Condensed Matter Physics

JINR has a unique base for experimental research (the IBR-2 pulse reactor and the DRIBs-III accelerator complex) allowing its scientists to conduct basic and applied research in the field of the physics of condensed state of matter and in adjacent areas — biology, medicine, materials science, etc., aimed at studying the structure and properties of nanosystems and new materials, biological objects, and biotechnologies.

I. Neutron scattering research methods

Neutron scattering research methods make it possible to obtain comprehensive information on the atomic and magnetic structure and dynamics of materials at the atomic and sub-atomic levels. Due to the peculiarities of interaction of slow neutrons with matter, neutron scattering is the most powerful technique to locate light atoms among heavy ones, to study the distribution of elements with close atomic numbers, and to investigate isotope substitution processes and magnetic structures.

Expected results and realization periods:

1. Physics and chemistry of novel functional materials

1.1. Determination of the parameters of atomic and magnetic structure of bulk and nanostructured functional materials demonstrating interesting physical phenomena and prospective for technological applications in a wide range of thermodynamic parameters; determination of the influence of structure parameters and cluster formation on physical properties — 2017–2023.

1.2. Determination of microscopic mechanisms giving rise to the magneto-electric effect in complex multiferroic oxides — 2019–2023.

1.3. Determination of the parameters of crystal and magnetic structures of new forms of simple transition metal oxides formed under extreme conditions — 2017–2021.

1.4. Determination of the effect of electrode microstructure on charging/ discharging processes in compact electric current sources — 2017–2021.

1.5. Determination of atomic structure and vibrational spectra of molecular complexes: ionic-molecular inclusive materials and complexes with electric charge transfer, structural and dynamical parameters of hydrogen bonding in bioactive materials — 2017–2019.

2. Physics of nanosystems and nanoscale phenomena

2.1. Clarification of proximity effects in magnetic layered nanostructures and analysis of their magnetic properties in permanent and varied magnetic fields — 2017–2019.

2.2. Determination of the structure of a number of promising nanosystems on the basis of composite carbon and silicon-containing materials including those based on fullerenes, nanodiamonds and their bioactive derivatives — 2017–2021.

2.3. Study of nanosystems by the positron annihilation spectroscopy (PAS) method. The PAS method of material study allows detailed information to be obtained about the atomic structure of materials at the atomic and subatomic levels. The main area of research is diagnostics of defects (vacancies and dislocations) in the surface layers, to a depth of about 1–20 mg/cm^2 (1 to 25 microns in iron), in metals, alloys, polymers, semiconductor, carbon and other materials. The PAS set-up, developed at JINR using a unique source of monochromatic positrons, allows one to obtain the distribution of defects over the sample's depth and (in one of the method versions) to distinguish between types of defects. The main application of the PAS method is to study near-surface layers of materials — metals and semiconductors, in which various ions are implanted and which alters the properties of these materials. This relates, in particular, to materials modified by the implantation of heavy ions or subjected to ion or neutron irradiation. Such studies open up the possibility of experimental study of the mechanism of radiation damage of materials, which is practically important for structural materials in atomic power engineering, semiconductor components in microelectronics (including space vehicles), etc. The studies by PAS of porous materials are of special interest because this method is one of the few allowing one to detect pores with dimensions of the order of a few nanometers. Such studies open new opportunities associated with the study of new polymeric materials and membranes, as well as technologies for the development of chemical catalysts.

2.4. Structural diagnostics and "in-operando" studies of physical process at electrochemical interfaces — 2017–2020.

3. Physics and chemistry of complex fluids and polymers

3.1. Comparative analysis of structural aspects of stabilization of disperse systems and complex liquids including biorelevant systems with nonmagnetic and magnetic nanoparticles in the bulk and at the interfaces — 2017–2023.

3.2. Determination of structural characteristics of magnetic elastomers and carbosilane dendrimers holding promise for technological applications — 2017–2019.

4. Molecular biology and pharmacology

4.1. Determination of structural characteristics of lipid nanosystems modeling the upper skin layer of humans and mammal animals to study the transport of pharmacological drugs through the skin. Determination of the phospholipid transport nanosystem morphology — 2017–2021.

4.2. Determination of structural and functional characteristics of biological nanosystems: protein macromolecules, DNA, RNA and their complexes — 2019–2023.

4.3. Analysis of structural features of the interaction of nanoparticles and functional complexes on their basis with biological macromolecules in the bulk and at the interfaces, the effect of the structural and cluster stability of nanosystems on the biocompatibility of complex solutions — 2017–2020.

5. Materials science and engineering

5.1. Determination of residual stresses in engineering materials for nuclear reactors, industrial materials and products — composites, reinforced systems, metal ceramics, shape memory alloys — 2017–2023.

5.2. Determination of characteristics of the internal structure of meteorites and construction of 3D models of their main fractions — 2020–2023.

5.3. Analysis of metamorphic, geodynamic and evolution processes in the lithosphere using data about the texture of deep and near-surface rocks. Exploration of the seismic anisotropy origin — 2017–2021.

5.4. Development of the model of solid polycrystalline materials for prediction of their elastic, strength and thermal properties, taking texture, inclusions, pores and microcracks into account – – 2021–2023.

II. Optical methods of research

In the past few years, the condensed matter investigations have been supplemented and enriched by Raman scattering spectroscopy and microscopy on the basis of modern confocal laser scanning microscope "CARS".

Research fields:

Raman spectroscopy and microscopy. Spectral and microscopic studies of membrane proteins, cells and organisms.

Upconversion luminescence. Investigation of structural and luminescence characteristics of nano-glass-ceramics.

Expected results:

1. Determination of the role of lipids and detergents in the crystallization of membrane proteins by Raman and CARS spectroscopy.

2. Creation of in meso membrane protein crystallization concept on the basis of Raman, CARS and SERS spectroscopy and microscopy.

3. Demonstration of the possibilities of enhanced Raman spectroscopy and microscopy (including 3D-visualization) in studying various cells and organisms.

4. Integration of Raman spectroscopy with atomic force microscopy (Raman AFM): spectroscopy/microscopy with a resolution of up to 10 nm.

5. Achievement of highly efficient conversion of infrared radiation to upconversion luminescence in nanoceramic matrices doped with ions of rare earth elements (Er, Eu, Pr, Tm, Yb, and others) and making recommendations on their practical application.

III. Applied research with heavy ions

Techniques combining exposure to heavy-ion beams and other physico-chemical interactions give unique possibilities for changing the properties of materials and for creating new functional structures. The main emphasis is put on the modification of materials at the nanometer scale and on the study of the effects produced by heavy ions in matter with the aim of revealing the fundamental mechanisms and of developing nanotechnology applications. They include the development of new types of track membranes and functional materials based on track membranes used in various fields of technology and medicine; the production of ultrapure isotopes and the study of the properties of practically important radionuclides; the upgrade of the FLNR experimental equipment for the production of isotopes and materials modification. Further progress requires a significant improvement of instrumentation, covering the entire range of equipment, beginning with accelerators and extending to modern high-precision instruments for the study of the micro- and nanostructural characteristics of matter. New specialized channels will be constructed at the DC-280 cyclotron and at the modernized accelerator U400R. The equipment park will be significantly augmented with modern analytical methods, including scanning electron microscopy, high-resolution transmission electron microscopy, atomic force microscopy, scanning probe tomography, X-ray photoelectron spectroscopy, energy dispersive and crystal diffraction X-ray spectroscopy and many other complementary techniques. Ion track technology approaches will be used in combination with new thin film, multilayer technologies and new promising materials (graphene, plasmonic materials). The fields of applications will be focused on the strategic areas such as energetics, safety, ecology and health.

Expected results:

1. Detailed study of heavy-ion-induced structural effects in materials aimed at understanding the fundamental mechanisms of ion-matter interaction and at applications of beams of accelerated ions in nanotechnology.

2. Investigation of the radiation resistance of materials irradiated with high energy multi-charged ions, including real-time testing of microelectronic components for space applications.

3. Synthesis of nanostructured materials and study of their optical, electrical and magnetic properties.

4. Development of next-generation functional track membranes and track-membrane-based advanced materials for optical, medical, biochemical and sensor applications.

5. Development of hybrid nanotechnologies, combining methods of ion track technology and coating, thin-layer, multi-layer composite and surface modification technologies.

6. Production of radioisotopes for nuclear medicine and radioecological studies with γ-quanta, α-particle-, and heavy-ion beams.

7. Development of specialized ion beam leading lines for applied research at the new DC-280 and modernized U400R accelerators.

8. Development of the laboratory complex in the new FLNR Laboratory Building in cooperation with the International Innovation Centre of Nanotechnology (a joint project between JINR and Rosnano).

Financing schedule (k$)

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**Total**
Materials, equipment	500.0	500.0	500.0	500.0	500.0	500.0	500.0	**3 500.0**

Radiobiological and astrobiological research

Radiobiological research in 2017–2023 will be focused on studying heavy-ion action mechanisms at the molecular, cellular, tissue, and organism levels of biological organization. Special attention will be given to experimental animals' central nervous system (CNS) disorders because CNS has to be considered as a critical system when evaluating the radiation exposure risk for the interplanetary mission crews.

Astrobiological research will be focused on the problem that is central for understanding the production of the prebiotic compounds underlying the formation of the living systems: what is primary in the origin of life, genetics or metabolism? The planned research will be aimed at the development of unified theoretical and experimental approaches allowing for a possible influence of the following factors on the phenomenon of the origin of life on Earth: energy, evolutional, protometabolic, and the primordial environment. The second field of the astrobiological research is the search for and study of microfossils in meteorites and early Precambrian terrestrial rocks using electron microscopy and nuclear physics methods.

The main fields of research:

1. Research on the mechanisms of the induction of molecular disorders of the DNA structure by heavy charged particles of different energies and their repair

1.1. Damage in the nuclei of individual cells will be studied and the fine structure of clustered DNA damage will be analysed.

1.2. The influence will be evaluated of the distributions of DNA damage of different types on cell repairability.

1.3. Mechanisms will be clarified and dynamics will be described of the protein recognition of DNA clustered damage and its subsequent repair.

2. Research on the regularities and formation mechanisms of gene and structure mutations in mammalian and human cells under exposure to heavy charged particles of different energies

2.2. Specifics will be studied of the mutagenic action of sparsely and densely ionizing radiations on mammalian and human cells.

2.3. The mutagenic action of radiations of different quality on prokaryote and eukaryote cells will be analysed and compared.

2.4. Genetic instability mechanisms of mammalian and human cells will be cleared up.

3. Research on the mechanisms of heavy charged particle-induced morphological and functional disorders of the retina and different parts of the central nervous system and their repair

3.1. Morphological, cytological, neurochemical, molecular, and physiological disorders of the retina and central nervous system structures will be studied.

3.2. Modifications of behavioral functions in irradiated animals will be studied.

3.3. In experiments on primates, the effect of radiations of different quality on operator's activity elements will be assessed.

3.4. The neurophysiological and neurochemical mechanisms underlying these processes will be studied.

4. Mathematical modeling of the effects of ionizing radiations with different LET at the molecular and cellular levels. Development and analysis of mathematical models of the molecular mechanisms of high-energy charged particle-induced disorders in the CNS structure and functions

4.1. Mathematical models describing radiation-induced damage repair will be developed.

4.2. Models will be improved that describe the stages of DNA damage induction by ionizing radiations of different quality

4.3. Models will be developed describing the action of radiation on CNS structures and functions — in particular, models of the disorder of signal transport, ion regulation and synapse functioning, gene expression and protein synthesis, and hippocampus-based neurogenesis.

5. Radiation research

5.1. Physical support of the radiobiological experiments at JINR's nuclear physics facilities will be continued.

5.2. The development of the NICA complex will be continued as regards the design and calculation of its biological shielding, prediction of the radiation conditions at the facility and its environment, evaluation of the induced radioactivity of the equipment, evaluation of staff radiation exposure, organization of radiation safety measures, and development of radiation monitoring systems.

5.3. As part of cooperation in nuclear planetary science with JINR’s Frank Laboratory of Neutron Physics and the Institute of Space Research of the Russian Academy of Sciences, it is planned to study the performances of the instruments and to calibrate them using different planetary soil models at the already operational JINR-based DAN experimental stand.

6. Astrobiological research

6.1. A possibility will be studied of the self-assembly of 3',5'-cyclic nucleotides in the system "formamide + meteorite matter" under exposure to high-energy charged particles.

6.2. To study the mechanism of nucleoside synthesis reactions, sugars and nucleic bases that were obtained in earlier experiments by proton irradiation of formamide in the presence of meteorite matter will be irradiated with accelerated high-energy charged particles.

6.3. The synergy effect will be studied in biomolecule synthesis during irradiation of formamide in the presence of amino acids.

6.4. One-pot phosphorylation of nucleosides during proton irradiation of formamide in the presence of meteorite matter and inorganic phosphates will be studied.

6.5. A search for microfossils in meteorites and early Precambrian terrestrial rocks will be performed with the use of electronic microscopy.

6.6. Criteria will be formulated and techniques will be developed for the determination of the terrestrial microorganism contamination of meteorite matter samples to prevent false identification of the extraterrestrial origin of microorganisms.

6.7. The elemental composition of cosmic dust and other materials of extraterrestrial origin will be determined by multi-element neutron activation analysis at the IBR-2 reactor.