ELECTROSTATIC ACCELERATOR AND NEUTRON GENERATOR

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1. Introduction

At PNPI there are several small energy working accelerators: a Van de Graaf electrostatic accelerator with the energy of 1.6 MeV (ESA) and a neutron generator with 14 MeV monoenergetic neutrons (NG). These accelerators were built and put into operation under leadership of Doctor Aleksey Dyumin. The main parameters of the accelerators – energy stability of proton and deuteron beams $\Delta E / E = 10^{-4}$ for the electrostatic accelerator and neutron yield of $2 \cdot 10^{12}$ n/s for neutron generator corresponds the modern level of these devices [1–3]. These accelerators were designed for a wide program of fundamental research (nuclear physics, physics of solids, films and surface, semiconductors) as well as for technical and applied investigations (new materials, nuclear detectors).

2. Electrostatic accelerator ESA-2

The ESA-2 accelerator of protons, deuterons and electrons up to 1.6 MeV is operated from 1978. The ion tract with the 15 m length has ion-optical elements (electrocorrector, electromagnetic quadrupole lens), slit, and beam control devices, and analyzing magnet with diameter of 1.2 m. This makes possible to form and to lead to the investigated target ion beam with desired size and intensity as well as to stabilize its energy.

Table 1

The parameters of electrostatic accelerator beams

Accelerated particles	Energy, MeV	$\Delta E / E$, %	Intensity, part. / s	Beam diameter on a sample, mm
Protons, deuterons	0.3 – 1.6	0.01	$5 \cdot 10^{9} - 2 \cdot 10^{14}$	0.5 – 8
Electrons	0.3 – 1.6	1	$5 \cdot 10^{9} - 1 \cdot 10^{15}$	~ 10

The parameters of ion and electron beams are presented in Table 1. The vacuum in the ion tract is free of oil and made by means of sputter-ion pumps. It is 10^{-6} Torr.

The irradiation by proton and deuteron beams can be in vacuum chamber only. The electron beam can be extracted from the vacuum chamber through an aluminum window of 50 μm thick. The beam spot diameter on the investigated sample is 12 mm. It can be swept on the horizontal plane in the angle range $\pm 15^{o}$ with the frequency of 50 Hz.

The light ion (proton, deuteron) beams have been used widely for microanalysis of solids and films by means of nuclear physics techniques: proton induced *X*-ray emission (PIXE), nuclear reaction analysis (NRA) and Rutherford backscattering spectrometry (RBS). To realize these techniques the experimental analytical equipment on the base of the electrostatic accelerator for investigation of materials was designed. It is shown in Fig. 1 [3]. It consists of target vacuum chamber, Si(Li)-detector of *X*-rays (15), Ge(Li)-spectrometer of γ-rays (14), detectors for ions (12, 13). Information from detectors is collected with electronics and is stored on a computer.

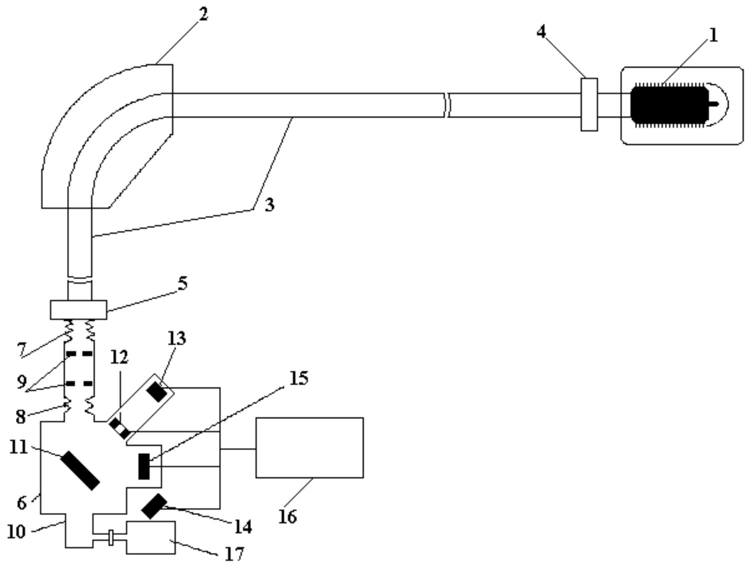

Fig. 1. General scheme of the analytical installation on the electrostatic accelerator base:
1 – accelerating tube and high pressure tank; 2 – analyzing magnet; 3 – ion tract; 4, 5 – vacuum valve; 6 – vacuum camera for samples; 7, 8 – vacuum flexible connector; 9 – beam collimators; 10 – Faraday cap; 11 – sample device; 12 – a circular surface-barrier Si(Au)-detector of ions with an aluminum filter-absorber; 13 – planar Si-detector of scattered beam ions; 14 – Ge(Li)-spectrometer of γ-rays; 15 – Si(Li)-spectrometer of *X*-rays; 16 – readout; 17 – vacuum pump

Nuclear physics techniques are nondestructive, high sensitive and precise. However the possibilities of the PIXE, RBS and NRA methods for the detection of elements with low and high atomic number "*Z*" and for measurement of their contents in the investigated samples are different. The RBS is more sensitive to heavy elements (with the atomic number greater then 30). In favorable cases 10^{12} atoms/cm^2 can be detected. In spite of the lower sensitivity for high *Z* elements the PIXE can give better element resolution then the RBS.

Nuclear reactions (d,p), (d,α), (p,α), $(p,\alpha\gamma)$, and (p,γ) are ideal for the detection of low *Z* impurities (beryllium, lithium, boron, carbon, nitrogen, oxygen, fluorine) and, hence, complement RBS and PIXE.

The knowledge of the depth concentration distributions of implanted atoms in the near-surface region of solids is of interest in the field of basic research in the interaction of ions with matter, applied physics and technology. The measurement of depth profiles provided information on the diffusion of implanted ions, the radiation damage of an irradiated material, the reemission of foreign atoms (carbon, nitrogen, and oxygen) from an environment and a substrate. The RBS and the NRA permit to determine such the depth profiles without a destruction of sample. The RBS is used to measure a depth profile of middle and heavy mass elements where as the NRA can be used for the same purpose for many of light mass elements ($Z < 20$).

The simultaneous usage of these methods (PIXE, RBS, NRA) in the single installation allows to obtain detail and precise information on a composition and a structure of investigated sample from one experiment. Analytical characteristics of used nuclear physics techniques are presented in Table 2.

These methods permit to investigate:

- element and isotope composition of films and bulk materials,
- the structure of films and the outer layers of solids,
- thickness of films and outer layers of solids,
- depth concentration profiles of elements in films and in a near surface region of solids,
- interaction of layers in multilayer structures,

- interaction of surface films with a substrate, a vacuum, and an atmosphere,
- quantitative determination of trace elements.

Such studies are fundamental in solid physics, semiconductor, high temperature superconducting technique, new materials investigation, ecology, *etc*.

Table 2

Analytical characteristics of nuclear physics techniques

Technique	Detection elements	Thickness of investigated layers, μm	Depth resolution, nm	Sensibility %	Accuracy, %
PIXE	$Z > 10$	1 – 20	–	$10^{-3} - 10^{-4}$	~ 5
NRA	$1 < Z < 20$	1 – 5	≤ 10	$10^{-1} - 10^{-3}$	3 – 5
RBS	$Z > 1$	1 – 10	≤ 30	$1 - 10^{-3}$	1 – 2
NAA	$Z > 2$	Volume distribution	–	10^{-4}	~ 5

3. Neutron generator

The neutron generator is operated from 1961. Its basic parameters are presented in Table 3, the scheme is shown in Fig. 2. The NG includes ion source (1), accelerating tube with extracting, focusing and accelerating electrodes (3–6), vacuum valve (8), beam interrupter (10), rotating vacuum connector (11), neutron tritium target (12) with a cooling system (13), vacuum chamber with pumps (7).

14 MeV monoenergetic neutrons are obtained in the $T(d,n)^4$He reaction by irradiating tritium target 160 keV accelerated deuterons. The heat on the target (in our case 4 kW/cm^2) is taken off with the help of the rotating vacuum tightening up, as in most modern generators. The speed of rotating target is 1000 min^{-1}.

The main parameter of the neutron generator – neutron yield of $2 \cdot 10^{12}$ n/s correspondents the modern level of the devices [2]. The irradiated sample can be placed at a small distance of ~ 6 cm from the neutron target and this disposition provides the neutron flux up to 10^{11} n·cm^{-2}·s^{-1} on the irradiated sample. The neutron flux is measured by the proportional ^{3}He-counter calibrated by activation of copper foils.

On the NG there is installation of neutron-activation analysis on fast neutrons including short-level nuclei. To move an investigated sample to the position of neutron irradiation and back to the detector there is a pneumatic transport system. Transportation time of irradiated targets is 1.5 s.

Table 3

Basic parameters of the neutron generator

Type reaction	$T(d,n)^4$He
Neutron yield (E_n = 14 MeV)	$\leq 2 \cdot 10^{12}$ s^{-1}
Neutron flux	$\leq 10^{11}$ n · cm^{-2} · s^{-1}
Time of double decrease of neutron yield	2 h
Deuteron energy	160 keV
Beam diameter on target	(10–20) mm
Radioactivity of the tritium target	≤ 150 Ci
Rotation velocity of target	1000 min^{-1}
Power on target	≤ 4 kW
Vacuum	10^{-6} Torr

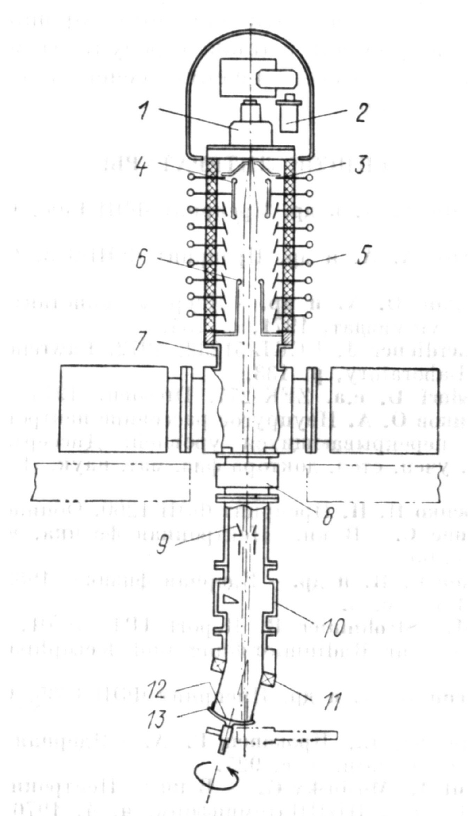

Fig. 2. Scheme of the neutron generator NG-200: 1 – ion source; 2 – palladium filter; 3, 4 – extracting and focusing electrodes; 5 – accelerating tube; 6 – accelerating electrode; 7 – vacuum chamber with pumps; 8 – vacuum valve; 9 – limiting diaphragm; 10 – beam interrupter; 11 – rotating vacuum connector; 12 – tritium target; 13 – target cooling system

4. Conclusion

After the 20 years operation, the PNPI electrostatic accelerators and neutron generator continue to be ones of the most active facilities in investigations of materials by the nuclear physics methods. The simultaneous usage of these methods (a proton induced *X*-ray emission, a Rutherford backscattering spectrometry and a nuclear reaction analysis) in the single installation allows to obtain unique, detail and precise information on a composition, a structure and properties of investigated sample from one experiment. These techniques permit to investigate thin films, near surface region of solids, thin wires one its destruction.

The main directions of investigations include:

- research of high temperature superconductivity materials (films, crystals, ceramics),
- investigation of fullerene containing materials,
- research of metal nanoclusters in dielectric matrices of hydrogenated amorphous carbon α-C:H,
- investigation of lithium diffusion mechanism and intercalation processes in nanoporous carbon materials,
- aging investigations of straw drift-tubes, proposed for experiments on Large Hadron Collider (LHC) and Deutches Electronen Synchrotron (DESY).

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References

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