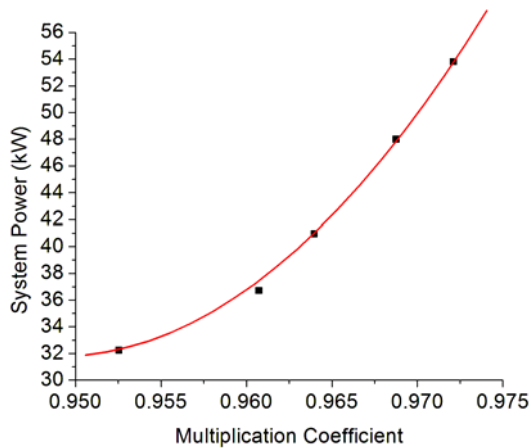


Fig. 18. The dependence of the energetic gain per 1 kW beam power at various Keff.

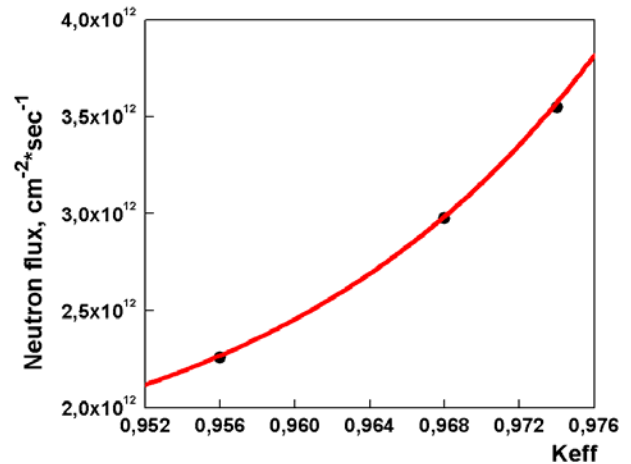


Fig. 19. The dependence of the neutron flux gain per 1 kW beam power at various Keff.

The dependence of the neutron flux in vertical experimental channel (near the target) for different Keff is presented on Fig.19.

Maximum neutron flux is  $2.26 \cdot 10^{12} \text{ cm}^{-2} \cdot \text{s}^{-1}$ ,  $3.55 \cdot 10^{12} \text{ cm}^{-2} \cdot \text{s}^{-1}$ , for different Keff (0.952 for 133 TVS and 0.972 for 141 TVS) in experimental channel near target.

The dependence of the neutron flux in experimental channel per 1 kW proton beam on neutron multiplication coefficient Keff is shown in Fig.20. As we can see from figure the high-energy part of spectrum is the same for different Keff.

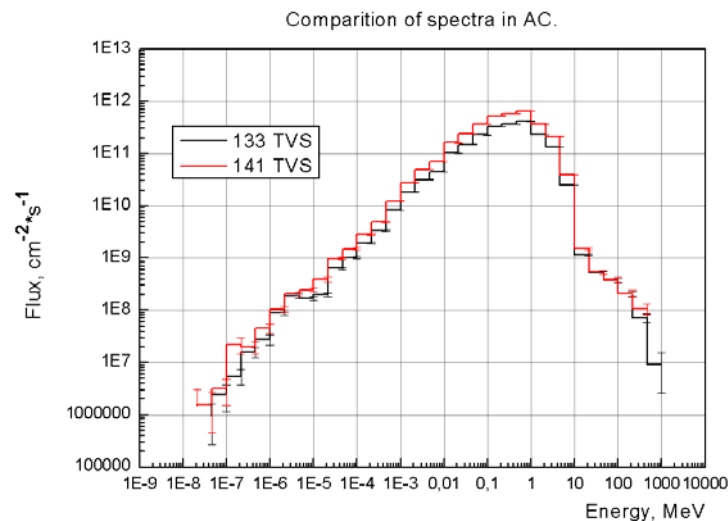


Fig. 20. Comparison of neutron spectra for different Keff (0.952 for 133 TVS and 0.972 for 141 TVS) in experimental channel.

Based on maximum target power of 2 kW and on sub-criticality level slightly below 0.972, the SAD experiment could be run for specific experiments at a level of about 100 kW, if these conditions are shown to be useful [93]. Cooling aspects at this power level can be easily solved by the change of the central part of lead target on tungsten target (see Fig.17). The energy deposition in lead and tungsten target is presented in Tab.6.

<b>Lead target</b>				
	MeV/p	Error	kW	Err, kW
Central target element energy deposition	3,06E+02	0,0062	4,63E-01	2,87E-03
First layer of lead blocks (six) round centre	1,04E+02	0,0143	1,58E-01	2,26E-03
Second layer of lead blocks (twelve)	5,82E+01	0,0166	8,82E-02	1,46E-03
TOTAL	4,68E+02	7,59E-03	7,09E-01	5,38E-03
<b>Tungsten target</b>				
Central target element energy deposition	3,87E+02	0,0158	5,86E-01	9,26E-03
First layer of lead blocks (six) round centre	6,04E+01	0,0497	9,15E-02	4,55E-03
Second layer of lead blocks (twelve)	5,14E+01	0,0463	7,78E-02	3,60E-03
TOTAL	4,98E+02	2,32E-02	7,55E-01	1,76E-02

Tab.6. The energy deposition in lead and tungsten target for beam power 1 kW.

As we can see (Tab.6.) the main part of energy is realised in central section of the target. It means that for beam power 2 kW it will be better to use as central part the tungsten target with molten point bigger than for lead.

75. *V.S. Barashenkov, A.Polanski, A.N. Sosnin.* //Application of Low Energy Accelerators in Electronuclear systems.// Preprint JINR E2-97-304.Dubna,1997. Kerntechnik, Vol.63, No 4, (1998),p.197.
76. *V.S. Barashenkov, G.N.Pogadaev, A. Polanski, Yu. P. Popov, I.V. Puzynin, A.N.Sissakian, A.N.Sosnin.* // Physical Aspects of an Electronuclear set up On the Basis of the Subcritical Zone of the IBR-30 Reactor and 660MeV proton Phasotron.// Comm. JINR P2-98 -74 ,Dubna, 1998.
77. *A. Polanski et all.* // Plutonium Based Energy Amplifier Testing Concept. // Proc. Conf. on Nuclear Energy in Central Europe'98. Terme Catez, Slovenia, September 7-10, 1998, p.67.
78. *A. Polanski et all.* //An Experimental Accelerator Driven System Based on Plutonium Subcritical Assembly and 660 MeV Accelerator. // Preprint JINR E2-99-207. Proc. 3rd International Conference on Accelerator Driven Transmutation Technologies and Applications, June 7-11,1999,Praha, Czech Republic.p.93
79. *V. A Arkhipov, V. S. Barashenkov, V. S. Buttsev, D. Chultem, S. Yu. Dudarev, V. I. Furman, W. Gudowski, J. Janczyszyn, A. A. Maltsev, L. M. Onischenko, G. N. Pogodajev, A. Polanski, Yu. P. Popov, I. V. Puzynin, A. N. Sissakian, and S. Taczanowski* //Accelerator driven system based on plutonium subcritical reactor and 660 MeV phasotron //AIP Conference Proceedings, 1999 Vol. 495, Issue 1, pp. 478-481
80. *V. A. Arkhipov, V.S. Barashenkov, V.S.Buttsev, A.Polanski et al.* // Research Programme for the 660 MeV proton Accelerator Driven Plutonium Subcritical Assembly. // Proc. Conf. on Experimental Nuclear Physics in Europe (ENPE 99) Seville (Spain) 21-26 June 1999, p.478-481, Editor AIP.
81. *A. Polanski.* // Monte Carlo Modeling of Electronuclear Processes in Experimental Accelerator Driven Systems. // Acta Phys. Polonica, Vol. B11, No.1, p. 95,2000.
82. *V.S. Barashenkov, I.V.Puzynin, and A.Polanski.* //ADS's based on the 660 MeV proton Phasotron of JINR for Research on utilization of Plutonium.//Tenth International Conference on Emerging Nuclear Energy Systems.// Petten, The Netherlands, 24-28 September 2000. p.429.
83. *V.S. Barashenkov, V.S.Butsev, G.I.Butseva, Ju.Dudarev, A.Polanski, I.V.Puzynin, A.N.Sissakian.* // Research programme for the 660 MeV proton accelerator driven MOX-Plutonium subcritical assembly.// Proc.Topical Confer. on Plutonium and Actinides. // Sants Fe, New Mexico, USA, July 2000, p.194.
84. *A. Polanski, V.Barashenkov, I.Puzinin, I.Rakhno, and A.Sissakian.* // Monte Carlo modelling of fast sub-critical assembly with MOX fuel for research of accelerator driven systems. // International Conference on Advanced Monte Carlo on Radiation Physics, Particle Transport Simlution and Applications. Lisbon, Portugal, 23-26 October 2000. p.253.
85. *Барашенков В.С., Филинова В.П.* // Зависимость параметров электроядерной системы от состава топлива MOX. // Дубна, 2001. Препринт ОИЯИ P2-2001-125, Атомная энергия, 2002, т.92, вып.1, стр. 75-78.

86. *V.S. Barashenkov, I.V. Puzynin A.Polanski.* // Mathematical Experiments with Electronuclear Systems.// Journal of Computational Methods in Science and Engineering,vol2, no1-2,2002,pp5-11 ISSN 1472-7978.
87. *V.S. Barashenkov, A.Polanski.at al.* // Fast sub-critical assembly with MOX fuel for research on nuclear waste transmutation.// Belarus NSA Journal,Physics and techniques, series, 3,150-153,2001.
88. *V.S. Barashenkov, Kumar V., Kumawat H, Lobanova V.A.* Mathematical model of the electronuclear set-up on the beam of the JINR synchrotron. JINR E2-2-2003-55, Dubna, 2003, NIM 2003, v. 217(2), p. 352.
89. *G. Domańska, S. Taczanowski, J. Janczyszyn, W. Pohorecki, V.S. Shvetsov.* // Investigations of the SAD Design Parameters for Optimum Experimental Performance. // Annals of Nuclear Energy, 31 (No 18) 2004, pp 2127-2138
90. *A. Polanski.* // Monte Carlo Modeling of Processes in Electronuclear Systems. V International Congress on Mathematical Modeling. // Dubna, September 30 - October 6, 2002.
91. *S. Taczanowski, G. Domańska, M. Kopeć, J. Janczyszyn, W. Pohorecki.*// Considerations on the Design and Experimental of Accelerator-driven Subcritical Assembly in Dubna (SAD) in materials of the Workshops on ISTC Project No 2267 and SAD/YALINA-B Steering Committee // 12-13 July 2004, Dubna, JINR CD-ROM.
92. *S. Petrochenkov, A. Polanski, I. Puzynin.* // Mathematical Modeling of Parameters of Subcritical Assembly in Dubna (SAD), preprint JINR (in press).
93. *A. Polanski, C. Broeders, W. Gudowski, S. Petrochenkov.* // Possible extension of experimental program. Increase of system power to maximum 100 kW. Materials of the Workshops on ISTC Project No 2267 and SAD/YALINA Steering Committee // 24-25 January 2005, Dubna, JINR CD-ROM.