# Study of deep subcritical electro-nuclear systems and feasibility of their application for energy production and radioactive waste transmutation

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## Introduction.

The physical aspects of electro-nuclear energy production method are actively studied today in many scientific centers all over the world: USA, Germany, France, Sweden, Switzerland, Japan, Russia, Belarus, China, India etc. Most activities are concentrated on the classical electro-nuclear systems – Accelerator Driven Systems (ADS) – based on spallation neutron generation, with a spectrum harder than that of fission neutrons, by protons with an energy of about 1 GeV in a high-Z target. These neutrons can also be used for generating nuclear energy in the active zone having criticality of 0,94-0,98 and surrounding the target.

The large national projects devoted to the creation of industrial ADS demonstration prototypes are implemented in Japan (JPARC) [1], USA (RACE) [2], the joint European project EUROTRNS is carried out [3].

The main advantage of electro-nuclear technology, as compared to conventional reactor technologies, is that subcritical active core and external neutron source (accelerator and neutron-producing target) are used. This advantage not only provides intrinsic safety of the system but also makes it possible to obtain high fluxes of high energy neutrons independent of fission neutrons of the subcritical assembly material. The high-energy neutrons are an ideal tool to induce fission in most trans-uranium isotopes and thus transmute most of the dangerous radioactive waste from nuclear power production and other sources.

## MOTIVATION

The results on Plutonium yield and number of fission events per proton in quasi infinite targets with a mass of about 3,5 t made from depleted and natural uranium under 660 MeV proton irradiation at synchrotron DLNP JINR, obtained by R.G.Vasilkov and V.I.Goldansky et al. [4], are presented in Table 1. These targets are equivalent to those with a mass of 6,0 t due to non-central beam injection.

The general view of a part of uranium target [4] in a lead shielding is shown in Fig.1. The system of channels for detector and beam input are shown.

Table 1

Plutonium yield and number of fission events in targets per one 660 MeV proton [4]

| | Plutonium yield (number of nuclei) | Number of fissions |
|---|---|---|
| Depleted uranium | 38±4 | 13,7±1,2 |
| Natural uranium | 46±4 | 18,5±1,7 |

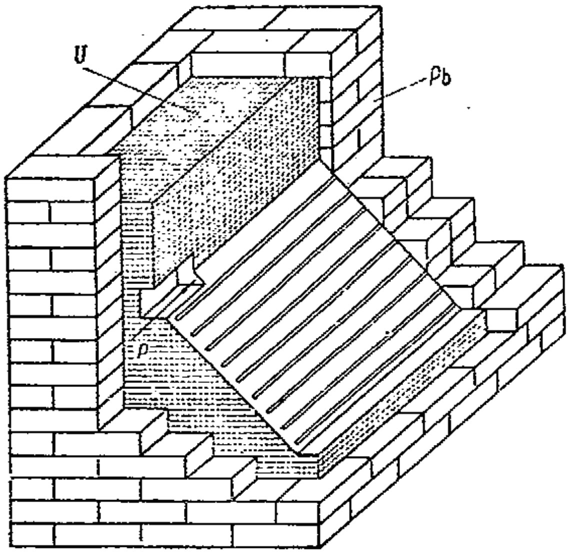


Fig. 1. Schematic cut-open view in the target containing 3.5 t of uranium inside a lead shield. The opening "p" on the left side is the beam entrance and long holes traversing the uranium block are experimental openings for detectors.

The energy release was on average ~3950 MeV per proton in depleted Uraniun and ~4900 MeV per proton in natural uranium. Therefore the power amplification of the 660 MeV proton beam is ~6,0 in depleted Uraniun and ~7,4 in natural uranium for a system subcriticality of about $K_{eff} \sim 0{,}3$.

It should be noted that in the experiments of C.Rubbia and his group [4] at CERN with a large 3,6 t target from natural Uranuim the neutron spectrum in the active core was fully thermalized at a primary proton energy of 0,6 ÷ 2,75 GeV. So these experiments are the opposite extreme case to experiments [4] in which the hardest neutron spectrum was obtained. In [5] the obtained amplification coefficient was about 20 for an energy of 0,6 GeV and deeply subcritical active core, $k_{eff} \sim 0{,}9$.

Calculations by V.S. Barashenkov et al. [6-9] were performed to predict the dynamics of $^{239}$Pu and $^{233}$U accumulation in quasi-infinite fissionable targets from natural uranium and thorium, correspondingly. These calculations showed in particular that the neutron flux increases dramatically with increasing $^{233}$U concentration in the quasi infinite thorium target with lead core irradiated by high-current 1 GeV proton beam.

The $^{233}$U accumulation rate in a $^{232}$Th core is largest for a concentration ≤1,5% of $^{233}$U, then it rapidly decreases with increasing concentration and reaches saturation, or equilibrium, around a level of maybe 8% (see Figure 2, where the line $n_u$ reaches n=0).

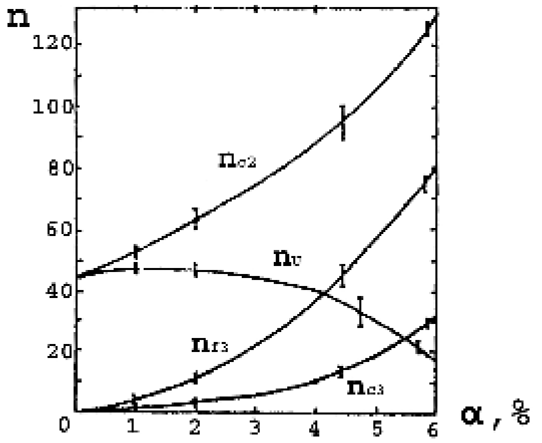


Fig.2. Calculated numbers of events “n” per one incoming 1 GeV proton in a metallic $^{232}$Th target with lead core [9]. The value “α” denotes the assumed concentration of $^{233}$U in the $^{232}$Th matrix.
$n_{C2}$ is the number of (n, γ) capture reactions in $^{232}$Th producing $^{233}$U,
$n_{C3}$ is the number of (n, γ) capture reactions in $^{233}$U depleting $^{233}$U,
$n_{f3}$ is the number of fissions of $^{233}$U depleting $^{233}$U and
$n_U$ is the number of accumulated $^{233}$U atoms. Statistical uncertainties of calculation are shown by vertical error bars.

Taking into account that in the range under study the ratios $\alpha = \sigma_\gamma / \sigma_f$ for $^{239}$Pu and $^{233}$U , as well as radiation capture cross-sections $\sigma_\gamma$ of $^{232}$Th and $^{238}$U, are close, it can be assumed that parity in quasi infinite uranium active core will occur at a concentration of easily fissionable $^{239}$Pu of ~4%.

In [8, 9] the energy release due to fission as a function of $^{239}$Pu and $^{233}$U concentration was estimated. It can be seen from Fig. 3 that the estimated 1 GeV proton beam power amplification is about ~6,5 for total energy release and about 20 for the part connected with the $^{233}$U (n,f) reaction for $^{233}$U concentration of 4% .

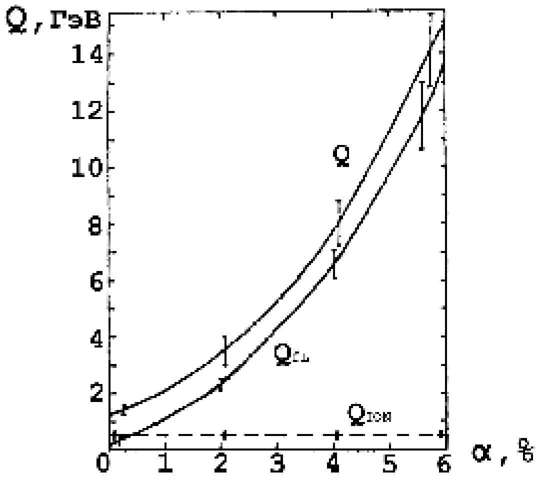


Fig.3. Calculated heat release in GeV in a target from metallic $^{232}$Th with lead core as a function of enrichment “α” of $^{233}$U (per one primary 1 GeV proton) [9].
Q is the total full heat release
$Q_{fL}$ is the heat releasing from fission induced by neutrons in the low-energy region $T \leq 10{,}5$ MeV, $Q_{ION}$ is the heat produced by ionization losses. Statistical uncertainties of calculation are shown by vertical error bars.

A weak dependence of basic parts of neutron energy spectra on enrichment was calculated for quasi-infinite targets from uranium and thorium (see [7-9]) for the studied concentration range (0-6%). This allows one to expect deep subcriticality of the system upon reaching parity concentration of easily fissionable isotopes $^{239}$Pu and $^{233}$U.

Energy characteristics of neutron radiation depending on incident proton energy are given in Table 2. The experimental data were obtained by V.I.Jurevich et al. [10] at LHE JINR.

Table 2.

Energy characteristics of neutron radiation leaving a limited Ø20×60 cm lead target depending on protons energy [10].

| $E_p$, GeV | < E >, MeV | $E_{kin}$, MeV | $E_{kin}$ / $E_p$, % | W, MeV | W / $E_p$, % |
|---|---|---|---|---|---|
| 0,994 | 8,82 | 213 | 21,3 | 382 | 38,2 |
| 2,0 | 11,6 | 513 | 25,6 | 822 | 41,1 |
| 3,65 | 13,7 | 1106 | 30,3 | 1670 | 45,6 |

Here, < E > is the average neutron energy, $E_{kin}$ is the total kinetic energy of neutron radiation, $E_p$ is the proton energy, and W is the energy of the proton beam spent for neutron production.

It can be seen from Table 2 that the average neutron energy, the kinetic neutron energy $E_{kin}$, and the proton beam energy W spent for neutron production increase with increasing beam energy. The fraction of primary proton energy spent for neutron production for a proton energy of ~ 660 MeV is ~ 20 % according to our estimates of data [4]. It follows from [10] that for $E_p \approx 1$ GeV it increases to 38,2%, reaching almost 46 % for 3,65 GeV. The extrapolation of this dependence to $E_p$ = 10 GeV results in the following estimate of this fraction: ~ 60% (see [11] for details). Note that the growth of the ratio W / $E_p$ is to a large extent connected with the growth of meson production with increasing incident proton energy.

The estimates of proton ionization energy losses at a path length of inelastic interaction for different primary proton energies are given in Table 3 [11].

Table 3.

| $E_0$ | 0,7 | 1 | 1,5 | 2 | 3 | 5 | 10 | 15 | 20 | 30 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ΔE | 250 | 229 | 215 | 210 | 215 | 226 | 247 | 258 | 268 | 282 | 295 |
| $E_{in}$ | 0,45 | 0,77 | 1,285 | 1,79 | 2,785 | 4,774 | 9,753 | 14,75 | 19,73 | 29,72 | 49,71 |
| $\Delta E/E_0$ | 35,7 | 22,9 | 14,3 | 10,5 | 7,2 | 4,5 | 2,5 | 1,7 | 1,3 | 0,9 | 0,6 |

Here, $E_0$ is the incident proton energy, GeV; ΔE is the ionization losses at the path length $L_{in}$ of inelastic collision with target atoms, MeV; $E_{in}$ is the energy of the particle initiating a cascade ($E_{in} = E_0 - \Delta E$), GeV; and $\Delta E/E_0$ is the ratio of ionization losses at the path length and primary particle energy, percent.

It follows from the data given in Table 3 that ionization losses have a flat minimum at an energy of 2 GeV and slowly increase with increasing energy. However, the ratio $\Delta E/E_0$ steadily decreases with increasing energy.

Thus, one proton with an energy of 10 GeV is more advantageous than ten protons with an energy of 1 GeV (at the same beam power), because in the first case ionization losses make 247 MeV, and in the second case, 2290 MeV.

Table 4 gives conservative estimates of expected power amplification ($K_{PA}$) in a quasi-infinite natural uranium target for different proton beam energies ($E_P$), based on extrapolation of data [4] and considering of experimental results [10] and calculations [8, 9]. Values $K_{PA}$ are listed for the initial configuration containing no $^{239}$Pu and for the equilibrium configuration reached after long irradiation.

Table 4.

Estimates power amplification coefficient for proton beam incident on quasi-infinite target from metallic natural uranium.

| $E_p$, GeV | Initial $K_{PA}$ | Equilibrium $K_{PA}$ |
|---|---|---|
| 0,66 | 7,4 [4] | ~40 |
| 1,0 | 12,0 | ~70 |
| 10,0 | 22,0 | ~130 |

Results obtained by the collaboration of State Research Center Institute of Physics and Power Engineering & Center of Physical and Technical Projects “Atomenergomash” & Petersburg Nuclear Physics Institute RAS in a series of methodical experiments [12] on calorimetry of uranium (3.2 kg) and geometrically identical lead targets placed inside the lead matrix with a mass of ≈550 kg irradiated by 1 GeV protons have proven the validity of the method [13] used for $K_{PA}$ estimates from Table 4.

The results of recent measurements of yields of delayed neutrons emitted by massive (315 kg) target from natural uranium irradiated by 1 and 4 GeV deuteron beams [14] definitely point to the fact that estimates of initial amplification coefficients (second column in Table 4) are underestimated.

The absolute values of $K_{PA}$ and their dependence on the energy $E_p$ given in Table 4 contradict result [5]; in [5] it was obtained that the power amplification coefficient for the proton beam reached saturation at $K_{PA} \approx 30$ in the neighborhood of 1 GeV. This discrepancy is probably related with significant thermalization of the neutron spectrum in experiment [5] and correspondingly relative suppression of the influence of its high energy part in the target volume.

It should be noted that for $K_{PA}$ shown in the last column of Table 4 the important parameter requiring special study is the time of achieving equilibrium concentration of $^{239}$Pu isotope in the target after the beginning of operation of the electronuclear system.The predicted values of power amplification coefficients for the proton beam presented in Table 4 are one of the key elements of the scheme of elecronuclear method proposed in [11]; in the case of its feasibility it opens new prospects of energy production and processing of nuclear wastes based on efficient use of the hard part of the neutron spectrum in a deep subcritical quasi-infinite breeding system.

This is a serious stimulus for detailed study of space-energy neutron distributions inside and outside a quasi-infinite target from natural uranium. Elucidation of the role of the hard neutron spectrum in increasing energy release in the target under the action of the beam of relativistic particles requires special attention. Taking into account results [4, 8, 9] the dynamics (space-time aspects) of production of $^{239}$Pu isotope should also be studied in detail; the presence of this isotope essentially changes the characteristics of the subcritical system, providing additional growth of the power amplification coefficient of the incident beam.

From the point of view of efficiency of nuclear waste transmutation it is extremely important to study the ratio of reaction rates for (n, $\gamma$), (n,xn), and (n,f) reactions for typical long-lived nuclides of spent nuclear fuel with account of space-energy neutron field distribution inside the active zone. Thus, the basic idea of the promising electronuclear technology of nuclear wastes production and power production proposed in [11] can be verified.

The realization of the purposeful complex of measurements briefly outlined above is topical, taking into account that modern widely used models and transport codes do not provide required accuracy for reliable description of characteristics of electronuclear systems.

For illustration of capabilities of modern transport codes let us consider the case of practically non-fissionable lead target studied in [10]. Table 5 gives the results of calculations using different transport codes in comparison with experimental data [10].

It can be seen from Table 5 that all variants of the code describe well the total neutron yield Y in the whole proton energy range, except for INCL4+ABLA model for which calculation deviates from experiment at energies above 2 GeV.

All codes essentially underestimate high energy component $Y_{20}$, of the neutron yield in the whole proton energy range [10].

Let us consider unique experiment [4] considered above to illustrate capabilities of modern codes for calculation of a quasi-infinite target from natural uranium. Table 6 gives the results of calculation of the number of produced $^{239}$Pu nuclei, Y; the number of fission events of the basic $^{238}$U isotope and easily fissionable $^{235}$U isotope, $\eta_{38}$ and $\eta_{35}$, respectively, per one 660 MeV proton obtained using MCNPX 2.5 code. The ratios *C/E* of calculated and experimental values of the corresponding quantities are also given.

Table 5.

Average total Y and partial $Y_{20}$ (for neutron energies higher than 20 MeV) neutron yields for long lead target (Ø 20 × 60 cm) irradiated by proton beams in comparison with calculated yields. Ratios of calculated and experimental yields are also given [10] C/E.

| $E_p$, GeV | Experiment (n/p) | | MCNPX: INCL4+ABLA | | MCNPX: BERTINI | | Fluka 2008.3 | |
|---|---|---|---|---|---|---|---|---|
| | Y | $Y_{20}$ | Y | $Y_{20}$ | Y | $Y_{20}$ | Y | $Y_{20}$ |
| 0.994 | 24.1±2.9 | 2.1±0.4 | 23.7(2%) | 1.62(2%) | 24.1 | 1.45 | 24.4 | 1.40 |
| **C/E** | | | 0,983 | 0,771 | 1,000 | 0,690 | 1,012 | 0,667 |
| 2.0 | 44.4±5.3 | 4.7±0.8 | 46.1(2%) | 3.29(3%) | 49.7 | 3.02 | 48.7 | 3.21 |
| **C/E** | | | 1,038 | 0,700 | 1,119 | 0,643 | 1,097 | 0,683 |
| 2.55 | 63.5±7.6 | 5.8±1.9 | 50.5(1%) | 3.99(1%) | 62.5 | 3.88 | 60.1 | 4.10 |
| **C/E** | | | 0,795 | 0,688 | 0,984 | 0,669 | 0,946 | 0,707 |
| 3.17 | 71.6±8.6 | 6.8±1.2 | 57.9(1%) | 4.66(1%) | 76.3 | 4.89 | 72.14 | 5.03 |
| **C/E** | | | 0,809 | 0,685 | 1,066 | 0,719 | 1,008 | 0,740 |
| 3.65 | 80.6±9.7 | 8.5±1.5 | 62.6(1%) | 5.14(1%) | 86.8 | 5.5 | 80.2 | 5.67 |
| **C/E** | | | 0,777 | 0,605 | 1,077 | 0,647 | 0,995 | 0,667 |

Table 6.

$^{239}$Pu yield and number of fission events in natural uranium target

| | $E_p$ = 660 MeV | | |
|---|---|---|---|
| | Y | $\eta_{38}$ | $\eta_{35}$ |
| Experiment [4] | 46.4 ± 4 | 14.6 ± 1.3 | 3.9 ± 0.4 |
| Calculation | 36.0 ± 0.1 | 9.05 ± 0.01 | 2.25 ± 0.01 |
| C/E | 0.776 | 0.620 | 0.577 |

It can be seen from Table 6 that the code essentially underestimates both the $^{239}$Pu yield and the number of fission events which are responsible for the energy balance in breeding targets. The deviation is even more pronounced due to the fact that the total number of fission events was calculated, while experimental data given in Table 6 [4] additional 3-4 fission events in the central region of the target that could not be directly experimentally measured are not taken into account.

For higher incident particle energies calculations worse reproduce integral characteristics of fissionable breeding systems [13]. Concerning corresponding "differential" characteristics, space-energy parameters of neutron fields and $^{239}$Pu isotope production dynamics in an extended target from natural or depleted uranium, thorough verification and improvement of existing transport codes is required for their reliable description. It can be performed only based on a complex of new experimental data which should be obtained, in particular, in the course of execution of the proposed project.

## OBJECTIVES

The project objectives are:

1. To study the possibilities and specific features of using hard neutron spectrum of deeply subcritical quasi-infinite uranium target irradiated by 1-10 GeV protons and deuterons for implementation of a new scheme of electro-nuclear method for energy production and transmutation of long-lived radioactive wastes – relativistic nuclear technology (RNT).
2. To improve existing theoretical models and verify computer codes for guaranteeing precise simulation of electro-nuclear systems for RNT experimental-industrial prototype design.

## PROGRAM

A set of integral macro- and micro-experiments in combination with necessary theoretical calculations will be carried out during the project realization.

The reliability and completeness of experimental data are provided by application of independent mutually verifying systems for measurement of physical processes in a quasi-infinite uranium target under the action of relativistic protons and deuterons.

The project schedule includes experiments in the framework of the physical program at the facilities are: "Energy + Transmutation" (Fig.4) [14, 15] and "Gamma-3" (Fig.5) [16]. It is planned to develop and test measurement systems for experiments with the new uranium target in parallel with these experiments.

The main experiments of the project are planned to be performed on the basis of the new flexible target diagnostic complex "EZHIK" (Fig.6) which represents a quasi-infinite target from metallic uranium equipped by measurement channels whose position and design should provide optimal execution of the research program (see Table 7 for details).

Fig. 4.

Fig. 5.

The target-diagnostic complex “EZHIK” will be realized in 2 modifications.

The “EZHIK-Pb” modification is geometrically identical to the basic modification “EZHIK-U” but with the whole inner volume filled by lead. It is designated for complex verification and adjustment of basic measurement systems and methods and background measurements with proton and deuteron beams in the planned energy range before main experiments with uranium target «EZHIK-U».

The basic modification of target-diagnostic complex «EZHIK-U» (Fig.6) implements in a somewhat modified form the original technical solution on asymmetric beam input into a quasi-infinite target first applied in [4]. It provides obtaining results equivalent to those that could be obtained with a 8 t uranium target in the case of conventional axial beam input into a cylindrically symmetric target, but with just about a 3 t target from natural uranium.

Figures 7-9 show the results of calculation of the influence of replacement of uranium by lead in most of the volume of the target « EZHIK-U» obtained using MCNPX 2.5 in the variant of Bertini cascade model for 5 GeV incident protons.

Figure 7 shows the spatial distributions of the low-energy and high-energy components of neutron spectra in the targets containing ~ 3 and ~ 8 t of uranium. Figures 8 and 9 show the results of similar calculations of neutron flux densities and energies for two variants of reflectors surrounding the target, those from graphite and lead.

The analysis of Figs. 7-9 demonstrates that the results of measurements performed in the volume and on the surface of the left upper part (along the beam, see Fig. 6) of the target «EZHIK-U» can be correctly related to the equivalent symmetric target with a mass of about 8.0 t.

The scientific program of the proposed project include activities in four basic directions which represent a complex of self-consistent mutually complementary experiments, numerical, and theoretical studies.

Direction 1 ("Integrals"). The first direction includes the set of integral experiments with the targets « EZHIK-U», proton energies from 1 to 10 GeV and deuteron energies from 1 to 5 GeV/nucleon.

These experiments include:

1) study of neutron spectra at various points in the target volume in the presence and absence of graphite reflector (below, different target configurations) ;
2) study of spatial distributions of fission rates and transmutation cross sections of actinide fission fragments at different target configurations for determination of optimal transmutation regimes;
3) study of spatial distributions of radiative capture (n, $\gamma$) and (n,xn) reactions in samples from long-lived isotopes of spent fuel placed in measurement channels for different neutron spectra;
4) measurement of heat release distribution in the target volume depending on the target configuration and different enrichment by easily fissionable isotopes;
5) study of spatial distributions of parity between $^{239}$Pu isotope accumulation and fission for determination of the value and time of achieving equilibrium concentration of this isotope for different target configurations;

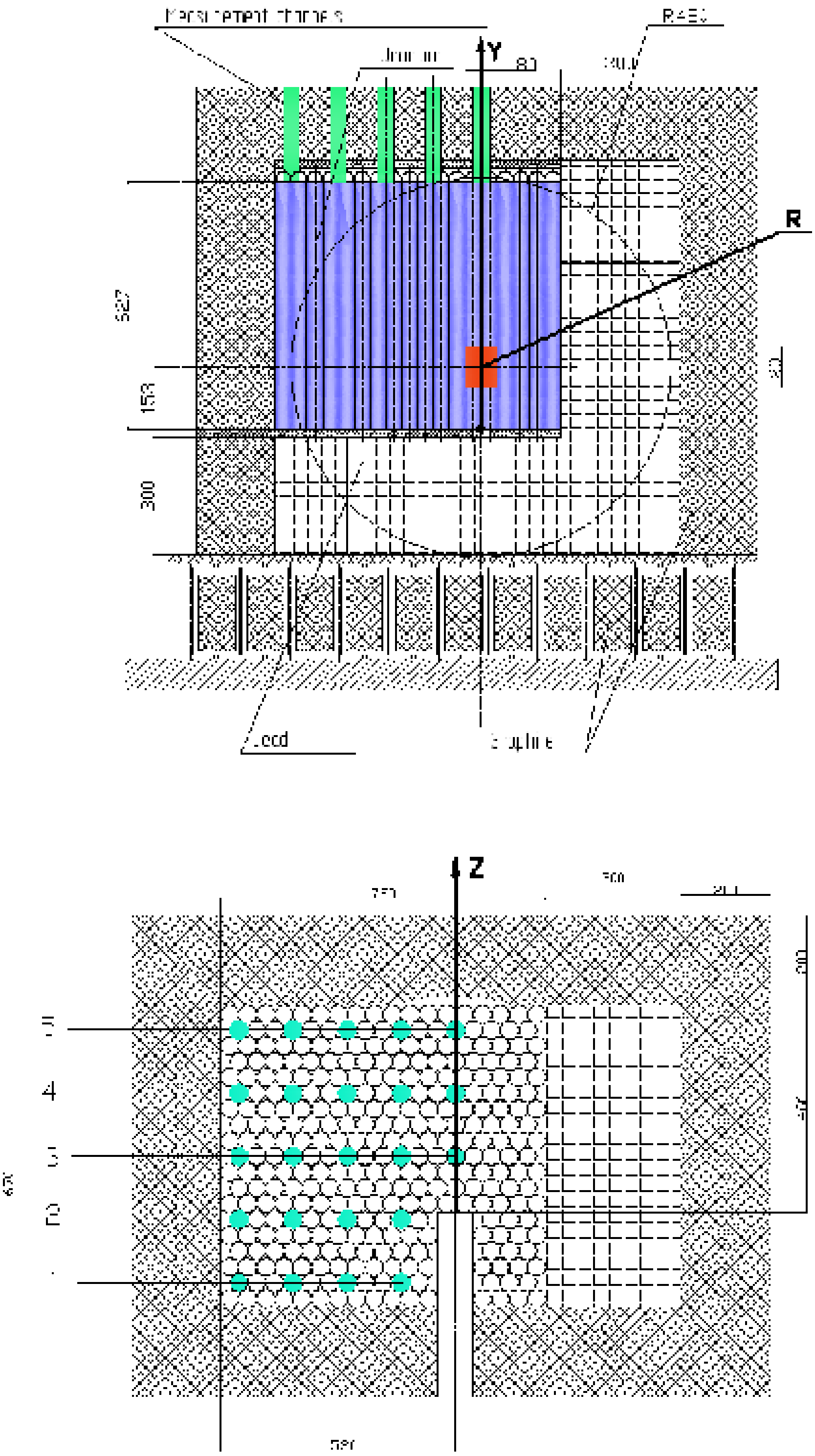
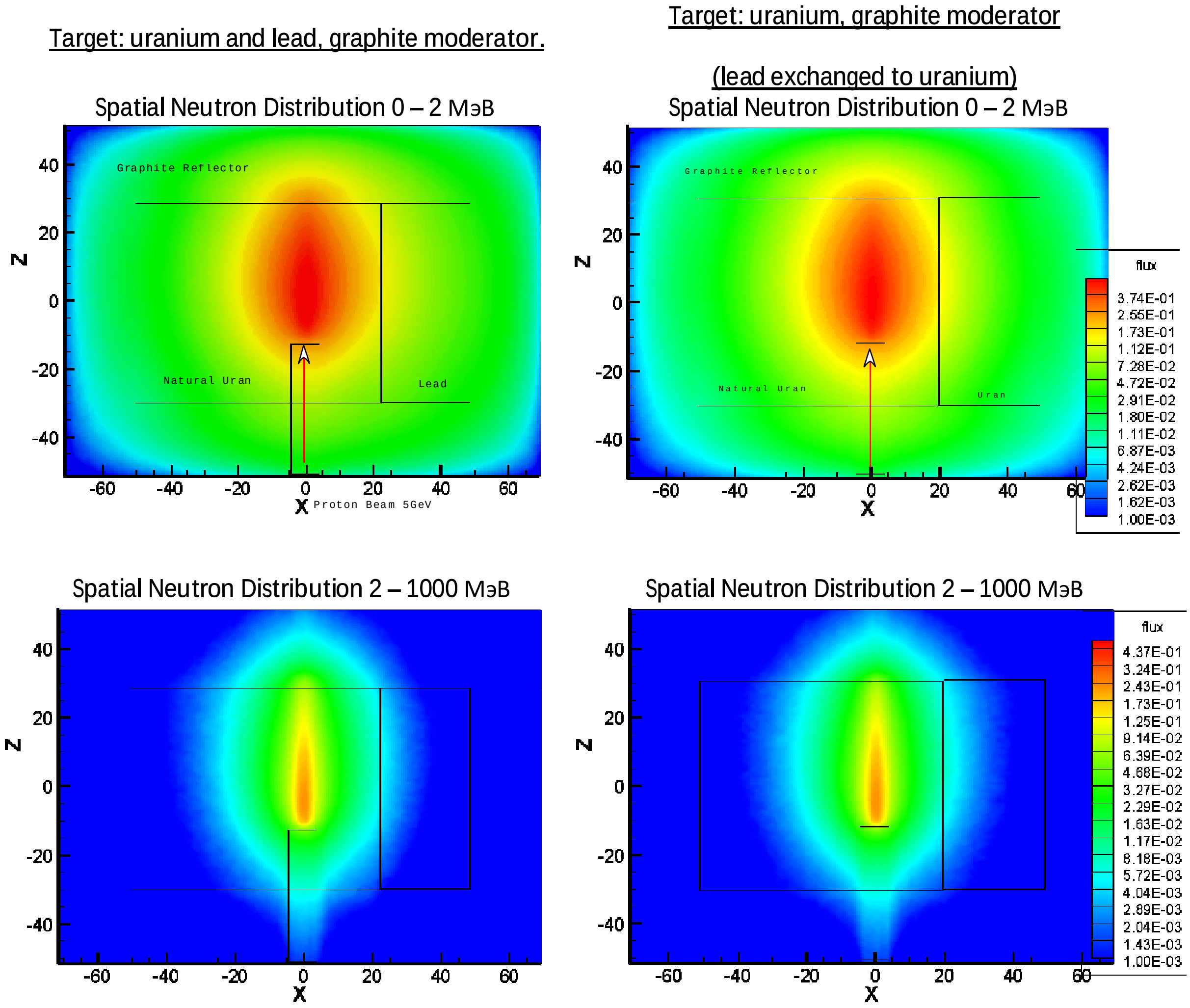

Measurement channels
Uranium
Y
80
R
527
153
300
Lead
Graphite
Z
5
4
3
2
1

Fig. 6.



Target: uranium and lead, graphite moderator.

Target: uranium, graphite moderator

(lead exchanged to uranium)

Spatial Neutron Distribution 0 – 2 МэВ

Spatial Neutron Distribution 0 – 2 МэВ

Spatial Neutron Distribution 2 – 1000 МэВ

Spatial Neutron Distribution 2 – 1000 МэВ

Fig. 7.

6) obtaining power amplification coefficients depending on the characteristics of the neutron spectrum inside the target determined by its configuration and beam particle type and energy;

7) study of prompt and delayed neutron spectra and multiplicity depending on the target configuration, particle type and energy;

8) improvement and optimization of on-line and off-line methods for monitoring intensity, geometric characteristics, and Nuclotron beam position on the target;

9) study of desactivation rates for targets irradiated with different doses.

These studies will be accompanied by numerical and theoretical simulation in combination with activities in Direction 3 described below.

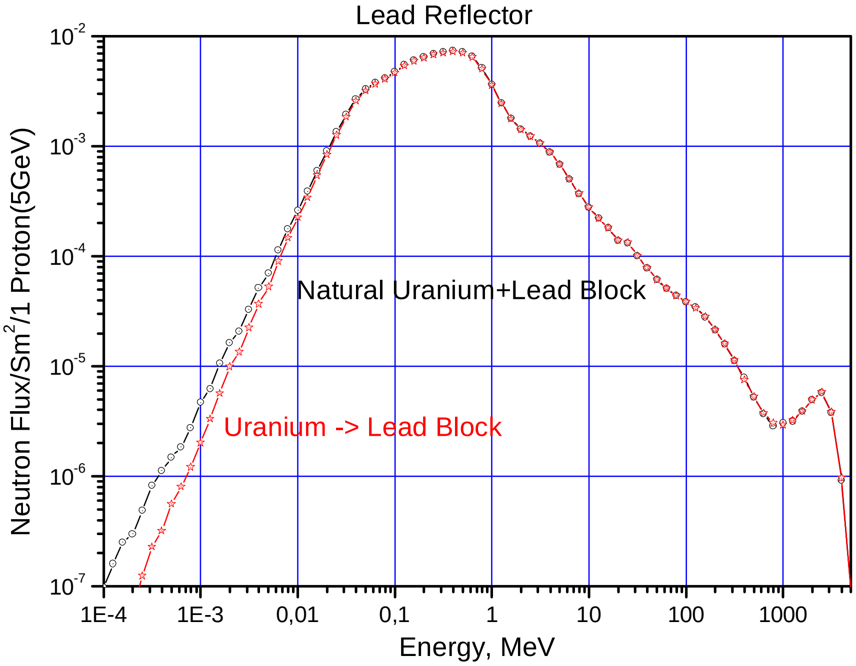

Lead Reflector
Neutron Flux/Sm$^2$/1 Proton(5GeV)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
1E-4
1E-3
0,01
0,1
1
10
100
1000
Energy, MeV
Natural Uranium+Lead Block
Uranium -> Lead Block

FIg. 8.

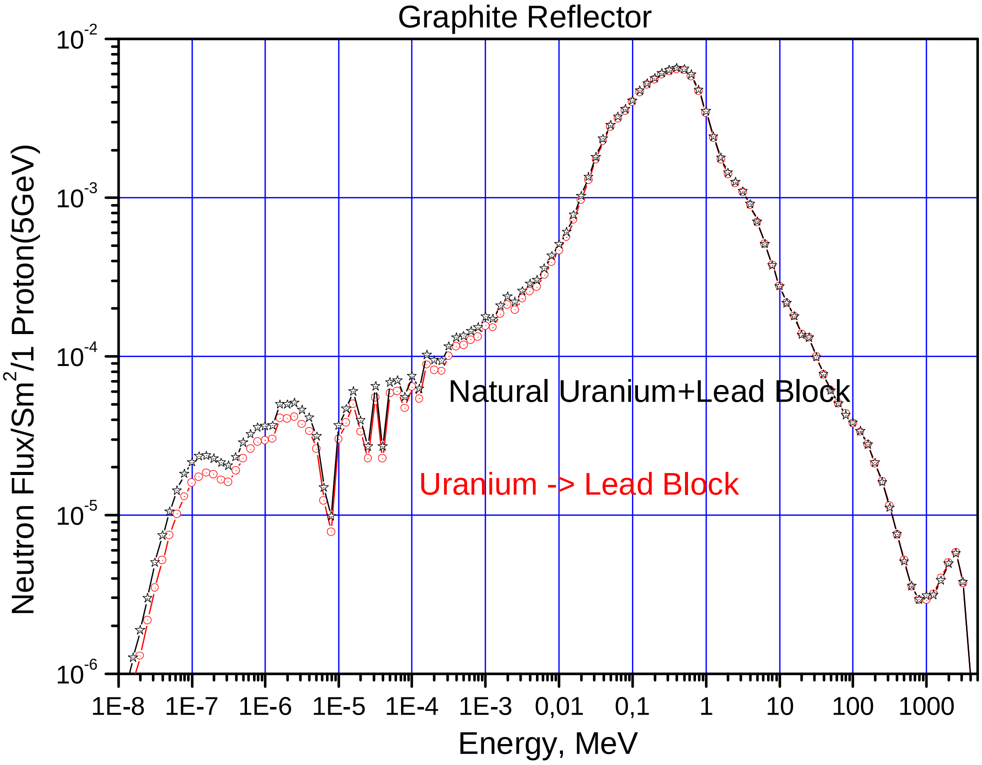

Graphite Reflector
Neutron Flux/Sm$^2$/1 Proton(5GeV)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
1E-8
1E-7
1E-6
1E-5
1E-4
1E-3
0,01
0,1
1
10
100
1000
Energy, MeV
Natural Uranium+Lead Block
Uranium -> Lead Block

Fig. 9.

The basic types of measurement systems and detectors that will be used for execution of the scientific program of the project are given Table 7.

Table 7

| No | Basic types of measurement | Basic measurement systems (detectors types, techniques) | Brief description of measurement systems (detectors types, techniques) |
|---|---|---|---|
| 1. | Spatial-energetic distribution of neutrons | Activation samples;<br>SSNTD;<br>$\gamma$ spectrometers;<br>Small ionization chambers. | 53 reactions at each measurement point;<br>7 reactions at each measurement point;<br>HPGe;<br>$^3$He - detectors. |
| 2. | Spatial distribution of fission reaction rates and fragment mass spectra | SSNTD | 7 reactions at each measurement point |
| 3. | Spatial distribution of (n, $\gamma$) and (n, xn) reactions rates | Samples from spent fuel;<br>$\gamma$-spectrometers;<br>Radiochemistry | Sets of samples at each measurement point;<br>HP Ge. |
| 4. | Spatial distribution of energy release in the target | Sets of heat-insulated uranium samples with thermal sensors | Heat-insulated uranium samples with different enrichment levels (natural; 2-3% and 5-6%) – three samples at each measurement point |
| 5. | Parity (Pu accumulation and burn up) distributions in the target volume | Sets of samples from natural uranium containing Pu-239;<br>$\gamma$-spectrometers;<br>Radiochemistry | Seven samples containing Pu-239 (from 0 to 6%) at each measurement point;<br>HP Ge; |
| 6. | Beam power amplification | Systems for thermophysical measurements (item 4);<br>System for fission rate measurement (item 2) | Solution of direct of heat exchange problem by volume integration;<br>Volume integration of the number of fission events. |
| 7. | Prompt and delayed neutron spectra, neutron multiplicity | System of neutron multiplicity measurement based on $BF_3$ counters;<br>System of neutron multiplicity measurement «Isomer-M» based on $^3$He counters;<br>Precision spectrometer based on $^3$He ion chamber with a Frisch grid;<br>Stilben detector;<br>$LaBr_3$(Ce) detector | 15 Boron counters in a polyethylene moderator.<br>12 $^3$He counters in a polyethylene moderator;<br>Neutron spectra in the energy range up to 5 MeV<br>Ø 3×3 inch |

| | | | |
|---|---|---|---|
| 8. | Beam monitoring | Aluminum foils ;<br>SSNTD;<br>System for on-line beam monitoring based on ion chamber and scintillation telescope. | |
| 9. | Decontamination rates for targets after irradiation | Standard set of dosimetric devices | |

Direction 2 (“Constants”). Carrying out a complex of constant measurements with thin samples, proton energies from 0,6 to 10 GeV and deuteron energies from 1 to 5 GeV/nucleon.

It is planned to perform the series of experiments for obtaining data on energy dependence of fission cross sections of the required set of target nuclei by relativistic protons and deuterons; delayed neutron yields, and fission products.

For reliable simulation of electronuclear systems it is necessary to know the characteristics of corresponding reactions in both thin and thick ($\geq$2000 g/sm$^2$) targets.

Particularly, dielectric track detectors will be used to measure the cross-sections of fission reactions induced by primary and secondary particles.

This method is practically the only one that provides measurement of fission cross-sections for intensive primary and secondary particles fluxes. Track detectors with different registration thresholds provide distinguishing fission fragments from protons and neutrons, the mass spectrum of fission fragments can be also studied.

All data obtained within the second direction “Constants” should be converted into the complete nuclear data files according to the existing standards adapted for basic computer codes.

Direction 3 (“Simulation”). Improvement of physical models, constant base, and computer programs by taking into account neutron multiplicity in extended fissionable media, especially in the energy range above 10 MeV.

The task of obtaining neutron-physical characteristics of the electro-nuclear method under study applies to two physics areas: interaction of high energy beams with condensed matter and reactor physics.

An appropriate account of high energy fission channels is of great importance for calculating neutron fields and heat release in such systems, because the results obtained using existing numerical models differ greatly (several times) from very limited experimental data obtained with small targets, and for quasi-infinite fissionable matter the expected deviation is more pronounced.

The complex of theoretical and numerical activities in the field of phenomenology of multiple particle production in a quasi-infinite fissionable target irradiated by a high energy beam will be performed in the framework of the third direction (“Simulation”).

The theoretical activity and simulations performed to support preliminary planning of experiments in the framework of the project and subsequent processing of results of measurements will make a reliable basis for creation and development of models, methods, and algorithms. The activity in this direction should provide reliability of simulation support for designing future prototypes of experimental-industrial RNT-setups after the proof of principle of the proposed electronuclear scheme [11].

Direction 4 ("Materials"). Investigation of relativistic beam impact on structural and fuel materials.

Within this direction we plan to carry out measurements of integral gas ($^{3,4}$He) production rates in interaction of relativistic beams and fast neutrons with the structural elements and the fuel. Radiation damage depending on the energy and type of primary particles will also be studied.

The activities within this direction are performed in parallel with the activities within the first and second directions. For this activity is necessary to provide minimal possible Nuclotron beam size in front of the target.

## ORGANIZATIONAL AND TECHNICAL ASPECTS

The project “E&T – RAW” will be performed in the framework of a large scientific and technical cooperation including: JINR (LHEP, DLNP, FLNP et al.), Center of Physical and Technical Projects “Atomenergomash” (Moscow), State Research Center Institute of Physics and Power Engineering (Obninsk), JINPR-Sosny NASB, IF NASB, and participants of “Energy plus Transmutation” and “GAMMA-3” collaboration. Positive experience of joint activities, including long-term fruitful experiments at JINR, as well as successful experience of performing a complex of experimental studies initiated by Center of Physical and Technical Projects «Atomenergomash» at JINR and Petersburg Nuclear Physics Institute RAS in 2008-2009 and the GAMMA—3 / E+T Collaboration ensure successful realization of the proposed research program. It is very important that JINR possesses unique capabilities for performing planned experiments, namely, operating relativistic particle accelerator Nuclotron, required amount of fissionable materials, developed measurement methods, as well as the basic international team of highly qualified scientists and technicians.

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The approximate plan of works under the project

## “Study of deep subcritical electro-nuclear systems and feasibility of their application for energy production and radioactive waste transmutation”

| Stages of the project | 2011 | | | | 2012 | | | | 2013 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | I | II | III | IV | I | II | III | IV |
| I. Design. | | | | | | | | | | | | |
| Design of large uranium target EZHIK-U and identical target EZHIK-Pb | 🟦 | | | | | | | | | | | |
| Choice, preparation, testing of systems of experimental and measurement equipment | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | |
| Development of experimental schemes for setups «Energy-Transmutation», «Gamma-3», «EZHIK-U», «EZHIK-Pb», «Study of Materials Resistance and Gas Production » | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | |
| | | | | | | | | | | | | |
| II. Manufacture, mounting, and adjustment of experimental equipment and measurement systems. | | | | | | | | | | | | |
| Manufacture of large uranium target EZHIK-U and identical target EZHIK-Pb | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | | | |
| Development and adjustment of methods and systems of experimental and measurement equipment. | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | |
| III. Physical experiments at «Nuclotron-M» (according to the schedule the installation) | | | | | | | | | | | | |
| “Energy plus Transmutation” | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | | | |
| “Gamma-3” | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | | | |
| «EZHIK-Pb» | | | | | 🟦 | 🟦 | | | | | | |

| Stages of the project | 2011 | | | | 2012 | | | | 2013 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | I | II | III | IV | I | II | III | IV |
| «EZHIK-U» | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | | |
| «Study of materials resistance and gas production» | | | | | | | | 🟦 | 🟦 | 🟦 | | |
| | | | | | | | | | | | | |
| IV. Complex of numerical and theoretical activities of predictive and improving character | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |
| | | | | | | | | | | | | |
| V. Processing of experimental results. More precise determination and development of new algorithms, models, and programs for realization of the project objectives. | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |

THE DIRECTOR OF LABORATORY V.D.KEKELIDZE

THE PROJECT HEAD S.I.TYUTYUNNIKOV