ABOUT POSSIBILITIES OF THE PNPI NUCLEAR FACILITIES TO BE USED FOR SOLVING THE PROBLEMS OF ADS, TRANSMUTATION, AND RELATED FUEL CYCLES

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Petersburg Nuclear Physics Institute of the Russian Academy of Sciences (PNPI) has a long-standing and rich experience in some scientific fields close connected with the problems of Nuclear Energy Generation and Transmutation and Related Fuel Cycles, as follows:

1. Theoretical investigations in the field of the Hybrid Concepts for Nuclear Energy Generation and Related Fuel Cycles (Prof. Yu.V. Petrov);
2. Investigations of the Physics and Technology of the light charged particles accelerators with intermediate energies (Dr. N.K. Abrosimov);
3. Investigations, developments and experimental employment of spallation neutron source at the 1 GeV proton beam (Prof. G.A. Petrov, Dr. O.A. Shcherbakov, Dr. N.K. Abrosimov);
4. Experimental and theoretical studies of the Physics and Technology of nuclear research reactors and critical assemblies (Dr. K.A. Konoplev, Prof. Yu.V. Petrov);
5. Measurements of thermal neutron cross-sections for radioactive nuclei produced in nuclear fission and neutron capture reactions with some structural materials (Prof. G.A.Petrov , Dr. Yu.E.Loginov)
6. Measurements of the fast neutron-induced and 1 GeV proton-induced cross-sections for heavy nuclei including the fissile ones (Prof. G.A. Petrov, Dr. O.A. Shcherbakov, Dr. G.E. Solyakin).
7. Experimental investigations of the gamma-rays spectra from the fuel elements of the active zone of the WWR-M reactor (Prof. O.I.Sumbaev, Dr. V.L. Alexeev)

To perform the widespread scientific investigations, the PNPI uses the following large and medium size physical installations:

1. Proton synchrocyclotron with the energy of 1 GeV and extracted beam current ~ 1 μA (extraction efficiency ~ 30 %), coupled with:
   - spallation neutron source with the lead target and average neutron intensity $3\cdot10^{14}$ n/s;
   - on-line mass-separator on the proton beam for measurements of the radioactive nuclei yields from thick targets;
2. Research nuclear reactor WWR-M with thermal power of 16 MW and neutron flux in the light water trap about $2\cdot10^{14}$ n/cm$^2\cdot$ s, equipped with:
   - critical assemblies of the WWR-M reactor and new PIK reactor (under construction);
   - four-rotor chopper system for producing the pulsed monochromatic nneutron beam for the measurements of neutron-induced cross-sections with small size radioactive targets.
3. Neutron time-of-flight spectrometer GNEIS based on the spallation neutron source of the 1 GeV proton accelerator of PNPI.

   Besides, the new large physical installations are now under construction:
   - research high flux nuclear reactor PIK with project power of 100 MW and neutron flux about $3\cdot10^{15}$ n/s (70 % of readiness);
   - isochronous cyclotron with proton energy of 80 MeV and current up to 100 μA (50 % of readiness).

All experimental installations are placed on the same site. The PNPI has also modern systems of radiation control, as well as for radioactive waste processing and utilization.

Taking into account all aforesaid, the following wide range investigations can be performed in the nearest future by PNPI scientists, under appropriate financing:

- Development of the theoretical concepts of the nuclear energy generation and transmutation, and related fuel cycles;
- Measurements of the fast neutron-induced and 1 GeV proton-induced cross-sections for different isotopes and materials planned to be used for ADS;
- Measurements of slow neutron cross-sections of radioactive isotopes produced in fission and other nuclear reactions being of interest for ADS and transmutation problems;
- Measurements of the yields of different radioactive isotopes from the sick targets, irradiated by 1 GeV protons;
- Development and investigations of the different accelerator-driven models of subcritical assemblies using 1 GeV proton external beams.

Main parameters of the PNPI nuclear facilities.

1. Proton synchrocyclotron of PNPI.

This machine was put into operation in the beginning of 1970 and since that time was used very effectively for different fundamental nuclear studies and applied investigations (about 5,000 - 6,000 hours per year during about 20 years). Starting from 1990, the effectiveness of the accelerator employment is decreasing steadily because of financial difficulties.

By now, this accelerator is the largest operated synchrocyclotron with the proton energy 1 GeV and internal current about 3.3 μA. The accelerator is situated in the round hall with diameter 32 m. The semicircular experimental hall 25 m wide is immediately adjacent to the main hall and separated from it with the heavy concerete wall of 8 m thickness. Such accelerator disposition enables an easy arrangement of different models of ADS. The substracted 1 GeV proton beam (~ 1 μA) is transported through one of four collimators in the experimental hall.

The beams of secondary particles have the main parameters, as follows:

Table 1.

Particles	Linear momentum P, MeV/c	ΔP/P, %	Intensity, s^{-1}
$\pi^{\pm}$	450	6	10^6
$\pi^{\pm}$	250	2.5÷12	$10^5 \div 10^7$
$\mu^{\pm}$	160	10	$(1 \div 3)\ 10^5$

1.1. On-line mass-separator IRIS on the extracted proton beam.

This ISOL system was put into operation in 1975 and since that time was used effectively till nowadays in the wide international collaboration (CERN, GSI et al.) for the spectroscopic studies of the nuclei far from β - stability line.

The main parameters of this installation are as follows:

Table 2

Characteristics	Type or value
Proton intensity on the target, s^{-1}	~ 10^{12}
Electromagnet	sector type
Deflection angle	55^0
Radius, m	1.5
Targets	W, Ta, Nb foils, Au, U, Th
Radioactive nuclide flux, s^{-1}	up to $10^7 \div 10^8$

1.2. Spallation neutron source on the internal proton beam.

This type of neutron source has been arranged shortly after synchrocyclotron starting. Fast neutrons are produced in water-cooled lead target after deflection of the circulating protons from the median plane by means of high voltage pulse. The main parameters of the source are presented in the Table 3:

Table 3

Parameter	Value
Target dimensions	40 x 20 x 5 cm^3
Internal proton beam current	up to 3.3 μA
Repetition rate	50 Hz
Width of the fast neutron flash	≤ 10 ns
Average fast neutron production rate	~ $3 \cdot 10^{14}$ n/s

2. Research nuclear reactor WWR-M.

The first physical starting of the modernized water-water reactor WWR-M had place in December 1959. Since the middle of 1960 and till now the WWR-M reactor is successfully used for fundamental investigations in the fields of nuclear and solid state physics. Besides that, the WWR-M is used for development of research reactor technology, for production of isotopes, and for activation analysis. The reactor has 16 horizontal channels including two tangential and one through-going channels. One of the vertical channels (the central one) is used for unique source of cold and ultracold neutrons, containing about 1 litre of liquid hydrogen just inside reactor active zone. Among the other peculiarities of the WWR-M, which could be useful for ADS problem studies, it should be stressed that reactor is fitted with special over-reactor radioprotected chamber for the express works with neutron exposed materials. It seems to be interesting to point out that at the WWR-M reactor the intensive studies of strength properties of the materials exposed with high neutron fluxes are carried out in collaboration with other laboratories during many years.

2.1. Intensive pulsed source of slow neutrons at the WWR-M reactor.

It is well known that in some neutron experiments (for example, the total cross-section measurements with small amount of radioactive isotope) in the energy range $E_n < 20$ eV, the steady high flux reactors may have definite preponderances as compared with accelerator-driven sources.

With the aim to realize such a possibility at the new high flux reactor PIK (under construction), the joint project (ITEP-PNPI) of multirotor mechanical chopper-monochromator has been created. The model of such instrument, including four synchronized identical

rotors, situated one after another along the radial neutron beam axis, now is into operation at the WWR-M reactor. Each metallic rotor 30 cm of diameter has ten rectangular straight-through slits 0.8 x 3.0 cm^2 and is hanged in magnetic field. The quasi-monochromatic pulsed neutron beam with the energy spread ΔE and the mean energy E can be obtained at the exit of installation by means of proper selection of relative phases and angular velosity of the rotors. Neutron energies inside ΔE interval can be measured by the time-of-flight technique.

Neutron intensity at the detector position (flight path length ~9 m) has been found to be equal to

$$I_n \approx 10^5 \cdot 1/E \ cm^{-2} \cdot s^{-1} \cdot eV^{-1}$$

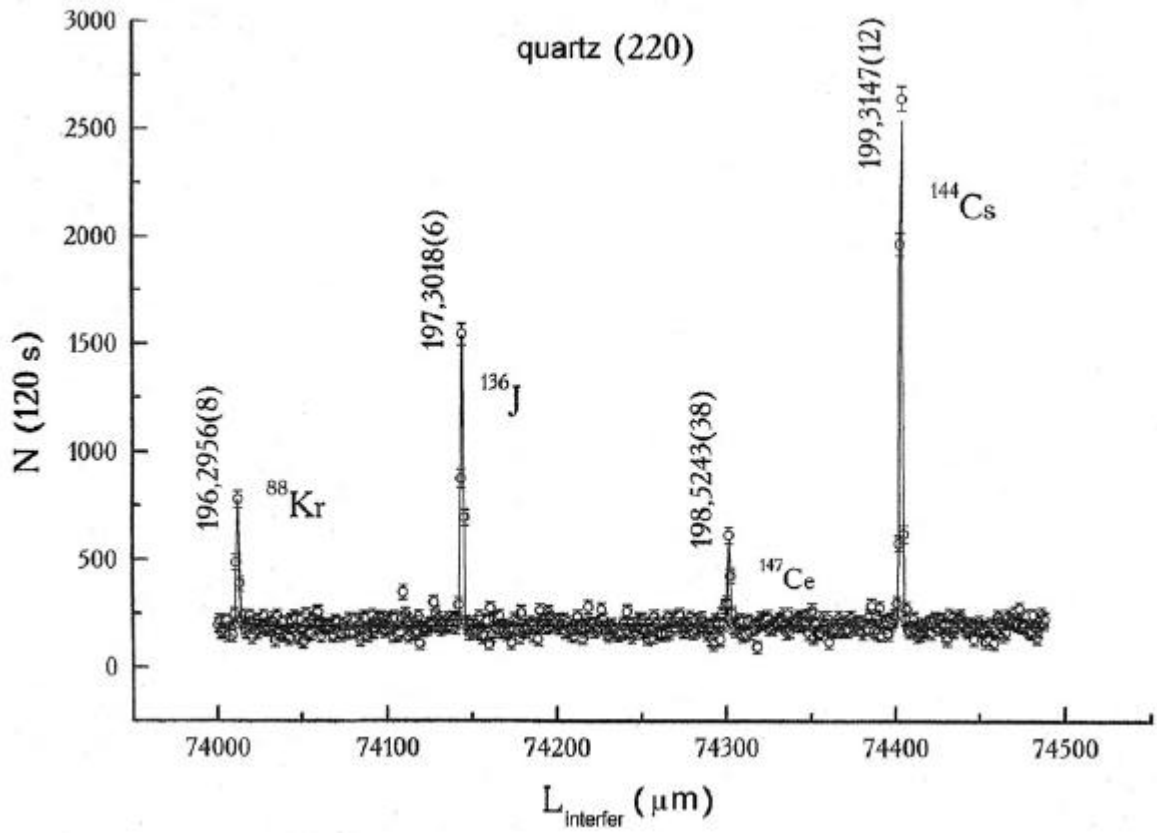
(at the reactor power about 16 MW). This instrument can be useful under measurements of total cross sections of radioactive wastes.

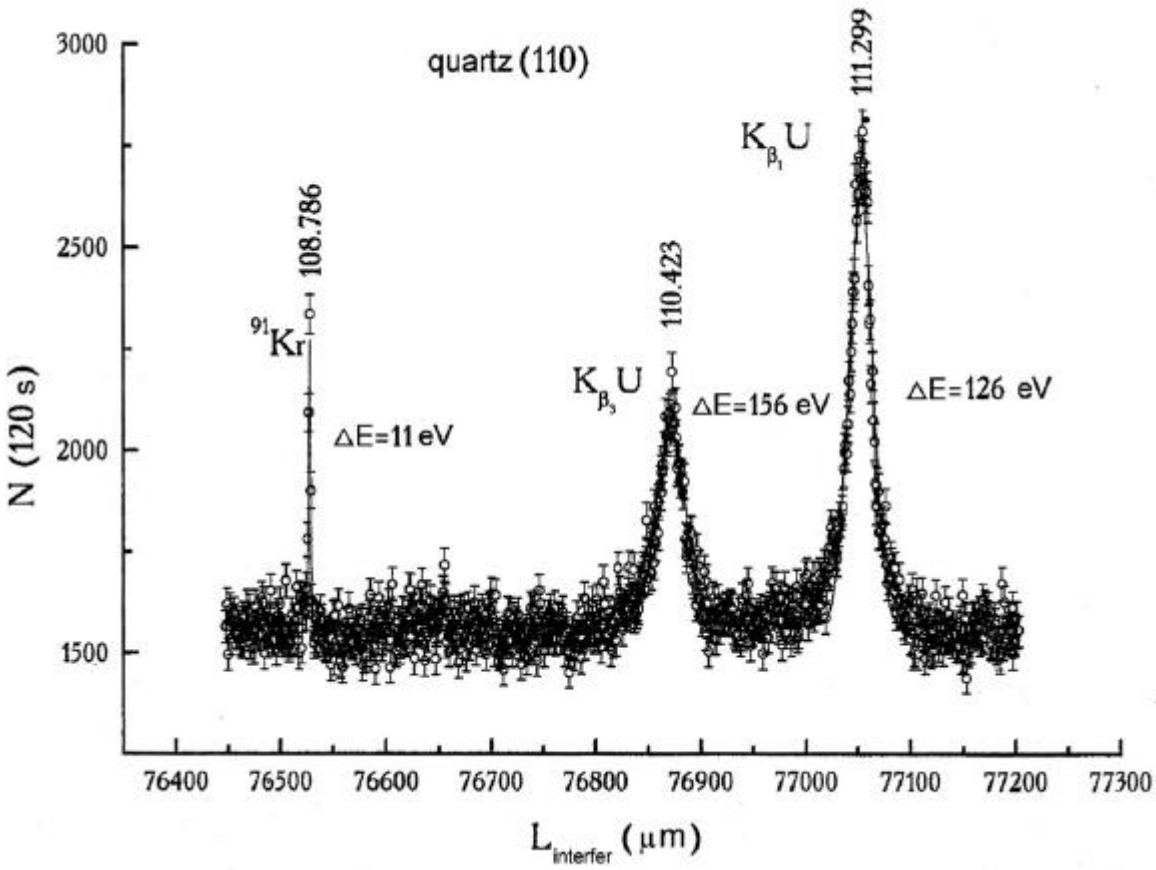
2.2. Cauchois crystal diffraction spectrometer at the radial horizontal neutron beam of WWR-M reactor.

This instrument with high quality bent quartz crystal (R=4 m.) is installed on the radial horizontal beam of the WWR-M reactor and was used formerly for the spectroscopics investigations of the gamma-rays spectra from (n,gamma)-reactions. Recent modernization of the instrument with the use of laser-reading device permitted to achieve the record energy resolution as follows:

$\Delta E = 8 \times 10^{-7} \times E_\gamma / n$, keV, where n being reflection order.

The precise measurements of gamma rays energies, which can be used as the signatures of the isotopes of interest, can be performed into the energy range (20 – 1200 keV). Some fragments of the spectra from activated fuel elements of the reactor are presented in the Figs below. All gamma-rays energies are shown in keVs. This method seems to be usefull for diagnostics of the transmutation processes.





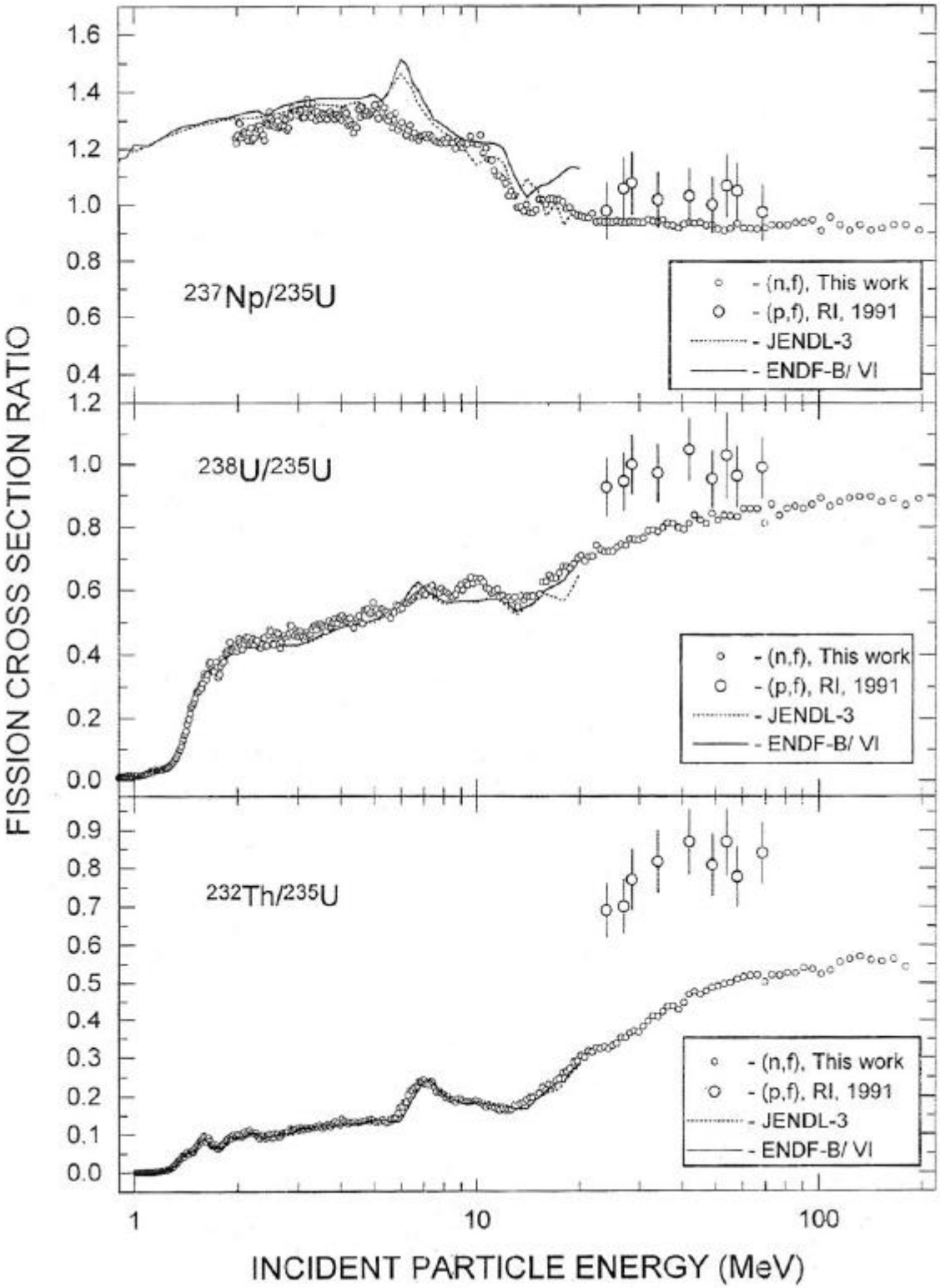
3. Neutron time-of-flight spectrometer GNEIS at the 1 GeV proton synchrocyclotron.

The Gatchina Neutron Spectrometer GNEIS is intended for neutron-nucleus interaction studies utilizing the time-of-flight technique in the wide range of neutron energy from thermal up to ~ 200 MeV. This facility includes the spallation neutron source based on the 1 GeV synchrocyclotron of PNPI, the system of 5 flight paths 35 - 50 m of length, coming through the main hall of the accelerator into the GNEIS building, where a number of detector devices, such as fission ionization chambers, scintillation detectors for registration of neutron and gamma-rays, 4π- and 2 x 2π-large liquid scintillation tanks, and associated electronic equipment are situated. The four neutron beams, looking at the surface of polyethylene moderator coupled with lead target, are used for measurements with resonance and keV-neutrons, while the neutron beam, looking at the bare lead target, is used for measurements at intermediate neutron energies up to 200 MeV.

3.1. Measurements of neutron-induced fission cross-section ratios for U238, Th232 and Np237 relative to U235.

Fission cross-section ratios for U238, Th232 and Np237 relative to U235 have been measured using the neutron time-of-flight spectrometer GNEIS in the energy range from 1 MeV to 200 MeV. The measurements were performed at the 50 m flight path, a neutron burst width 10 ns and repetition rate 50 Hz. The fast parallel plate ionization chamber containing 4 foils of oxide fissile materials gave a possibility of measuring fission cross-sections in the whole energy range for all samples simultaneously. At present, the measurements of fission cross-sections in the energy range above 20 MeV with continuous

spectrum neutrons are performed only at the WNR/LAMPF facility in Los Alamos and the GNEIS facility in Gatchina. Analysis of the experimental data available in the energy range 20-200 MeV shows that there is a need in new measurements aimed to improve fission cross-section data base above 20 MeV. Some results of the recent measurements of fission cross section ratios are presented in the Fig. below. Similar measurements for another nucleus being of interest for the transmutation problem are now under investigation.



4. Research high flux reactor PIK.

The high flux beam-type research reactor PIK is intended for a broad range of investigations in the fields of fundamental nuclear and solid state physics, biology, and different application studies. The reactor will have 10 horizontal neutron channels including one radial, five tangential, three through-going, and one V-shaped channels. Besides that, there will be six inclined and 6 vertical channels for different uses. Maximum neutron fluxes inside these channels will be as high as $(1 \div 9) \cdot 10^{14}$ n/cm^2 ·s. Neutron flux at the bottom of central experimental channel, placed just in the center of active zone, is expected to be about $4 \cdot 10^{15}$ n/cm^2·s at the thermal power of 100 MW.

The main technical parameters of the PIK reactor are presented in the Table 4:

Table 4

Power	100 MW
Moderator and coolant	H_2O
Reflector	D_2O
Diameter	2.5 m
Height	2 m
Core: - diameter - height	 0.39 m 0.5 m
U235 charge (90 % enrichment)	27.5 kg
Fuel element type	cross-shape pins

A full-scale physical mockup was built for the reactor PIK. This mockup is used usually for accurate measurements of the reactor performance, as well as to determine the neutron flux and energy realized in different experimental devices which are difficult to calculate. The accumulated experience of the investigations with physical mockups of the PIK and WWR-M reactors may be useful in the design of different models of subcritical assemblies for ADS.

It is expected that reactor PIK will be put into operation in the 2002 - 2003 year.

5. Future trends of the accelerators in PNPI.

The future trends of the accelerator base development in PNPI is connected with creation of isochronous cyclotron with the energy of negative hydrogen ions about 80 MeV and the current about 100 μA. This instrument is planned to be used as an injector for the proton synchrocyclotron to increase beam intensity and as an accelerator itself with for following purposes:

- for special radionuclide production;
- for proton therapy of malignant tumors of the skin, larynx, eyes et al.;
- for further investigations of the properties of nuclei far from stability region.