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SCIENTIFIC ACHIEVEMENTS OF THE BOGOLYUBOV INSTITUTE FOR THEORETICAL PHYSICS OF THE NAS OF UKRAINE (to the 55th anniversary of its foundation)

In January 2021, 55 years passed since the foundation of the Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine (NASU). The creation of the center of theoretical research was initiated by the outstanding theoretical physicist and mathematician, Academician Mykola Mykolayovych Bogolyubov. He began his creative path in Kyiv, where he became a famous theorist. Mykola Mykolayovych knew Ukrainian scientists very well and highly appreciated the level of their studies. Therefore, naturally, he got an idea to join theorists under the same roof. In the creation of a new institute, he was assisted by his disciple V.P. Shelest. The support obtained from the President of the Academy of Sciences of the Ukrainian SSR B.Ye. Paton and the supreme party leader of Ukraine P.Yu. Shelest was very important.

Four years had passed since 1966, and in 1970, on the occasion of the 15th Rochester Conference on High Energy Physics, which was held in Kyiv, the Institute got a new building in the Theophania tract. Everything – from the choice of the site for the new building and the interior decoration to the formation of the scientific research directions and the selection of personnel – took place with the participation of Mykola Mykolayovych. He became the first director of the Institute (in 1966–1972). At first, such research directions as the nuclear theory, the theory of elementary particles, and the quantum field theory were selected. Accordingly, three departments were created: the department of the nuclear theory (headed by O.S. Davydov), the department of the theory of elementary particles (headed by A.N. Tavkhelidze and, later, by V.P. Shelest), and the department of mathematical methods in theoretical physics (headed by O.S. Parasyuk). Later, the area of research was extended and new departments were created. In due time, three of them were transformed into separate institutes. In particular, the department of the Statistical Theory of Condensed Matter headed by I.R. Yukhnovskii – it was a subdivision of the Institute in 1969–1990 – became the Institute for Condensed Matter Physics of the NASU, the department of Hadron Theory (1977–1979) headed by Yu.M. Lomsadze became a nucleus of the Institute of Electronic Physics of the NASU, and the department of Solid State Theory (1982–1985) headed by V.G. Bar'yakhtar was separated into the Institute of Magnetism of the NASU.

The new deal initiated by M.M. Bogolyubov attracted skilled theorists from other institutions. Several years later, the Institute staff included well-known experts in the quantum field theory, the theory of elementary particles, the gravitation theory, the theory of nucleus and nuclear reactions, the solid state theory, the plasma theory, and the mathematical physics. Among them, these were the Academicians O.S. Davydov, O.S. Parasyuk, O.Z. Petrov, O.G. Sitenko, and I.R. Yukhnovskii, the Corresponding Members V.P. Shelest and P.I. Fomin, the doctors of sciences in physics and mathematics V.Ya. Antonchenko, I.P. Dzyub, G.F. Filippov, V.P. Gachok, Yu.B. Gaididei, L.L. Jenkovszky, V.F. Kharchenko, A.U. Klimyk, M.A. Kobylinsky, V.M. Loktev, Yu.M. Lomsadze, A.F. Lubchenko, V.I. Ovcharenko, D.Ya. Petryna, E.G. Petrov, I.V. Simenog, A.I. Steshenko, B.V. Struminsky, I.I. Ukrainskyi, I.P. Yakymenko, G.M. Zinovjev.

It is worth mentioning some results from the world's treasury of scientific achievements, which are associated with the names of the Institute founders. These are the Bogolyubov–Parasyuk renormalization method in the quantum field theory; the Davydov splitting in the light absorption spectra of molecular crystals; the Sitenko–Glauber diffraction theory of nuclear processes; the Petrov classification of gravitational fields; the color of quarks proposed by M.M. Bogolyubov, B.V. Struminskyi, and A.N. Tavkhelidze; and the P.I. Fomin model describing the birth of the Universe from the physical vacuum. Shortly after its foundation, the Institute became well known throughout the world. It attracted young talented scientists who considered themselves fortunate to become its employee or graduate student.

After M.M. Bogolyubov, the Institute was headed by the distinguished theoretical physicists O.S. Davydov (in 1973–1988) and O.G. Sitenko (in 1988–2002). There appeared new areas of research, seminars were actively held, and dissertations were defended. In due time, new scientific schools have been formed: the M.M. Bogolyubov and O.S. Parasyuk school of mathematical physics and quantum field theory, the O.S. Davydov school of the solid state theory and the theory of nucleus, the O.G. Sitenko school of theoretical nuclear physics and plasma theory, and the P.I. Fomin school of relativistic astrophysics, cosmology and elementary particles. At present, the Institute consists of seven scientific departments and six laboratories. Its staff includes 93 scientists, among which there are 42 doctors of sciences (including 3 Academicians and 5 Corresponding Members of the NASU) and 39 candidates of sciences. The author of this article has been the director of the Institute since 2003. Our research covers various domains of theoretical physics ranging from the microworld to the Universe. These are astrophysics and high-energy physics, the relativistic and quantum cosmology, the theory of nuclear systems and the quantum field theory, the theory of nonlinear processes in condensed media and plasma, the structure of macromolecules, molecular electronics, statistical and mathematical physics and their applications to economics. Let us recall some of the results recently obtained by our research workers.

G.M. Zinovjev has considered the generation of intensive synchrotron radiation at relativistic collisions of heavy ions as a result of the interaction between quarks and a collective color field that provides their confinement. A comparison of the calculated spectrum of photons characterized by a large transverse momentum with experimental data demonstrates the feasibility of this type of radiation. An azimuthal anisotropy in the angular distribution of dileptons was revealed, and it was shown that this feature can provide a probe of quark-gluon plasma.

M.I. Gorenshtein has proposed an extension of the ideal hadron-resonance gas model, which takes into account the attractive and repulsive van der Waals interaction between baryons. The model describes the liquid-gas phase transition and the critical point in the nuclear matter at low temperatures and high baryon densities. Taking the interaction between baryons into account leads to qualitative changes in charge fluctuations. In the interval of transition temperatures (140–190 MeV), the calculation results turned out close to those obtained in the lattice quantum chromodynamics. The model predicts a specific behavior of proton number fluctuations at relativistic nuclear-nuclear collisions.

With the help of developed formalism K.A. Bugaev derived a new equation of state for mixtures of hadrons and light nuclei. It became a basis for the model of a hadron resonance gas which described with high accuracy the multiplicities of baryons, mesons, and light (anti-, hyper-)nuclei measured in the central collisions of heavy ions by the ALICE CERN Collaboration at the center-of-mass collision energy equal to 2.76 TeV, and by the STAR BNL Collaboration at the center-of-mass collision energy to be 200 GeV.

A hydrokinetic model describing the evolution of strongly interacting matter that is created at relativistic collisions of heavy ions in modern accelerators has been proposed by Yu.M. Sinyukov, S.V. Akkelin, and V.M. Shapoval. This model recovers the spatiotemporal picture of particle production. The behavior of the observed quantities at the collisions of lead ions (at an LHC collider energy of 5.02 TeV per nucleon pair) and gold ions (at an RHIC collider energy of 200 GeV per nucleon pair) was calculated.

The research by Yu.I. Izotov and N.G. Guseva was aimed at determining the main ionization sources of intergalactic matter. During the Universe evolution, there were several global transformations of the matter from one state to another one. The last of those transformations was the secondary ionization of the Universe, when the latter was from 200 to 1000 million years old. But the main sources of intergalactic matter ionization were uncertain. It could be young galaxies provided that the ionizing radiation was capable to go out in large quantities from the galaxy into the intergalactic space and ionize the neutral gas. An international team headed by Yu.I. Izotov has analyzed a huge body of observational data, the results of which showed that young galaxies can completely ionize the matter in the Universe.

On the basis of the combined analysis of classical spheroidal dwarf galaxies, D.O. Savchenko and A.V. Rudakovskyi have determined a new mass limit for the fermionic particle of dark matter. While simulating the kinematics of eight such galaxies, they used the halo density profile of the fermionic dark matter, which was calculated making use of a new method proposed three years ago. According to their calculations, the minimum mass of the fermionic dark matter particle should be at least twice as large as the values that were obtained earlier by analyzing separate objects.

O.M. Gavrylyk, A.V. Nazarenko, and M.V. Khelashvili have generalized the model of cold Bose-condensate dark matter by introducing bosons with μ-deformed thermodynamics into consideration. Taking the modification of the theory of gravitation at subgalactic scales into account allowed them to estimate more precisely the mass of dark matter in dwarf galaxies and improve the description of the observed rotation curves. They paid attention to the effects resulting in the structuring of dark matter and demonstrated the role of correlations on the scales comparable with the galactic ones.

New features of spin-orbit interaction in modern functional materials have been discovered by V.M. Loktev, L.S. Bryzhik, and O.O. Yeremko. Based on the Dirac relativistic equation, they considered the influence of an external potential on the electron spin states. A generalized spin-orbit interaction operator was found in the nonrelativistic approximation. This operator contains the Thomas–Frenkel correction term, as well as a new, previously unknown one. The dependence of the state of a system of particles on their spins, which was predicted by the scientists, was confirmed experimentally. The found correction is important for improving modern technologies, in particular, in spintronics, where the control over the device properties is performed via spin-orbit interactions.

Yu.B. Gaididei and V.P. Kravchuk have developed the theory of Néel magnetic skyrmions (topological solitons) on curved ferromagnetic films. They showed that the skyrmion can be effectively pinned at a local film curvature and found the spectrum of its spin perturbations. The inverse effect, when the skyrmion induces a deformation in the elastic ferromagnetic film, was also considered. On the basis of the equation derived for the skyrmion motion on a curved surface, the scientists predicted that the Néel skyrmions can drift, with the effective driving force being proportional to the gradient of the film curvature. Because of their topological structure, magnetic skyrmions are stable with respect to external perturbations, so they are considered as memory and logic elements for spintronics.

A method to study the band structure in new materials, which can be used to detect topological phase transitions, has been proposed by V.P. Gusynin and S.G. Sharapov. They showed that the characteristic feature of a two-dimensional system undergoing Lifshitz topological transitions is the appearance of spikes of entropy per particle with a quantized amplitude at low temperatures. The dependence of the entropy per particle on the chemical potential exhibits a dip-and-peak structure in the temperature vicinity of the Dirac point. These features can be detected in transport experiments where the temperature is modulated in gated structures.

Ya.O. Zolotaryuk and I.O. Starodub have studied the dynamics of a Josephson vortex in a large symmetric array of point Josephson junctions containing a ferromagnet in their structure. Under certain conditions, there appears a new mode of free nonradiative vortex motion in such a system, i.e. there arise the so-called "nested solitons" moving at a certain constant velocity. The parameters were found for such solitons moving in an array, where the inductive coupling takes place not only between the nearest neighbor cells but also with the next ones. This interaction can be both destructive and favorable for the formation of nested solitons. The existence of nested solitons can be verified by measuring the current-voltage characteristics of the Josephson junction array.

E.G. Petrov has developed a modified super-exchange model describing the formation of a nonresonance tunnel current through a molecular wire consisting of a regular chain and terminal units. A corresponding interpretation was given to the dependence of the experimental current-voltage characteristics of alkane chains on the number of C–C bonds. The criteria were also formulated for the validity of the simplest model with a rectangular barrier and an effective tunneling electron mass, as well as for its application to the processing of experimental data.

A theory of stimulating the mechanical rotation of a metal nanoparticle arranged in a medium with a given dielectric constant by means of ultrashort laser pulses has been developed by M.I. Grygorchuk. He proposed a polarization mechanism governing the generation of a rotational force in a frequency interval close to the surface plasmon resonances. Under the laser field action, an asymmetric metal nanoparticle becomes polarized and transforms into a dipole. It was shown that the dipole rotation direction can be controlled by varying the wavelength of incident light.

Yu.O. Sitenko has developed a theory of chiral effects in the hot dense relativistic spinor matter that is spatially confined in a strong magnetic field. He showed that the chiral magnetic effect disappears in this case, and the chiral separation effect depends not only on the chemical potential but also on the temperature and the boundary conditions in the system. This result points to the important role of boundaries for such physical systems as compact astrophysical objects, the reaction products obtained at relativistic collisions of heavy ions, and novel materials known as Dirac and Weyl semimetals.

The polarization effects at the interaction of two charged dusty particles in a plasma environment were studied by the author of this paper. An interesting feature is that the potential of a graine charged by plasma currents is long-range over long distances, unlike the potential of a particle with a fixed charge. On the basis of the developed theory of large-scale electromagnetic fluctuations in weakly ionized dusty plasma, the spectra of collective fluctuations were calculated with account for particle collisions. The obtained results are important for improving the methods of dusty plasma diagnostics.

A substantial contribution to the theory of liquid crystal colloids was made by B.I. Lev. He predicted the existence of a Coulomb-type interaction between colloidal particles in a nematic liquid crystal, which was observed in experiments. This interaction is a result of the violation of all symmetry elements in the elastic-field director distribution around a single particle, which is induced by the boundary conditions at the surfaces of the cell and the particle itself.

V.I. Zasenko, O.M. Chernyak, and the author of this article have studied the transport of charged particles across a magnetic field under the influence of random electric fields. On the basis of the developed formalism, an analytical description of the transport characteristics for different modes from diffusion to convection was made. The calculated transport coefficients were consistent with the simulation results in a wide range of correlation times and Larmor radii. Understanding the factors influencing the transport rate helps to increase the time of plasma confinement in magnetic traps.

Yu.A. Lashko, G.F. Filippov, and V.S. Vasylevsky have found that the polarization of the binary subsystems ^{2}He and ^{8}Be (changes of their shapes and sizes at the interaction with the third cluster) substantially enhances the mutual attraction of clusters in the ^{10}Be compound system, which gives rise to a considerable energy reduction in both the bound and resonance states. In lots of cases, the cluster polarization also diminishes the width of the resonance states of the three-cluster system ^{10}Be, thus increasing their lifetime. The results are in good agreement with the experimental data for the states in the discrete and continuous spectra of the ^{10}Be nucleus.

A new approach to the description of quantum atmospheric channels has been proposed by A.O. Semenov and D.Yu. Vasylyev. Their theory combines the atmospheric and quantum optics and can form a basis for such a direction as quantum optics of turbulent atmosphere. The scientists considered the properties of quantum channels with various configurations, in particular, the intra-urban and satellite ones. They also took atmospheric precipitation into account. The theoretical results were found to be in good agreement with experimental data. Several quantum communication protocols in atmospheric channels, as well as the transmission of nonclassical light properties associated with quantum teleportation, Bell nonlocality, and Gaussian entanglement, were analyzed.

The deactivation mechanisms of the DNA macromolecule in cancer cells under the action of high-energy ion beams have been considered by S.N. Volkov, D.V. Pyatnytskyi, and O.O. Zdorevskyi. According to their hypothesis, the passage of ions through living tissues is accompanied by the formation of the products of the aqueous medium radiolysis, among which hydrogen peroxide molecules are the most long-lived ones. The interaction of hydrogen peroxide with the atomic groups of the DNA macromolecule was studied and the effective lifetime of those molecules in a vicinity of the double helix was calculated. The calculations showed that hydrogen peroxide molecules form complexes with atomic DNA groups. Those complexes are more stable than water molecules and, at a certain concentration, can block the genetic activity of DNA in cancer cells.

S.M. Perepelytsya studied the interaction of natural polyamines with the DNA macromolecule using molecular dynamics simulations. The polyamines molecules were found to be localized mostly in the minor groove of the double helix in the region with the specific sequence of nucleotides of A-tract type. These results agree with experimental data and explain the preferential localization of polyamines molecules in fixed DNA sites.

The results presented above illustrate only a small part of the scientific achievements of the Institute. About a thousand scientific articles have been published during the last five years (more than 80% of them in international scientific journals), as well as ten monographs and three collections of scientific papers. The works of our researchers are recognized by the scientific community both in Ukraine and abroad, as is evidenced by their high citation level. The Institute also promotes the publication of works made by physicists from other institutions. The Institute is the basic organization of the Ukrainian Physical Journal, the scientific journal of the Department of Physics and Astronomy of the NASU.

Our Institute continues to cooperate with leading international centers, such as CERN, the Joint Institute for Nuclear Research, the Abdus Salam International Center for Theoretical Physics (Italy), as well as a lot of universities and laboratories throughout the world. In 2018, the Center for collective usage "Resource Center for Grid and Cloud Technologies" was created on the basis of the Institute. It was included into the European grid network of the European Grid Infrastructure (EGI) project, the common European and world research and information space.

During the last 5 years, the Institute co-hosted 50 scientific meetings, including about 20 international conferences. A significant event was the conference dedicated to the 110th anniversary of Academician Mykola Bogolyubov's birth. On this occasion, the book "Creator of Theoretical and Mathematical Physics" was published in 2019. Annually, the Institute holds readings dedicated to the memory of our outstanding teachers M.M. Bogolyubov, O.S. Davydov, O.G. Sitenko, and P.I. Fomin; seminars of the Kyiv branch of the Ukrainian Biophysical Society; thematic seminars in the departments; and conferences of young scientists. The Institute organizes schools on theoretical and mathematical physics for gifted youth, and it participates in annual science festivals. Our researchers lecture more than 20 courses at Kyiv universities. In 2017, on the basis of the Institute, the Department of Theoretical and Mathematical Physics was created at the Kyiv Academic University.

The activity of Institute's scientists was awarded the State Prize of Ukraine in science and engineering, the V.I. Vernadsky Gold Medal, several nominal awards of the NASU, as well as awards for young scientists of the President of Ukraine and the NASU. Scientists and the Institute itself have repeatedly received the Web of Science Awards.

Several generations of physicists grew up at the Institute. At present, those who have been here from the very beginning and those who have come recently are working together. Great changes in life have occurred since the time of the Institute foundation. But devotion to science is the invariable factor that unites generations, being a guarantee of the relentless progress of science in both favorable and hard times.

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