https://doi.org/10.15407/scine16.06.072

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COLLABORATION WITH JINR AS KEY FOR NUCLEAR PHYSICS DEVELOPMENT IN UKRAINE

Introduction. *Today, the Joint Institute for Nuclear Research (JINR) is a kind of scientific and technical framework for Ukrainian nuclear researchers who are directly involved in conducting the cutting-edge nuclear physics experiments.*

Problem Statement. *An important aspect of international cooperation for the Ukrainian researchers in the field of nuclear physics and materials science is to consolidate scholarly research, engineering, and financial resources of countries for creating international research organizations and implementing large-scale projects in modern science and technology.*

Purpose. *Analysis of the factors that contribute to the development of nuclear physics and research in related disciplines in Ukraine, involvement of Ukrainian researchers in international research processes, and assessment of the future prospects.*

Materials and Methods. *Analysis of scholarly research trends in the Joint Institute for Nuclear Research (JINR) and review of achievements of Ukrainian researchers, in particular, young researchers, in implementation of international projects in nuclear physics and related disciplines.*

Results. *The background of nuclear physics research in Ukraine, the way of international cooperation development, and its impact on education and training of researchers have been analyzed. The examples of research results of Ukrainian nuclear physicists have been given. The cooperation of Ukrainian R&D organizations and companies with JINR has been shown to have a positive effect on creative and innovative processes, including the development and study of new high-tech materials.*

Conclusions. *Collaboration with JINR gives Ukrainian researchers access to modern methods of physical research and unique equipment at leading international R&D centers, while planning and implementing large-*

Citation: Grynyov, B.V., Bulavin, L.A., Soloviov, D.V., and Stadnik, P.O. Collaboration with JINR as Key for Nuclear Physics Development in Ukraine. *Sci. innov.* 2020. V. 16, no. 6. P. 72—81. https://doi.org/10.15407/scine16.06.072

scale experiments in nuclear physics, and enables studying the problems of the Universe. Teachers, students, and schoolchildren from Ukraine have additional opportunities to work with the cutting-edge methods, modern equipment and innovative approaches in the field of science and technology.

Keywords: nuclear physics, research, and cooperation.

The beginning of systematic research in nuclear physics in Ukraine dates back to 1928, when the Ukrainian Institute of Physics and Technology (UIFT) was established in Kharkiv. According to one of the founders and the first director of the UIFT, later Full Member of the USSR Academy of Sciences, I.V. Obreimov, the Institute of Physics and Technology in Kharkov initiated the development of nuclear physics in the country. In his opinion, at that time, none of other institutes was interested in this problem or going to study it, since they believed for the national economy it was a matter of the distant future [1]. Nuclear physical research in UIFT started already at the stage of its formation, upon the initiative of then young researcher, later the UIFT director, Full Member of the Ukrainian Academy of Sciences O.I. Leipunsky [2]. Only three years after the establishment of the institute, he together with a group of young Kharkiv researchers K. Sinelnikov, A. Walter, and G. Latyshev, experimentally confirmed the accomplishment of the Cavendish Laboratory (where the "father" of nuclear physics E. Rutherford (England) did his experiments) on the successful split of lithium atomic nucleus with the use of artificially accelerated protons obtained several months before. The year 1932 was marked with a series of brilliant discoveries in the field of young nuclear physics. In addition to the mentioned event, this year, J. Chadwick, one of the Rutherford most talented students discovered neutron, while C. D. Anderson from the California Institute of Technology (USA), was the first to find positron. These results allowed young researcher D.D. Ivanenko, then the chief of the Theoretical Department of UIFT, to put forward a hypothesis about the neutron-proton structure of the atomic nucleus and the absence of light particles, electrons and positrons, and later to theoretically prove its correctness [3]. Further, UIFT researchers were actively involved in neutron physics research, the main result of which was systematic study of the cross sections of neutron scattering and capture by a large group of elements within the energy range of 0.1—1 MeV. In 1933, the UIFT action plan included the topic research of neutron as new type of matter, and in 1939, the Institute started studying a new problem, uranium fission [4].

In 1941, when the Second World War came to Ukraine, the Institute was evacuated to the eastern cities of the USSR, and almost all fundamental research at the UIFT was suspended for the sake of focusing on defensive technologies. After the liberation of Ukraine from fascist invaders, nuclear research was resumed not only in the UIFT. In 1943, the Department of Nuclear Physics was established at the Kyiv Institute of Physics and Mathematics of the USSR Academy of Sciences. The main problem to be studied there was neutron-nuclear interaction in terms of the development of nuclear technology and, in particular, nuclear reactors.

At that time, around the world, nuclear physics research, figuratively speaking, were developing as a chain reaction. The nucleus studies and the discovery of new elementary particles gained such a scope and required such material costs for the experiments that it was too difficult, or even impossible for one country alone to carry out them. Therefore, a group of prominent physicists proposed international cooperation in the peaceful uses of atomic energy in order to consolidate the efforts of many countries for conducting larger-scale experiments in high-energy physics, given their ever-increasing value.

In 1954, 12 European countries signed an agreement to establish a European Organization for Nuclear Research (CERN), which today has grown into the largest and the most influential research organization in the world in the field of high-energy physics [5]. The center is located in Switzerland, near Geneva. As of 2020, its members are 23 countries, 6 countries have the status of associate members and several states and international organizations have the status of observers at CERN. In 2016, Ukraine also joined CERN as an associate member, which gave Ukrainian researchers, specialists, and students an unprecedented opportunity to join the practice of working and conducting research on unique equipment, at the highest level and to attend lectures given by prominent modern researchers. Ukrainian corporations and organizations got entitled to take part in CERN competitions, demonstrating to the world the high level of Ukrainian science, professionalism of researchers and specialists, and the course of Ukrainian industry for innovation and high technology [6].

In 1956, representatives of 11 countries in Eastern Europe and Asia signed an agreement in Moscow to establish an international intergovernmental research organization, the Joint Institute for Nuclear Research (JINR), to combine their research and material capabilities to study the fundamental properties of matter. The institute is located in Dubna (Russia) and was registered with the UN on February 1, 1957. After the collapse of the USSR, former union republics became independent states, most of which joined the JINR as sovereign countries. Thus, today, the JINR has counted 18 member states. Agreements on cooperation within the JINR framework at the governmental level have been concluded with Hungary, Germany, Egypt, Italy, South Africa, and Serbia [7]. The highest governing body of the Institute is the Committee of Plenipotentiaries of all 18 member states. The JINR research policy is determined by the Academic Council that, in addition to prominent researchers representing the member states, includes well-known physicists from Germany, Greece, India, China, the United States, France, and Switzerland.

The main areas of theoretical and experimental research in JINR are: particle physics, nuclear physics, and condensed matter physics. At the Institute, researchers for the first ever time have synthesized new superheavy elements of the Mendeleev Periodic Table with ordinal numbers 105, 113, 114, 115, 116, 117, and 118.

The Institute maintains scientific relations with more than 800 research centers and universities from 62 countries, has its representative in the Expert Committee of the European Science Foundation.

CERN and the JINR have had the mutual observer status since 2014: CERN is an observer in the Committee of Plenipotentiaries of the governments of the member states, and so is JINR in the CERN Council. JINR physicists are involved in the implementation of 20 CERN projects.

Ukrainian researchers have been actively involved in conducting fundamental and applied research in all three areas of JINR since its foundation. Among them, there was Mykola Bogolyubov, a world-famous scientist in the field of mathematics and theoretical physics, who was developed into an outstanding scientist at the University of Kyiv. Since the JINR establishment, he was elected Director of the Laboratory of Theoretical Physics, and later, since 1965, he was holding the Director's office of this international institute for 23 years.

Today, the JINR consists of 7 laboratories, each being commensurate with a separate R&D institution in terms of the scope of research. JINR laboratories are equipped with many unique experimental facilities that enable conducting research in various fields of physics, chemistry, biology, and medicine. In addition, new experimental complexes are being built to implement promising research programs [8].

Ukraine, as an independent state, has been a member of the JINR since 1991. This international organization has become a kind of research and technical base for Ukrainian nuclear researchers who are directly involved in conducting cutting-edge nuclear physics experiments. Young researchers gain practical experience working on unique equipment for research in condensed matter physics; at the JINR request, R&D institutions and corporations of Ukraine are engaged in the development and creation of devices and components for modern research facilities and complexes, without which it is impossible to imagine today's nuclear experiments. Novokramatorsk Machine-Building Plant has mastered the manufacture of unique products for elements of magnetic systems of cyclotrons and synchrotrons, *Lvivska Politekhnika* has created ferromagnetic sensors for measuring magnetic fields with unique accuracy at cryogenic temperature. Representatives of Karazin Kharkiv National University have been participated in the calculations of superconducting magnets for the unique collider NICA that is under construction at the JINR. Its main difference from the Large Hadron Collider operating at CERN is low particle energies [9].

The National Academy of Sciences of Ukraine has been working side by side with the JINR. Two members of the NAS of Ukraine are members of the JINR Academic Council (Associate Member of the NAS of Ukraine G.M Zinoviev and Full Member of the NAS of Ukraine B.V. Grynyov. Full Member of the NAS of Ukraine L.A. Bulavin is a member of the JINR Program Advisory Committee. B.V. Grynyov has been successfully acting as the Plenipotentiary Representative of the Government of Ukraine in the JINR highest governing body for over 10 years. Coordinating Council for Cooperation with JINR and CERN has been established at the National Academy of Sciences of Ukraine. The JINR and the Junior Academy of Sciences of Ukraine have been closely cooperating.

The JINR actively cooperates with 25 organizations of Ukraine, in particular with 15 academic institutions and 8 leading universities: researchers of the Institute for Nuclear Research of the NAS of Ukraine are doing theoretical calculations of diffraction interaction of hyperons with nuclei within R&D program of the JINR High-Energy Physics Laboratory; the Faculty of Physics of the Taras Shevchenko National University of Kyiv have been taking part in joint research to study the structure and physicochemical properties of various nanosystems: magnetic fluids, solutions of surfactants, and fullerenes; Kharkiv Institute of Physics and Technology of the NAS of Ukraine, National Research Center (former UIFT) has been doing theoretical research on experiments with the use of polarized beams and polarized targets, etc. [10]. For many years, the JINR has been fruitfully collaborating with the Institute of Scintillation Materials of the NAS of Ukraine (ISMA). Once, plastic scintillators were developed for the CDF spectrometric complex at Tevatron Fermilab (Fermi National Accelerator Laboratory, USA) [11]. Subsequently, based on them, advanced scintillators were created for the ATLAS experiment at CERN. ISMA specialists have made more than 20,000 scintillation strips, each having a length of 7 m, of which JINR researchers have created a unique detector system for international neutrino oscillation experiment (OPERA project, Italy). Also, ISMA has developed and manufactured unique crystals for scintillation detectors used in neutrino experiments on rare meson decays at an accelerator in Zurich, Switzerland.

This list of researches within the framework of cooperation between the JINR and R&D institutions and universities of Ukraine may be extended. It should be noted that most works on the creation of unique new materials and technologies have been made at the expense of Ukraine's contributions to the JINR, instead of their payment in foreign currency. The agreement signed in March 2011 by the Plenipotentiary Representative of the Government (PRU) of Ukraine in the JINR B.V. Grynyov and the JINR Acting Director M.G. Itkis on the launch of the JINR-Ukraine Program in Theoretical Physics (Bogolyubov Program) significantly expanded the cooperation of Ukrainian researchers with the JINR. The purpose of the Program is to support bilateral and multilateral cooperation in the field of theoretical and mathematical physics and related disciplines. Thus, it provides support for fundamental research in the areas of high-energy physics, physics of interaction of heavy ions, the theory of nuclear structure, the theory of condensed matter and new materials, modern mathematical physics, and others. To achieve this goal, the parties have undertaken to provide financial support for high-level research projects, to support mutual exchanges of scientists, to encourage talented young researchers to participate in cutting-edge projects, to organize and to support the training of bachelors, masters and graduate students engaged in JINR-Ukraine programs, to help organize summer schools, student scientific seminars and other thematic events, to encourage cooperation of researchers of the Parties with well-known researchers from other countries. The Bogolyubov Institute for Theoretical Physics of the NAS of Ukraine has taken responsibility for efficient management of the Bogolyubov Program budget.

The JINR plan for research and international cooperation for 2020, foresees cooperation between Ukrainian organizations and specialists and the JINR in the following fields: theoretical physics (5 projects), elementary particle physics and relativistic nuclear physics (8 projects), nuclear physics (4 projects), physics of condensed matter, radiation, and radiobiological research (4 projects), networks, computing, computational physics (1 project), and academic program (1 project) [10, 12].

Given the opportunities for creative growth of young Ukrainian physicists, a particularly interesting area of cooperation between Ukraine and the JINR is training programs through which Ukrainian researchers have access to unique physical equipment, participate in modern research in nuclear physics, condensed matter physics, radiobiology, and so on.

From the first years of the JINR's existence, its top managers started pursuing a policy to attract talented young researchers to the Institute. They realized that undergraduate students shall be trained at the Institute laboratories, under the guidance of leading Institute researchers, with the use of all available state-of-the-art equipment. To begin with, D.I. Blokhintsev, the first Director of the Institute and V.I. Wexler, the Director of the Laboratory of High Energies opened branches of the departments they chaired at the Moscow State University, the Branch Department of Theoretical Nuclear Physics and the Branch Department of Elementary Particles, respectively.

Later it became clear that the branch departments could not meet the needs of the JINR in training a wide range of majors that were necessary for ensuring R&D activities of the Institute at the proper level and take into account the applications of other member states for internship of their young researchers and their involvement into creative research at the Institute. Given this, in 1991, the JINR, together with the leading Moscow higher educational institutions, established the JINR Training and Research Center (TRC). Since 1993, the TRC has been a JINR structural unit entrusted with organization, support, and development of the Institute's independent curriculum. In 1994, the *Dubna* international university of nature, society, and human being was established in Dubna, with the JINR involved, and in 1995, the JINR opened its own postgraduate education/fellowship program, the activities of which are supervised by the TRC. Today, the TRC provides targeted training for students from the member states, creates special lecture courses for undergraduates, and conducts important international events, including the International Summer Student Internship. Every year, several hundred senior and junior students of universities from the JINR member states are trained within various educational programs at the TRC. The TRC plays an important role in the activities aimed at students: conducting research conferences for students, workshops, tours to the basic facilities of the JINR, and so on. Workshops at the Institute's facilities are organized annually for university students of the JINR member countries.

In addition to the traditional forms of educational process, the TRC practices regular summer schools and specialized seminars, which are attended by students of the Institute and from Western Europe, Egypt, South Africa, and others. For future physicists from developing countries, the

Participants of the 7th annual reporting seminar of the Ukrainian researchers who work at the JINR in the research field of the Plenipotentiary Representative of the Government of Ukraine in the JINR

JINR provides scholarships to study at the Dubna International University. Among the teaching staff of the university are leading researchers of the Institute, world-class scientists. The JINR annually holds up to 10 major conferences, more than 30 international scientific meetings and seminars, traditional schools of young researchers, etc. [14].

In the community of JINR researchers, especially among the young researchers and interns, it is common to create informal national associations whose members are united by national traditions and interests, in addition to scientific issues. Over the years of its existence, in the JINR there have been established both relationships within national groups and forms of cooperation with between them. The Ukrainian national group is historically considered one of the most numerous associations [9]. Since 2011, on the initiative of the Plenipotentiary Representative of the Government of Ukraine in the JINR B.V. Grynyov, the Ukrainian group has launched annual scientific reporting seminars for Ukrainian researchers sent to the JINR, the results of which largely affect the decision of the Plenipotentiary Representative to extend or to terminate contracts for work at the JINR.

The Ukrainian national group in the JINR has become an example for other groups in conducting similar reporting seminars (Figure). Currently, such seminars are going mainstream among researchers in Poland, Kazakhstan, Azerbaijan, and other countries. To improve coordination and to increase efficiency, the group members elect a group leader at their meetings. Since 2015, the group leader for 5 consecutive years has been D.V. Solovyov, a senior researcher at the Franko Laboratory of Neutron Physics (LNF).

The majority of Ukrainian researchers who work at the JINR in the same research field as the PRU carry out research in the LNF. Among the LNF research directions there is materials science represented by the Department for Neutron Studies of the Condensed Matter. The Department uses neutronography techniques to study both crystalline bodies and soft matter. In particular, the structure of multicomponent liquid systems at the superatomic level is studied by the methods of low-angle neutron scattering and neutron reflectometry. The neutron scattering facility built around the IBR-2 pulse reactor has enabled measuring the characteristic sizes of inclusions (in colloidal systems, powders, and solid matrices) in the scale from 1—2 nm to 100 nm, which ensures the popularity of diffraction methods for solving problems of molecular physics and colloid chemistry [15]. Ukrainian researchers are regularly involved in the state-of-the-art laboratory research in the field of materials science, which has yielded many interesting results: dispersion curves of lipid membranes have been studied by the method of inelastic scattering of high-resolution X-rays; the existence of acoustic longitudinal and transverse phonon modes in lipid membranes, which testify to the presence of two different mechanisms of sound propagation has been proved; based on the obtained experimental data, a model of the lipid membrane structure according to which the passive transport of molecules through the membrane is realized by their transit between the areas of local ordering has been proposed [16]; the collective oscillations of molecules in two-component lipid membranes with cholesterol have been studied; the existence in such systems of optical phonon mode that is associated with antiphase oscillations of the lipid molecule and the cholesterol molecule in the lipid pair has been proven; for the first time, it has been found that the optical phonon mode in the lipid membrane has a gap because of the presence of lipid complexes, the size of which does not depend on the concentration of cholesterol in the membrane [17]; the behavior of lithium elements that are currently widely used in various fields of technology has been studied. The studies have shown that the lithium battery electrodes degrade in two stages: firstly, on the electrode surface, a dense layer of enriched lithium is formed from the products of chemical interaction between lithium ions and solvent, and at the second stage, a transition layer begins to form, which indicates the beginning of appearance of large mesoscopic inhomogeneities (needle structures). When modifying the electrolyte by adding a non-electroactive substance, a strong inhibition of growth and significant changes in the composition of the near-surface layer are reported.

Using the method of low-angle neutron scattering (LANS), the JINR researchers have studied the filling of carbon cathode wells with the final product of the electrochemical reaction — lithium peroxide — when discharging lithium-oxygen cells. This type of battery has a much larger capacity as compared with more widely used lithium-ion batteries. However, their use is complicated by many difficulties in blocking the diffusion of oxygen in the electrolyte because of clogging of the wells with lithium peroxide. LANS data have made it possible to combine nanometer-scale changes in the cathode with the electrical characteristics of the cells and helped to identify the mechanisms that limit cell capacity [18].

Ukrainian experts are directly involved in international studies of the crystal and magnetic structures of compounds based on barium and strontium hexaferrites [19] and double perovskites [20]. The evolution of the crystalline and magnetic structures of solid hexaferrites (Ba/SR) $Fe_{12-x}In_xO_{19}$ (x = 0,1—1,2) has been studied by X-ray and neutron diffraction methods. The degree of structural disorder of the Ba_2FeMoO_6 sample has been determined by the X-ray diffraction analysis method from the ratio of the integral intensities of diffraction peaks $I_{(101)} = (I_{(200)} + I_{(112)})$ The magnetoresistive effect in a wide range of temperature (10—300 K) and the intensity of magnetic field induction (0—12 T) has been measured. The influence of temperature on the spin polarization of Ba_2FeMoO_6 charge carriers has been established

The structural changes of ferrofluids caused by an electric field have been studied. It has been found that these changes in the ferrofluid viscosity are similar to the magnetically viscous effect and are caused by the effective electric polarization of nanoparticles in solution. It has been shown that this electro-reological effect shall be taken into account when choosing ferrofluids for use in high-voltage engineering, because it can affect the thermomagnetic convection or dielectric breakdown characteristics [21]. The theoretical calculations have shown that the homogeneous distribution of dielectric particles in a dielectric carrier can become inhomogeneous under the action of an electric field. The transition to a heterogeneous distribution has the threshold nature. The critical value of the applied field increases as the temperature grows, the number of particles and their radius decrease, and the difference between the dielectric constants of the particle and the medium is leveled. The distribution of nanoparticle concentration in accordance with the proposed theoretical approach is in good agreement with the experimental observations of the inhomogeneous distribution of ferrofluid particles under the action of an external electric field [22].

Over the last 10 years, researchers of the Ukrainian national group have defended more than ten PhD theses and three doctoral dissertations. In 2013, a series of joint works by young researchers of the Taras Shevchenko National University of Kyiv and the JINR was awarded with the Prize of the President of Ukraine. The active involvement of Ukrainian researchers in the implementation of mega-science project *NICA*, a world leader in research on physics of heavy high-energy nuclei is also noteworthy. More than 300 researchers and 70 R&D institutions from 32 countries have been already engaged in its preparation. The purpose of the project is to conduct fundamental research works not realizable in other world accelerating centers, which aim primarily at studying the superdense nuclear matter that had existed in the early stages of evolution of the universe and exist in the bowels of neutron stars, as well as at implementing a wide range of innovative and applied projects [12].

These examples clearly demonstrate the fruitfulness of cooperation with the JINR for Ukrainian scientists, especially for young researchers. Thanks to cooperation, there appears an opportunity to conduct experiments on unique equipment that Ukraine could not have built or manufactured alone. Another important factor in favor of this cooperation is numerous large international experiments of the European Union, the United States, Germany, France, and Italy, in the implementation of which nuclear researchers of Ukraine are directly involved through the JINR. It is difficult to quantify the benefits of this cooperation for teachers, high school students, and students of the Ukrainian community.

A serious obstacle to obtaining the highest results from cooperation is that Ukraine has not paid membership fees to the JINR since 2014. Although in 2017, the long-term efforts of the Plenipotentiary Representative of the Government of Ukraine in the JINR resulted in fixing Ukraine's debt to the JINR, the lack of current payments significantly reduces the possibility of sending Ukrainian researchers to this institution. For example, in 2015, the Plenipotentiary Representative of the Government of Ukraine sent 31 researchers to the JINR, while in 2020, their amount went down to 20. Because of the nonpayment, according to the JINR Statute, the Institute cannot send Ukrainian young researchers on business trips abroad to leading research centers in other countries, and the number of delegates from Ukraine to research and educational events regularly held at the JINR, etc. decreases.

The only hope is that Ukraine, having recovered from the coronavirus and the crisis associated with it, will be able to fulfill its financial obligations under international agreements, including those on conducting research, and the Ukrainian national group in the JINR will regain its leading place as one of the most effective and influential groups among the member states of one of the largest interstate scientific organizations.

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Received 23.04.20
Revised 26.06.20
Accepted 07.07.20

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СПІВРОБІТНИЦТВО З ОІЯД — ЗАПОРУКА РОЗВИТКУ ЯДЕРНОЇ ФІЗИКИ В УКРАЇНІ

Вступ. На сьогодні міжнародна організація Об'єднаний інститут ядерних досліджень (ОІЯД) є своєрідною науково-технічною базою для українських фахівців-ядерників, які безпосередньо беруть участь у проведенні новітніх ядерно-фізичних експериментів.

Проблематика. Важливим аспектом міжнародного співробітництва науковців України у галузі досліджень з ядерної фізики і матеріалознавства є об'єднання науково-технічних і фінансових ресурсів країн для створення міжнародних науково-дослідних організацій і реалізації масштабних проєктів з сучасних проблем науки і техніки.

Мета. Аналіз факторів, що сприяють розвитку досліджень в галузі ядерної фізики та супутніх дисциплін в Україні, а також залученню українських учених до міжнародних дослідних процесів та окреслення перспектив на майбутнє.

Матеріали й методи. Аналіз напрямів наукових досліджень ОІЯД та огляд досягнень українських вчених, зокрема молодих фахівців, у реалізації міжнародних проєктів з ядерної фізики і супутніх дисциплін.

Результати. Проаналізовано витоки досліджень з ядерної фізики в Україні, шлях розвитку міжнародного співробітництва та його вплив на підготовку вчених і фахівців цього наукового напрямку. Наведено приклади наукових результатів діяльності українських фізиків-ядерників, позитивного впливу співпраці українських наукових установ та підприємств з ОІЯД на творчі та інноваційні процеси, зокрема в галузі розробки і вивчення нових високотехнологічних матеріалів. Окреслено перспективи подальшої співпраці.

Висновки. Співробітництво з ОІЯД дає українським ученим можливість доступу до сучасних методів проведення ядерно-фізичних досліджень, до унікального наукового обладнанням провідних міжнародних наукових центрів при плануванні і реалізації масштабних експериментів з ядерної фізики, вивчення проблем існування Всесвіту. Викладачам, студентам та учням з України відкриваються додаткові можливості роботи з новітніми методами, сучасним обладнанням та інноваційними підходами в галузі науки і техніки.

Ключові слова: ядерна фізика, дослідження, співробітництво.