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«E&T RAW» Collaboration

# STUDY OF DEEP SUBCRITICAL ELECTRONUCLEAR SYSTEMS AND FEASIBILITY OF THEIR APPLICATION FOR ENERGY PRODUCTION AND RADIOACTIVE WASTE TRANSMUTATION

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Адам И. и др. (коллаборация «Энергия и трансмутация РАО») E1-2010-61
Исследование глубокоподкритичных электроядерных систем
и возможности их применения для производства энергии
и трансмутации РАО

Представлено физическое обоснование для продолжения и развития исследований новых схем электроядерного метода для производства энергии и трансмутации долгоживущих компонентов радиоактивных отходов (РАО), основанного на ядерных релятивистских технологиях (ЯРТ). Проект «Энергия и трансмутация РАО» нацелен на комплексное исследование взаимодействий релятивистских пучков нуклотрона-М с энергиями до 10 ГэВ в квазибесконечных мишенях.

На основе анализа результатов известных экспериментальных и расчетно-теоретических работ показано, что в рамках предлагаемой схемы можно рассчитывать на использование природного/обедненного урана или тория для производства энергии без добавления урана-235. Также возможна утилизация отработанных ядерных элементов атомных электростанций.

Показано, что выполнение проекта «Энергия и трансмутация РАО» даст возможность получить принципиально новые, отсутствующие в настоящее время совокупные данные и расчетные методы, необходимые для начала проектирования демонстрационных опытно-промышленных установок на основе этой схемы.

Работа выполнена в Лаборатории физики высоких энергий им. В. И. Векслера и А. М. Балдина ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 2010

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Adam J. et al. («E&T RAW» Collaboration) E1-2010-61
Study of Deep Subcritical Electronuclear Systems
and Feasibility of Their Application for Energy Production
and Radioactive Waste Transmutation

Physical substantiation for investigation of new schemes of electronuclear power production and transmutation of long-lived radioactive wastes based on nuclear relativistic technologies is presented. «E&T RAW» («Energy and Transmutation of Radioactive Wastes») is aimed at complex study of interaction of relativistic beams of the Nuclotron-M with energies up to 10 GeV in quasi-infinite targets.

Feasibility of application of natural/depleted uranium or thorium without the use of uranium-235, as well as utilization of spent fuel elements of atomic power plants is demonstrated based on analysis of results of known experiments, numerical, and theoretical works.

The «E&T RAW» project will provide fundamentally new data and numerical methods necessary for design of demonstration experimental-industrial setups based on the proposed scheme.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2010

## INTRODUCTION

The physical aspects of electronuclear energy production 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 electronuclear 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 generation of nuclear energy in the active zone having criticality of 0.94–0.98 and surrounding the target.

Large national projects devoted to the creation of industrial ADS demonstrator prototypes are implemented in Japan (JPARC) [1], USA (RACE) [2], and the joint European project EUROTRANS [3].

The main advantage of electronuclear technology, as compared to conventional reactor technologies, is that a subcritical active core plus an external neutron source (accelerator and spallation 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 transuranium isotopes and thus transmute most of the dangerous radioactive wastes from nuclear power production and other sources.

## MOTIVATION

The results on plutonium yield and number of fission events per proton in a quasi-infinite targets of about 3.5 t depleted and natural uranium under 660 MeV proton irradiation at the Phasotron LNP JINR, obtained by R. G. Vasilkov and V. I. Goldansky et al. [4], are presented in Table 1. The 3.5 t target was equivalent to a symmetric setup with a mass of 6.0 t due to asymmetric beam injection.

The cut-open view of the uranium target [4] inside a lead shielding is shown in Fig. 1. The structures of channels for detector and beam input are also shown.

The energy release was on average $\sim$ 3950 MeV per proton in depleted uranium and $\sim$ 4900 MeV per proton in natural uranium. Therefore the power

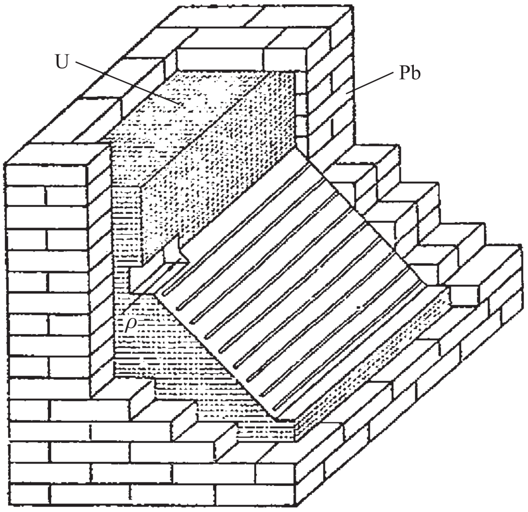

Fig. 1. Schematic cut-open view in the target containing 3.5 t of uranium inside a lead shield. The opening «$p$» on the left side is the beam entrance, and long holes traversing the uranium block are experimental openings for detectors

**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 | $38 \pm 4$ | $13.7 \pm 1.2$ |
| Natural uranium | $46 \pm 4$ | $18.5 \pm 1.7$ |

amplification of the 660 MeV proton beam was $\sim 6.0$ in depleted uranium and $\sim 7.4$ in natural uranium for a system having subcriticality of about $K_{\text{eff}} \sim 0.3$.

It should be noted that in the experiments of C. Rubbia and his group [5] at CERN with a large 3.6 t target from natural uranium the neutron spectrum in the active core was fully thermalized at primary proton energies from 0.6 to 2.75 GeV. These experiments are the opposite extreme case to the experiments [4] in which the hardest neutron spectrum was obtained. In [5] the measured amplification coefficient was about 20 for a beam energy of 0.6 GeV in a subcritical core having $k_{\text{eff}} \sim 0.9$.

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, respectively. These calculations showed, in particular, that the neutron flux increases dramatically with increasing $^{233}$U

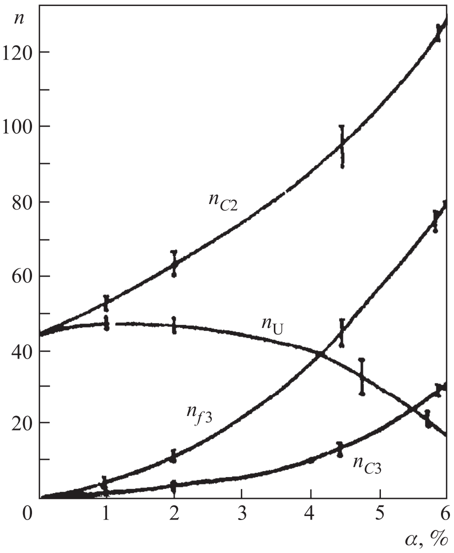

Fig. 2. Calculated numbers of events «$n$» per one incoming 1 GeV proton in a metallic $^{232}$Th target with lead core [9]. The value «$\alpha$» denotes the assumed concentration of $^{233}$U in the $^{232}$Th matrix. $n_{C2}$ is a number of $(n, \gamma)$ capture reactions in $^{232}$Th producing $^{233}$U;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

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 $\leqslant$ 1.5% of $^{233}$U, then it rapidly decreases with increasing concentration and reaches saturation, or equilibrium, around a level of maybe 8% (see Fig. 2, where the line $n_u$ reaches $n = 0$).

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 similar, it may be assumed that parity in quasi-infinite uranium active core will occur at a concentration of easily fissionable $^{239}$Pu of $\sim$ 8%. Experimental proof is requested.

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 $\sim$ 6.5 for the total energy release and about 20 for the part connected with the $^{233}$U $(n, f)$ reaction for $^{233}$U concentration of 4%.

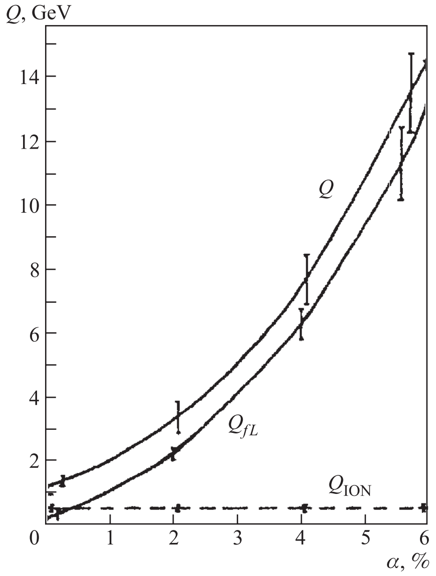

Fig. 3. Calculated heat release in GeV in a target from metallic $^{232}$Th with lead core as a function of enrichment «$\alpha$» of $^{233}$U (per one primary 1 GeV proton) [9]. $Q$ is the total full heat release; $Q_{fL}$ is the heat releasing from fission induced by neutrons in the low-energy region $T \leqslant 10.5$ MeV, $Q_{\mathrm{ION}}$ 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 and studied for quasi-infinite targets from uranium and thorium (see [7–9]) for the concentration range from 0 to 6%.

This allows one to expect deep subcriticality of the system upon reaching equilibrium 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. Yurevich et al. [10] at LHEP JINR. Here $E_p$ is the proton energy, $\langle E \rangle$ is the average neutron energy, $E_{\mathrm{kin}}$ is the total kinetic energy of neutron radiation, 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 $E_{\mathrm{kin}}$, and the proton beam energy $W$ spent for neutron production increase with increasing beam energy and that the efficiency of conversion from beam energy to neutron energy rises with increasing beam energy.

**Table 2. Energy characteristics of neutron radiation leaving a limited $\varnothing 20 \times 60$ cm lead target for various proton energies [10]**

| $E_p$, GeV | $\langle E \rangle$, MeV | $E_{\mathrm{kin}}$, MeV | $E_{\mathrm{kin}}/E_p$, % | $W$, 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 |

The fraction of primary proton energy spent for neutron production for a proton energy of $\sim 660$ MeV is $\sim 20\%$ 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: $\sim 60\%$ (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. The estimates of proton ionization energy losses**

| $E_0$ | 0.7 | 1 | 1.5 | 2 | 3 | 5 |
|---|---|---|---|---|---|---|
| $\Delta E$ | 250 | 229 | 215 | 210 | 215 | 226 |
| $E_{\text{in}}$ | 0.45 | 0.77 | 1.285 | 1.79 | 2.785 | 4.774 |
| $\Delta E/E_0$ | 35.7 | 22.9 | 14.3 | 10.5 | 7.2 | 4.5 |

| $E_0$ | 10 | 15 | 20 | 30 | 50 |
|---|---|---|---|---|---|
| $\Delta E$ | 247 | 258 | 268 | 282 | 295 |
| $E_{\text{in}}$ | 9.753 | 14.75 | 19.73 | 29.72 | 49.71 |
| $\Delta E/E_0$ | 2.5 | 1.7 | 1.3 | 0.9 | 0.6 |

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

It follows from the data presented in Table 3 that ionization losses have a shallow 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 ($E_{\text{p}}$), 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.

Results obtained by the collaboration of State Research Center Institute of Physics and Power Engineering & Center of Physical and Technical Projects

**Table 4. Estimated 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] | $\sim 40$ |
| 1.0 | 12.0 | $\sim 70$ |
| 10.0 | 22.0 | $\sim 130$ |

«Atomenergomash» and Petersburg Nuclear Physics Institute of 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 $\approx 550$ kg irradiated by 1 GeV protons have proven the validity of the method [13] used for $K_{PA}$ estimates from Table 4.

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 indicate that estimates of initial amplification coefficients (second column in Table 4) may be underestimated.

The absolute values of $K_{PA}$ and their dependence on the energy $E_p$ given in Table 4 contradict the result [5]. In [5] it was found that the power amplification coefficient reached saturation at $K_{PA} \approx 30$ around 1 GeV proton beam energy. This discrepancy is probably related to a significant amount of thermalization of the neutron spectrum in experiment [5] and the corresponding suppression of the influence of high-energy neutrons. It should be noted that for the definition of equilibrium $K_{PA}$ shown in the last column of Table 4 the important parameter requiring special study is the time to achieve the equilibrium concentration of $^{239}$Pu 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 among the key elements of the scheme of electronuclear method proposed in [11]. If these values can be confirmed it opens new prospects of energy production and processing of nuclear waste 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 studies of spatial and energy distributions of neutrons inside and outside of a quasi-infinite target from natural uranium. Elucidation of the role of the hard neutron spectrum in enhancing the energy release in the target requires special attention. Taking into account results of [4, 8, 9] the dynamics (space-time aspects) of production of $^{239}$Pu in a uranium target should also be studied in detail; the presence of this isotope essentially changes the characteristics of the subcritical system by increasing the power amplification coefficient of the incident beam.

From the point of view of efficiency of nuclear waste transmutation it is very important to study the ratio of reaction rates for $(n, \gamma)$, $(n, xn)$, and $(n, f)$ reactions for typical long-lived nuclides in spent nuclear fuel with respect to the spatial and energy distributions of the neutron field inside the active zone. Thus, the basic idea of a successful electronuclear technology for nuclear waste removal and simultaneous power production as 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 yet provide the required accuracy for reliable description of characteristics of electronuclear systems.

**Table 5. Average total yield $Y$ and partial yield $Y_{20}$ (for neutron energies higher than 20 MeV) of neutrons in a long lead target ($\varnothing 20 \times 60$ cm) irradiated by proton beams in comparison with calculated yields. Ratios of calculated and experimental yields C/E are also given [10]**

| $E_p$, 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** |

For illustration of present capabilities of modern transport codes let us consider the case of a practically nonfissionable 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 significantly underestimate the high-energy component $Y_{20}$ of the neutron yield for all proton energies.

Let us take the unique experiment [4] presented above to illustrate the 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, $Y$, as well an the number of fission events of $^{238}$U and of easily fissionable $^{235}$U isotopes, $\eta_{38}$ and $\eta_{35}$, respectively, per one 660 MeV proton, using the MCNPX 2.5 code. The ratios C/E of the calculated and experimental values of the corresponding quantities are also given.

It can be seen from Table 6 that the code significantly underestimates both the $^{239}$Pu yield and the number of fission events that 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 in the experimental data given in Table 6 [4] 3–4 fission events from the central region of the target that could not be directly experimentally measured were not taken into account.

For higher incident particle energies, calculations reproduce integral characteristics of breeding systems even worse [13]. The existing transport codes need thorough improvement so that they can reliably describe the neutron spectra and isotope production in an extended target made of natural or depleted uranium. This can be performed only on the basis of new experimental data which shall be measured, in particular, in execution of the proposed project.

## OBJECTIVES

The project objectives are:

1. To study the possibilities and specific features of a hard neutron spectrum interacting in a deeply subcritical quasi-infinite uranium target. Irradiations shall be made with 1 to 10 GeV protons and deuterons for implementation of a new scheme of electronuclear method for energy production and transmutation of long-lived radioactive waste — a relativistic nuclear technology (RNT).
2. To improve existing theoretical models and to verify computer codes for guaranteeing precise simulation of electronuclear systems for RNT prototype design.

## PROGRAM

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

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

The project includes experiments in the framework of the physical program of the facilities «Energy + Transmutation» [15, 16] and «Gamma-3». It is planned to develop and test various measurement systems for experiments with a new uranium target in parallel with these experiments.

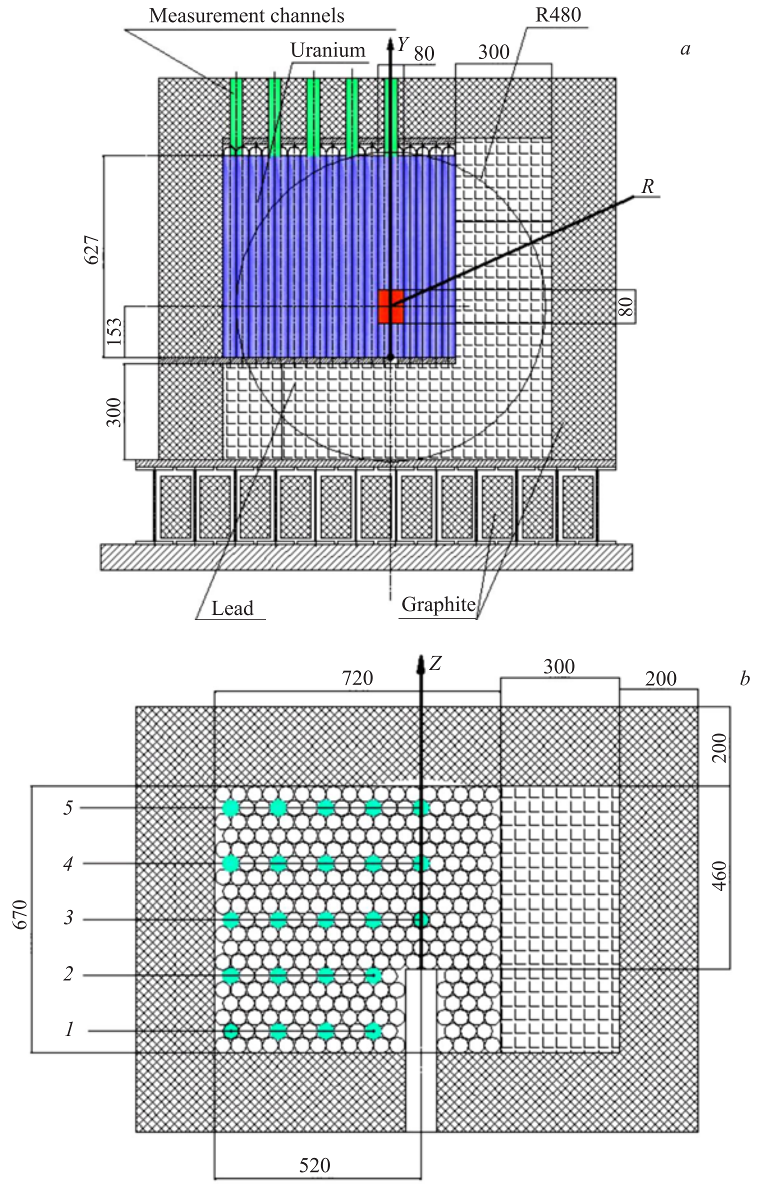

Fig. 4. The target complex «EZHIK-U»

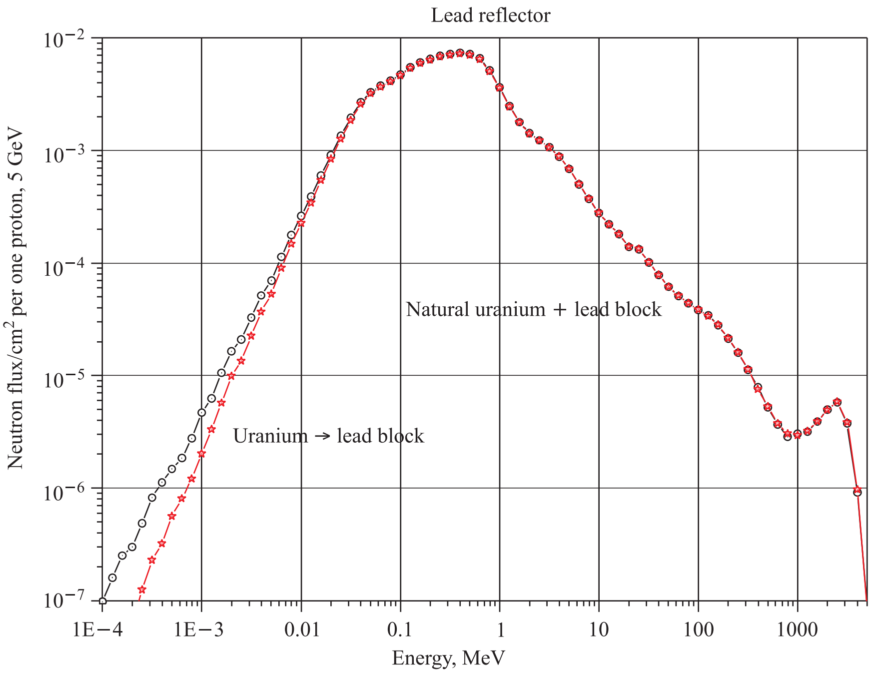

Fig. 5.

The main experiments of the project are then planned to be performed on the basis of the new flexible target complex «EZHIK» (Fig. 4) which is a quasi-infinite target from metallic uranium equipped with measurement channels whose position and design should provide optimal execution of the research program (see Table 7 for details).

The target complex «EZHIK» will be realized in 2 modifications, named «EZHIK-Pb» and «EZHIK-U».

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 verification and adjustment of basic measurement systems and methods as well as background measurements with proton and deuteron beams in the projected energy range before main experiments with uranium target «EZHIK-U» are made.

The basic modification of target complex «EZHIK-U» (Fig. 4) implements in a somewhat modified form the original technical solution of asymmetric beam input into a quasi-infinite target first applied in [4]. It provides 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 3 t of target material from natural uranium.

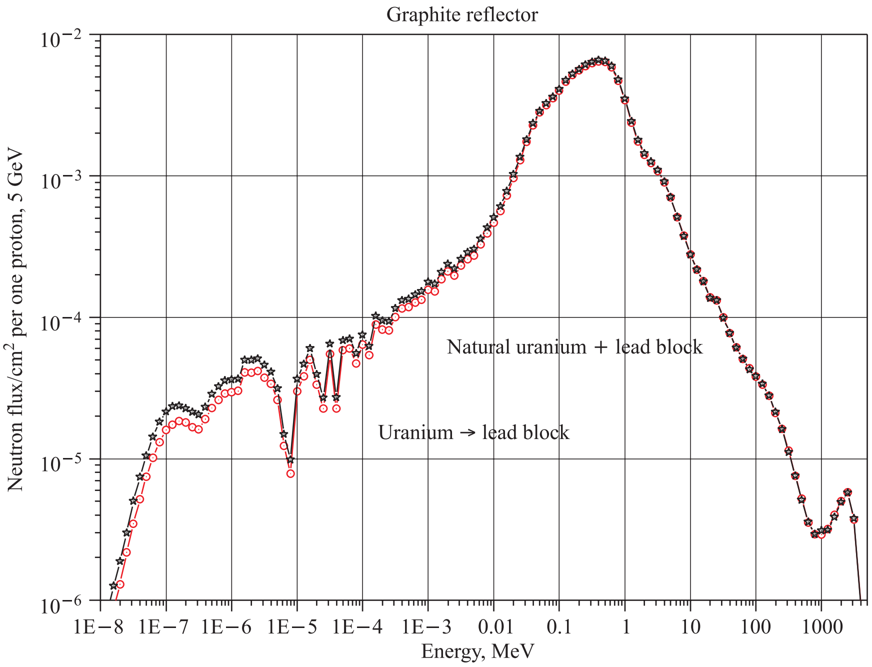

Fig. 6.

**Table 7. The basic types of measurement, measurement systems and detectors types**

| No. | Basic types of measurement | Basic measurement systems (detectors types, techniques) | Brief description of measurement systems (detectors types, techniques) |
|---|---|---|---|
| 1 | Spatial and energy distributions of neutrons | Activation samples;<br>SSNTD;<br>$\gamma$ spectrometers;<br>microionization 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 masses | SSNTD | 7 reactions at each measurement point |
| 3 | Spatial distribution of $(n,\gamma)$ and $(n,xn)$ reactions rates | Samples from spent fuel isotopes;<br>$\gamma$ spectrometers;<br>radiochemistry | Sets of samples at each measurement point;<br>HPGe |

*Table 7. Continuation*

| No. | Basic types of measurement | Basic measurement systems (detectors types, techniques) | Brief description of measurement systems (detectors types, techniques) |
|---|---|---|---|
| 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 | Equilibrium (Pu accumulation and burn up) distributions in the target volume | Sets of samples from natural uranium containing $^{239}$Pu;<br>$\gamma$ spectrometers;<br>radiochemistry | Seven samples containing $^{239}$Pu (from 0 to 6%) at each measurement point;<br>HPGe |
| 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.<br>Volume integration of the number of fission events |
| 7 | Prompt and delayed neutron spectra, neutron multiplicity | Neutron multiplicity measurements 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. 12 $^3$He counters in a polyethylene moderator<br>Neutron spectra in the energy range up to 5 MeV<br>$\varnothing 3 \times 3$ inch |
| 8 | Beam monitoring | Aluminum foils;<br>SSNTD;<br>system for on-line beam monitoring based on ion chamber and scintillation telescope | |
| 9 | Decay rates for targets after irradiation | Standard set of dosimetry devices | |

Figures 5, 6 show the results of calculations 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. Results of calculations of neutron flux densities and energies for two variants of reflectors surrounding the target, those from graphite and lead, are presented.

The analysis of Figs. 5, 6 demonstrates that results of measurements performed in the volume and on the surface of the left upper part (along the beam, see Fig. 4) of the target «EZHIK-U» can be correctly correlated with data on the equivalent symmetric target with a mass of about 8 t.

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

***Direction 1 («Integral Data»).*** The first direction includes sets of integral experiments with the target «EZHIK-U». Proton energies in the range from 1 to 10 GeV and deuteron energies from 1 to 5 GeV/nucleon shall be used.

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;

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 equilibrium between $^{239}$Pu production and fission for determination of the value and time of achieving equilibrium concentration of this isotope for different target configurations;

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

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

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

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

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

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

***Direction 2 («Constants»).*** Carrying out a series of constant measurements with thin samples, using proton energies from 0.6 to 10 GeV and deuteron energies from 1 to 5 GeV/nucleon.

It is planned to perform a 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 ($\geqslant 2000$ g/cm$^2$) 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 distinguish fragments from proton and neutron induced fission. The mass spectrum of fission fragments can also be studied.

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

***Direction 3 («Simulation»).*** Improvements of physical models, the database of constants, and computer programs by taking into account neutron multiplicity in extended fissionable media, especially in the energy range above 10 MeV shall be achieved.

The task of obtaining neutron characteristics of the electronuclear method under study applies to two areas in physics: interaction of high-energy beams with 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; for quasi-infinite fissionable matter the deviation is expected to be more pronounced.

The complex of theoretical and numerical activities in the field 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 planning of experiments in the framework of the project and subsequent processing of results of measurements will make a reliable basis for creation and further development of models, methods, and algorithms. The activity in this direction should provide reliability of simulations for designing future prototypes of experimental-industrial RNT setups after the proof of principle by 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 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 it is necessary to provide the minimal possible Nuclotron beam size in front of the target.

## CONCLUSIONS

The physical program will be performed in the framework of a large scientific and technical cooperation including Joint Institute for Nuclear Research (Dubna), Center of Physical and Technical Projects «Atomenergomash» (Moscow), State Research Center Institute of Physics and Power Engineering (Obninsk), JINPR-Sosny NASB, IF NASB (Minsk), and participants of the «Energy plus Transmutation» and «GAMMA-3» collaborations. Positive experience of joint activities in 2008–2009, including long-term fruitful experiments at JINR, as well as successful experience of performing a complex of experimental studies initiated by the Center of Physical and Technical Projects «Atomenergomash» at JINR, the Petersburg Nuclear Physics Institute of RAS and the GAMMA-3/E+T Collaboration ensure successful realization of the proposed research program. It is very important that JINR offers unique capabilities for performing projected experiments, namely, operating the relativistic particle accelerator Nuclotron, providing the required amount of fissionable materials, developing measurement methods, as well as hosting the international team of highly qualified scientists and technicians.

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