SECTION 4
IRRADIATION INSTALLATIONS, DIAGNOSTIC AND RESEARCH METHODS

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MODERNIZATION OF THE ANALYTICAL NUCLEAR-PHYSICAL COMPLEX SOKIL

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New modifications that have been used at the analytical nuclear-physics complex (ANPC) Sokil in recent years are described. They concerned an ion accelerator with an increase in the energy of accelerated ions and the separation of $^4He^{2+}$ and H^{2+} beams. A system for irradiating materials science samples with a beam of gas ions with the possibility of choosing the irradiated target space has been created. The use of electrostatic beam deflection made it possible to increase the service life of the foil for beam release into the atmosphere. The use of a pyrocarbon filter in the analysis of monoelements or objects with a high X-ray output of one or several elements changed the form of the spectrum. These modifications made it possible to improve the operation of the complex and obtain new possibilities in solving problems by analytical nuclear physics methods in the study of materials for nuclear power engineering and ecology.

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INTRODUCTION

Several hundred ion accelerators with energy up to several megaelectronvolt have been in the world, which can be used to solve analytical problems related to elemental and isotope analysis [1]. NSC KIPT was one of the first to create an accelerator that could become the basis for analytical nuclear-physical methods of substance (ANPM) [2]. The use of two or more methods of research on ion beam made it possible to expand the range of identified elements (isotopes) [3]. Currently, in the study of materials, more than 70% of works are carried out with the complex use of ANPM. Several analytical nuclear-physical complexes (ANPC) based on an electrostatic accelerator created at NSC KIPT were used to solve technological problems at the enterprise [4]. One of these complexes, which selves for testing new approaches, works at the National Science Center of Kharkiv Institute of Physics and Technology.

Over the past time, improvements and modernization of the ANPC Sokil nuclear power plant have been carried out, several experimental devices have been developed and created, which allow the implementation of almost all modifications and improvements of modern ion beam analysis.

The article shows new developments that were used at the ANPC Sokil.

EXPERIMENTAL EQUIPMENT

The ANPC Sokil (Fig. 1) consists of the following main systems:

– electrostatic accelerator (ESP);
– output devices;
– experimental channels for the use of ANPM;
– measuring and computing equipment.

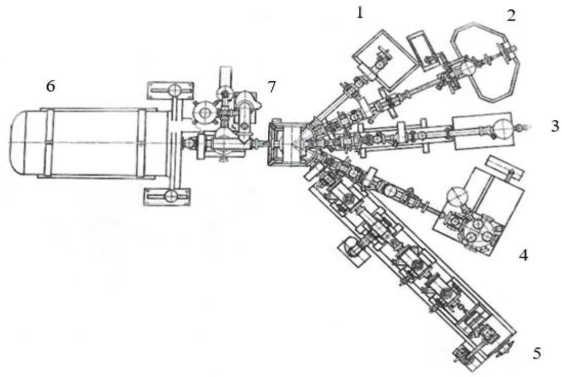

Fig. 1. ANPC Sokil: 1–5 – experimental channels; 6 – electrostatic accelerator; 7 – output devices

The created accelerator has the following technical characteristics.

Technical characteristics of the accelerator

The energy range of accelerated ions, MeV	0.2...2.0
The smoothness of energy regulation, keV	0.1
The maximum ion current at the direct output of the magnetic analyzer, μA	30
Beam current in experimental channels, μA	0.001…10
The largest diameter of the beam on the target, mm	5
The smallest diameter of the beam on the target, μm	3
Monoenergeticity and energy stability, %	0.1

The existing equipment at the ANPC Sokil has already been partially described [5], so the following will be about the existing modernization of the accelerator and experimental channels.

MULTICHARGED ION SOURCE AND INJECTOR

The radio frequency source of ions used on the electrostatic accelerator of the ANPC Sokil allows you to obtain only singly charged ions of gases, therefore, the energy of the ions is limited to the maximum potential on the high-voltage electrode. But in order to expand the capabilities of the complex, a source of multi-charged ions (MCI) was created at the ESP. Taking into account all factors, the following requirements were put forward to the future MCI:

– low consumption of working gas $Q < 10^{-4}(m^3 \cdot Pa)/s)$ to ensure a high vacuum in the accelerator tube;

– power consumption no more than 150 W;

– the source should have a small mass (about 4…5 kg) so as not to overload the tube of the horizontal type accelerator, and small dimensions for placement in a high-voltage conductor;

– ease of management;

– service life is more than 150 h.

The analysis showed that the source of ions with a high-voltage Penning discharge with a cold cathode and extraction of ions along the axis of the source best meets these requirements [6–8]. Calculations were carried out and experiments were carried out, which made it possible to coordinate the work of the created MCI and the accelerator tube of the ANPC Sokil. On the basis of this source, performed calculations, and experimental works, an injector of MCI was created [9]. Fig. 2 shows the appearance of the source and the ion injector created on its basis, which was used on the electrostatic accelerator of the ANPC Sokil.

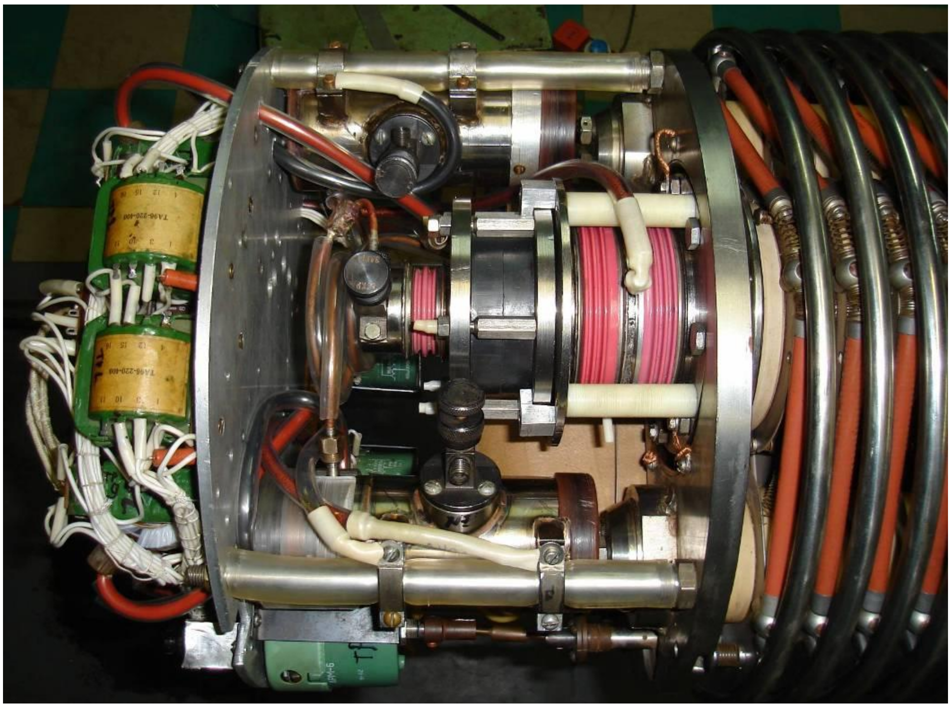

Fig. 2. Injector of MCI on the electrostatic accelerator of the ANPC Sokil

CHANNEL OF IRRADIATION OF MATERIALS WITH GAS IONS

When irradiating samples with hydrogen, carbon, nitrogen, and oxygen ions, it is necessary to separate the beam ions by mass, because the accelerated beam contains both atomic and molecular ions. Therefore, the irradiation channel must be located at some angle relative to the initial direction of the beam. The angle of rotation of the beam was chosen based on the geometric dimensions of the room, the installation and its structural features. The maximum possible angle of rotation was $5^0 40'$, which corresponds to the radius of rotation of the ion beam of 2.5 m. With this radius of rotation, it is possible to transport heavy ions up to Xe with an energy of 2 MeV into the irradiation channel. The scheme of the irradiation channel is shown in Fig. 3.

An important node of the irradiation channel is the beam scanning system of the irradiated sample. An electrostatic scanning system was chosen because it provides the same deflection of the beam ions regardless of mass.

The scanning system allows you to implement the following irradiation modes: irradiation of the entire surface of the sample; irradiation of any half of the sample surface; irradiation of any fourth surface of the sample. Irradiation of the sample is performed in the irradiation chamber. The chamber is equipped with a new high-performance pumping system based on a turbomolecular pump, which allows maintaining the residual pressure at the level of 10^{-4} Pa [9].

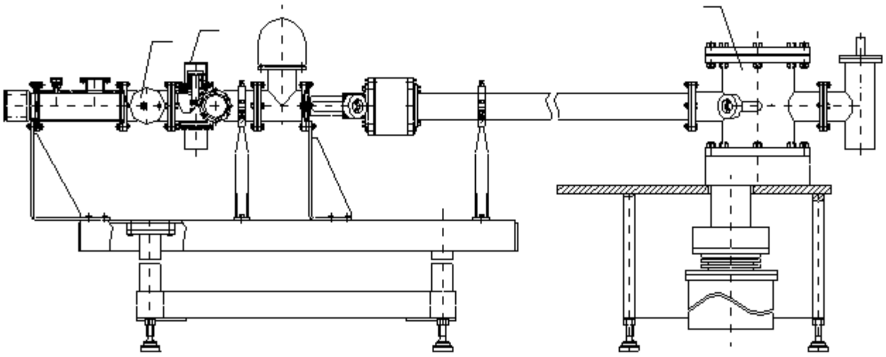

Fig. 3. Channel of irradiation of materials with gas ions

SEPARATION SYSTEM IN A BEAM OF $^4He^{2+}$ AND H^{2+} IONS

The use of multi-charged ions at the accelerator of the ANPC Sokil expands the analytical capabilities of the complex, as well as expands the ion energy range of the irradiation channel.

Since hydrogen and compounds with hydrogen are always present in the residual gas in the installation, H^{2+} ions are formed in the source along with $^4He^{2+}$ ions. The values of cross sections for the formation of H^{2+} are ~ 10^3 times higher than the values of the cross sections for the formation of $^4He^{2+}$ (Fig. 4). In this regard, the values of the currents of H^{2+} and $^4He^{2+}$ ions can be equal in magnitude, which is where the task of separating these ion beams arises.

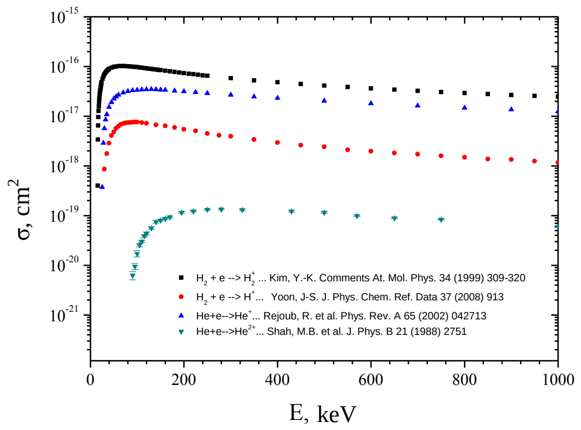

Fig. 4. Cross sections for the formation of H^+, H^{2+}, He^+, He^{2+} ions depending on the electron energy

There are several methods of separation by mass of streams of charged particles that can be considered as possible in our case for application:

– Wien filter;

– distribution magnet and electrostatic analyzer;

– destruction of H^{2+} molecular ions when passing through a carbon film.

At a conductor potential of 1.7 MeV and an ion beam diameter of about 4 mm, the deviation of H^{2+} ions by 0.8 mm or less will not lead to beam separation, i.e., the Wien ilter cannot separate H^{2+} and $^4He^{2+}$ beams under our conditions.

When separating the beams of $^4He^{2+}$ and H^{2+} ions, the other two possibilities were used. With the use of a distribution magnet and an electrostatic analyzer, the separation of helium and hydrogen ions was carried out according to the scheme (Fig. 5). The research used the method of measuring beam ion currents by detecting backscattered He and H particles on the Ta target.

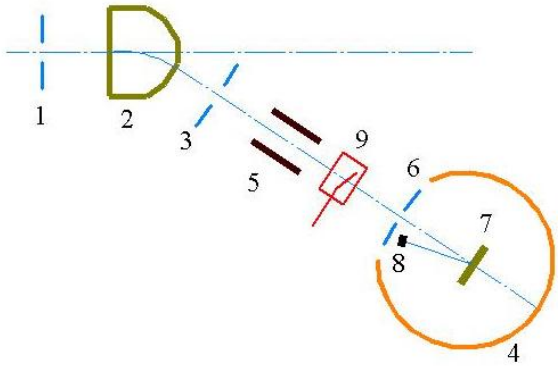

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Fig. 5. Scheme of the experiment on the separation of $^4He^{2+}$ and H^{2+} beams at outlet #4:
1 – diaphragm ∅5 mm; 2 – mass analyzer;
3 – slit device; 4 – experimental chamber;
5 – electrostatic analyzer; 6 – collimator slit 0.9x9 mm;
7 – Ta target; 8 – surface barrier detector;
9 – beam monitor

In Fig. 6 presents the profiles of the $^4He^{2+}$ and H^{2+} beams obtained by measuring the current. The obtained results show that the width of the $^4He^{2+}$ and H^{2+} ion beams is about 4 mm, and the distance between the peaks is ~ 4.5 mm, that is, the beams are separated.

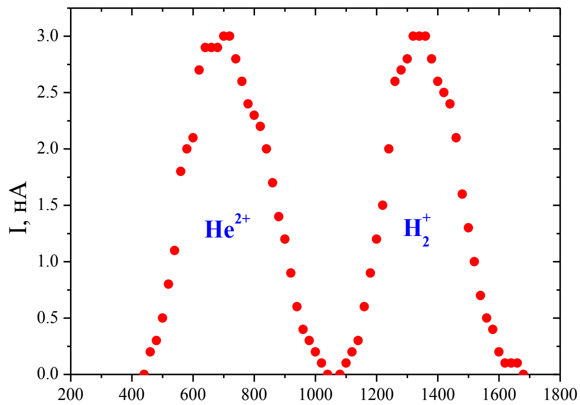


Fig. 6. Profiles of $^4He^{2+}$ and H^{2+} beams

SEPARATION OF $^4He^{2+}$ AND H^{2+} ION BEAMS USING CARBON FILMS

During the passage of ions through thin films, processes associated with the capture and loss of electrons (recharging, stripping, neutralization), as well as the disintegration of molecular ions are possible. Thus, if a thin carbon film is installed in front of the distribution magnet on the path of the beam, it is worth expecting the disintegration of H^{2+} ions into H^+ and H^0. These particles will not pass through the mass analyzer and the beam will not be cleaned of molecular hydrogen ions. But at the same time, the loss of a part of $^4He^{2+}$ ions is possible.

In the experiment on the separation of $^4He^{2+}$ and H^{2+} ion beams, free carbon films produced by the NSC KIPT, which were obtained by the method of vacuum-arc spraying, were used. The thickness of the films and their composition were determined using the RBS method. According to the data of RBS spectroscopy, the used films have a thickness of 79 and 300 nm and their composition includes: C (98 at.%), O (1.9 at.%), K (0.1 at.%).

The following results were obtained: for a film with a thickness of 300 nm, the ratio of $^4He^{2+}$ to H^{2+} currents was 88, and for a film with a thickness of 79 nm – 52 [10].

PULSE REJECTION SYSTEMS IN THE SPECTRA OF C.X.R.

In the version with a beam of protons released into the atmosphere, it is often important to carry out a non-destructive analysis of objects, which is a necessary condition in many cases (for example, when analyzing objects that represent historical value or biological objects). In addition, in this version of the analysis, the durability factor of the original vacuum-tight foil, which separates the vacuum part of the ion conductor from the atmosphere, becomes relevant. The use of the rejection system will reduce the destructive factor of the beam impact on the target and increase the service life of the original vacuum-tight foil.

In early work, the ion beam deflection scheme is fundamentally modified and allows working with several targets located off the beam axis, which allows the beam to be passed to subsequent chambers and to increase the efficiency of using the accelerating time.

When working with a beam emitted into the atmosphere, a beam deflection system is used, in which only one plate is switched, and the second is under a constant potential, and the target is in the path of the undeflected ion beam. Fig. 7 shows the scheme of the deflection system for a beam of ions released into the atmosphere [11].

When working with the beam, the proton energy was 1.8 MeV. For a more qualitative display of the effect of the application of the rejection system, both single-element (Ti, Cu, Zr) and multi-element (steel) objects were used as targets. Spectra obtained with the beam deflection system turned off and with the system operating were measured and compared for different load values of the spectrometric path.

In Fig. 8 presents the spectra of the steel sample obtained without the use of the deflection system and with its use. It can be seen that the use of the deviation system when loading the spectrometric path over 50,000 pulses per second allows to significantly improve the appearance of the X-ray spectra and improve the analysis errors.

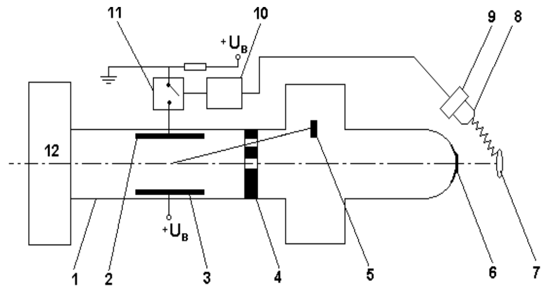


Fig. 7. Deflection system for a beam of ions released into the atmosphere: 1 – ion conductor; 2 – upper plate; 3 – lower plate; 4 – diaphragm; 5 – "graveyard"; 6 – output foil; 7 – analyzed object; 8 – detector; 9 – pre-amplifier; 10 –electronic switch with control system; 11 – electronic key; 12 – charged particle accelerator

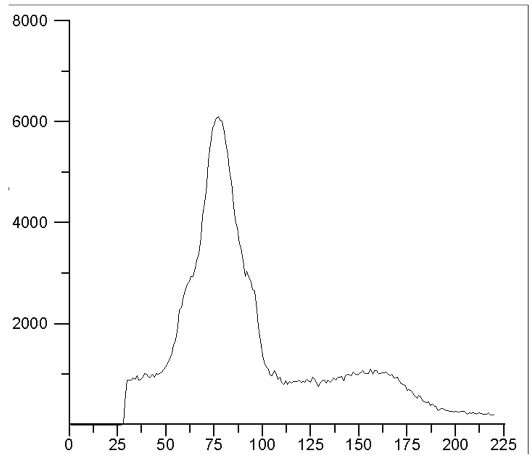
USING A PYROCARBON FILTER

The use of the PIXE method for the analysis of elements of the iron group in zirconia or similar tasks causes complications with intense radiation from matrix elements (for example, K-series zirconia). The principal scientific and technical solution to such a task would be the use of a broadband X-ray radiation filter with a rectangular band of spectral transmission. At the same time, it is necessary to achieve the maximum coefficient of selective transmission in the working range of the spectrum and the maximum absorption outside the transmission band.

A computer program "Monochromator" was created and designed to calculate the X-ray transmission function of a broad-band filter based on pyrocarbon. According to the developed program, calculations were carried out to determine the form of the pass function and to find out the influence of the geometric factors of the filter on it. The varied parameters were: the diameter of the proton beam on the target, the length of the pyrocarbon plates in the filter, and the diameter of the filter; the distance between the spot on the target and the filter, the distance between the filter and the detector, the diameter of the detector aperture.

As a result of the calculations and experiments, it was found that the plate material chosen for the filter reflectors is an almost perfect graphite single crystal. Such a filter was developed and created on the basis of pyrocarbon graphite. The spectral characteristics of the filter in the X-ray range of 4-20 keV were studied and the analytical capabilities of the X-ray spectral scheme with such a filter for the analysis of zirconium-based materials were determined.

The filter is a cylindrical assembly of plane-parallel plates of pyrocarbon graphite 3×1×30 mm in size, cut long the plane, reflection (002) with a mosaic of the order of 0.4^0 and a constant lattice of 6.713 Å.



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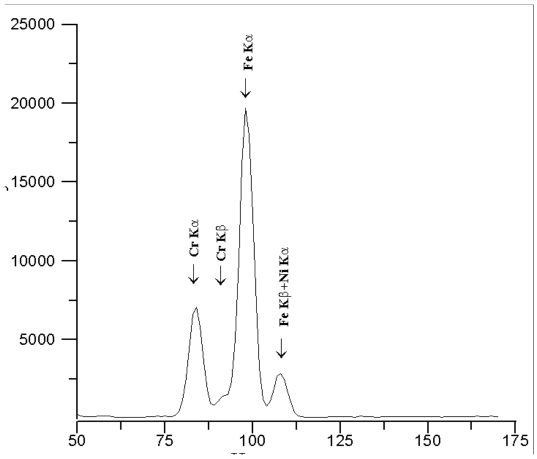

b

Fig. 8. X-ray spectrum of a steel sample:
a –when the rejection system is turned off;
b – with the rejection system turned on

The filter was located at the outlet of the ion beam into the atmosphere. The output of the proton beam into the atmosphere was carried out through a window made of aluminum foil with a thickness of 5 μm. The target was at a distance of 7 mm from the foil at an angle of 45^0. The energy of the proton beam in a vacuum was equal to 1.8…1.9 MeV. This value was chosen on the condition that the energy on the target will be about 1.6 MeV. The scheme of the X-ray channel with a filter is shown in Fig. 9.

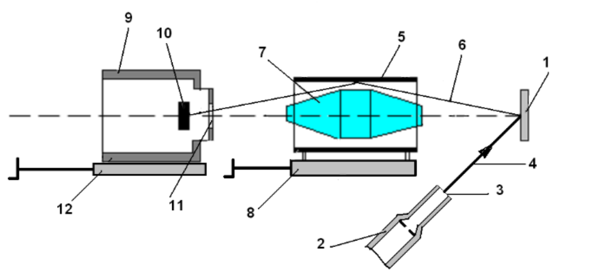

Fig. 9. Scheme of the channel on the released beam of the ANPC Sokil: 1 – target; 2 – output device of the ion channel; 3 – foil; 4 – proton beam; 5 – X-ray radiation filter; 6 – X-ray radiation from the target; 7 – absorber; 8 – filter movement mechanism; 9 – Si-detector; 10 – detector crystal; 11 – foil and detector diaphragm; 12 – detector movement mechanism

CONCLUSIONS

Two methods of separation of $^4He^{2+}$ and H^{2+} ions have been developed at the ANPC Sokil of the NSC KIPT. In the first case, a distribution magnet and an electrostatic analyzer installed after the magnet are used. In the second case, carbon films are used in front of the magnet, which should ensure insignificant losses of the He^{2+} beam and the final disintegration of the H^{2+} molecular ion.

The study of the interaction of a beam of accelerated gas ions with materials allows for studying the state and modification of nuclear energy materials.

The detection limit values achieved with the broadband filter allow the PIXE method to be used for the study of zirconium-based materials for the determination of elements of the iron and hafnium group.

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МОДЕРНІЗАЦІЯ АНАЛІТИЧНОГО ЯДЕРНО-ФІЗИЧНОГО КОМПЛЕКСУ СОКІЛ

С.Г. Карпусь, В.В. Кузьменко, В.В. Левенець, О.Ю. Лонін, А.П. Омельник, А.О. Щур, В.І. Сухоставець

Описано нові модифікації, які застосовувалися на аналітичному ядерно-фізичному комплексі Сокіл в останні роки. Вони стосувалися прискорювача іонів зі збільшенням енергії прискорених іонів і розділенням пучків $^4He^{2+}$ і H^{2+}. Створено систему опромінення матеріалознавчих зразків пучком іонів газу із можливістю вибору опромінюваного простору мішені. Використання електростатичного відхилення променя дозволило збільшити термін служби фольги для виходу променя в атмосферу. Використання піровуглецевого фільтра при аналізі моноелементів або об'єктів з високим рентгенівським випромінюванням одного або кількох елементів змінило форму спектра. Ці модифікації дозволили удосконалити роботу комплексу та отримати нові можливості вирішення задач аналітичними методами ядерної фізики при дослідженні матеріалів для атомної енергетики та екології.