I. Preamble

The Chair of the PAC for Nuclear Physics, M. Lewitowicz, presented an overview of the implementation of the recommendations taken at the previous meeting.

JINR Vice-Director S. Dmitriev informed the PAC about the resolution of the 129th session of the JINR Scientific Council (February 2021) and the decisions of the JINR Committee of Plenipotentiaries (March 2021).

The PAC is pleased to note that the recommendations of the previous PAC meeting concerning JINR research in the area of nuclear physics were accepted by the Scientific Council and the Directorate.

II. Reports on themes

"Synthesis and properties of superheavy elements, the structure of nuclei at the limits of nucleon stability"

The PAC heard a report on "SHE at FLNR: research and development" presented by Yu. Oganessian. The report gave an overview on the work performed during the last four years.

The most significant was certainly the start of the operation of the new cyclotron DC-280 in 2019. The PAC notes that the commissioning of SHE Factory whose key element is the DC-280 cyclotron, the upgrade of the U-400M cyclotron and construction of next-generation experimental setups considerably expand the possibilities for carrying out fundamental and applied research in nuclear physics at JINR at the highest level in broad cooperation with scientific centres of the Member States and other countries focused on research in Dubna.

The PAC highly appreciated the results of the first experiments at SHE Factory on the synthesis of Mc and Fl isotopes in $^{48}Ca + ^{243}Am$ and $^{48}Ca + ^{242}Pu$ fusion reactions, respectively. Sixty-one events of production of isotopes of moscovium $^{288, 289}Mc$ (compared to thirty-five chains detected previously) and ninety-nine $^{286, 287}Fl$ decay chains (to twenty-five chains for all previous years) have been registered. Owing to the high efficiency of the conducted experiments and sufficient background suppression, an alpha decay of ^{268}Db was registered for the first time, making the discovery of the new ^{264}Lr isotope possible.

The study of the chemical behaviour of the new elements and related relativistic effects is another goal of the experiments at FLNR. For this purpose, a new gas-filled separator, DGFRS-III, is already mounted in the experimental hall at DC-280.

For the years beyond 2023, further experimental setups are being planned, which will complement the experimental programme perfectly. These are, firstly, the cryogenic gas

catcher plus multi-reflection time-of-flight (MR-TOF) mass spectrometer and, secondly, the superconducting gas-filled solenoid (SC-GASSOL) for the chemical study of short living isotopes. The PAC is convinced that these experimental setups are necessary additions to the existing instrumentation. They will deliver new results and insights into the properties and decay modes of the heaviest isotopes and atoms.

A series of experiments were performed that aimed at studying mass-energy distributions of binary products formed in reactions with ^{52,54}Cr, ^{48}Ti, ^{86}Kr, and ^{68}Zn beams, leading to a composite system with Z = 114 and 120. The experiments allow the evaluation of quasi-fission contribution to the capture cross section, — which is of great importance to the planned experiments for the synthesis of new superheavy elements with Z = 119 and 120.

The PAC took note of the report on "SHE at FLNR: research and development". The PAC fully supports the presented scientific programme on the synthesis and studies of heavy and super-heavy nuclei and wishes the FLNR team every success in the ongoing and planned outstanding experiments.

"Development of the FLNR accelerator complex and experimental setups (DRIBs-III)"

The PAC heard a report on the implementation of the theme "Development of the FLNR accelerator complex and experimental setups (DRIBs-III)" for 2017–2021 presented by G. Gulbekyan. The PAC notes that within this period a wide variety of scientific and applied investigations in heavy-ion physics were conducted using FLNR cyclotrons (DC-280, U-400, U-400M, IC-100). The PAC is pleased with the high-quality results including the commissioning of the experimental building of the Factory of Superheavy Elements (SHE Factory) and the launch of its basic facility DC-280 cyclotron in March 2019. There are currently performed investigations for possible ways of increasing beam intensity primarily for titanium and chromium.

The PAC notes that the programme of experimental investigations at the FLNR accelerator complex U-400 was implemented under the work schedule. A major part of experimental efforts at U-400 was devoted to research with ^{48}Ca (DGFRS and SHELS) and ^{50}Ti beams (SHELS) and applied work (Roscosmos).

The U-400M cyclotron upgrade was started in July 2020, its commissioning being scheduled for the middle of 2022. The modernization aims first and foremost at enhancing the reliability and stability of the accelerator and at increasing the intensity and energy of heavy-ion beams. The main magnet coils, the components of the accelerator vacuum and radiation control systems will be completely replaced. Before the upgrade was initiated, the U-400M cyclotron had ensured the implementation of the programme of experimental

investigations with ^{11}B, ^{15}N, ^{32}S (ACCULINNA-1 and ACCULINNA-2 separators), ^{18}O, ^{22}Ne (COMBAS setup), and ^{40}Ar, ^{48}Ca beams (MASHA mass spectrometer).

The PAC acknowledges the importance of the reconstruction of the U-400 accelerator (→ U-400R) and the construction of the new experimental hall. The PAC highly appreciates the work on preparing the project of the new experimental hall for the U-400R accelerator which was approved by Glavgosexpertiza of Russia. The scheduled period for the construction of the new experimental hall is 2.5 years (2022–2024).

The PAC notes that much attention is paid to the construction and development of new experimental facilities at FLNR. The new gas-filled recoil separator DGFRS-II was commissioned. Moreover, the new expanded system of detectors was manufactured and tested. The system is located in the focal plane of DGFRS-II allowing for an increase in reaction product collection by factor 1.5. This is of paramount importance to the long-run experiments for SHE synthesis.

The new gas-filled recoil separator DGFRS-III for studying chemical properties of superheavy elements was constructed. An additional magnet was placed in the front separator's focal plane for transporting reaction products into a setup for radiochemical analysis. The commissioning of DGFRS-III is scheduled for the autumn of 2021. Furthermore, the construction of the ion gas catcher is continued, and the development of a multiple-reflection time-of-flight mass spectrometer for precision measurements of SHE mass has begun.

The PAC notes that ACCULINNA-2 separator was developed and commissioned within the theme. A series of methodological works to prepare experiments with ^{6}He, ^{8}He, ^{9}Li, ^{10}Be, ^{27}S, etc. beams were undertaken in 2017–2021. To prepare the new experiments aimed at studying light neutron-rich nuclei and scheduled for the end of 2023, a project for creation of a tritium target is implemented. The project involves the construction of a complex gas vacuum and tritium safety system for gas supply, cooling/heating, control of radiation safety, and handling gaseous waste. A radio-frequency filter (RF kicker) was also manufactured for additional purification of radioactive ion beams.

The PAC acknowledges that the high-resolution magnetic analyzer MAVR of U-400 cyclotron at FLNR was constructed and commissioned in 2019.

The PAC supports the decision of the JINR and FLNR directorates to construct a new DC-140 accelerator facility for applied investigations of solids, production of track membranes, and radiation resistance tests of electronic components performed at FLNR. The DC-140 accelerator complex will become one of the elements to be integrated with the currently developed JINR Innovation Centre.

The PAC took note of the report on the theme “Development of the FLNR accelerator complex and experimental setups (DRIBs-III)” for 2017–2021.

III. Extension of the themes “Development of the FLNR accelerator complex and experimental setups (DRIBs-III)” and “Synthesis and properties of superheavy elements, the structure of nuclei at the limits of nucleon stability”

The PAC heard a proposal for prolongation of the themes “Development of the FLNR accelerator complex and experimental setups (DRIBs-III)” and “Synthesis and properties of superheavy elements, the structure of nuclei at the limits of nucleon stability” for 2022–2023 presented by S. Sidorchuk.

Further implementation of the theme “Development of the FLNR accelerator complex and experimental setups (DRIBs-III)” includes: the upgrade and development of the FLNR cyclotron complex, the expansion of the experimental infrastructure of the laboratory (constructing new physics instruments), and the development of accelerator systems. The milestones of the theme are: the increased stability of the accelerators, the increased intensity and improved quality of ion beams of both stable and radioactive nuclides in the energy range from 5 to 60 MeV/nucleon with simultaneous reduction of power consumption.

The theme objective is to significantly improve the efficiency of experiments for the synthesis of superheavy elements and light nuclei at the limits of nuclear stability and study of their properties. The plans for 2022–2023 are:

- to continue increasing intensities and acceleration efficiency of heavy ions (primarily ^{48}Ca, ^{50}Ti, and ^{54}Cr);
- to complete the upgrade and to launch the U-400M accelerator;
- to work out a technique for producing uranium beams at U-400;
- to commence the construction of the new U-400R experiment building;
- to build the DC-140 accelerator complex for investigations in solid state physics, modification of the material surface, production of track membranes, and tests of the radiation resistance of electronic components;
- to continue the construction and development of the physics setups including commissioning DGFRS-III separator, completing the development of the ion gas catcher, designing and starting production of the multiple-reflection time-of-flight mass spectrometer and the cryogenic gas target complex of ACCULINNA-2 separator;
- to begin design work for constructing a radiochemical laboratory of the first class.

As to the theme “Synthesis and properties of superheavy elements, the structure of nuclei at the limits of nucleon stability” in 2022–2023, the experiments for the synthesis of isotopes of elements 114 (Fl) and 115 (Mc) in reactions of ^{48}Ca ions beam with ^{242}Pu and ^{243}Am targets will be continued at SHE Factory. The aim of the experiments is to thoroughly study radioactive properties of Lr to Mc isotopes. Furthermore, a series of experiments aimed at measuring production cross sections for SHE isotopes in reactions of actinides with ^{50}Ti and ^{54}Cr will be conducted allowing researchers to determine the prospects of synthesizing new elements 119 and 120 and to launch the first dedicated experiments.

The next step in the research of the heaviest nuclei will be the investigation of deep inelastic transfer and quasi-fission reactions (as instruments for the synthesis of heavy and superheavy nuclei with a large neutron excess) and study of the influence of nuclear shape and shell effects on the yields of produced nuclides. The emphasis will be put on the synthesis of neutron-rich nuclei near the neutron closed shell N = 126 as well as new isotopes of transuranic elements in multi-nucleon transfer processes in reactions induced by the interaction of uranium with actinide targets.

The experiments on α-, β-, and γ-spectroscopy of the isotopes of transfermium elements, which enable physicists to obtain data on the structures of nuclear levels, will be continued using SHELS and DGFRS-III separators and GABRIELA and SFiNX detecting systems. The first experiments on the spectroscopy of moscovium nuclei are planned.

The experiments for studying properties of SHE 112 and 114 in their ground state will be conducted using DGFRS-III (a new setup at SHE Factory) as a pre-separator for transporting nuclear reaction products to radiochemical setups.

ACCULINNA-2 fragment separator is the basic facility for investigations of properties of light exotic nuclei, medium-mass nuclei of $Z \leq 36$ and reaction mechanisms leading to their production. The analysis of the experimental data collected with ACCULINNA-2 separator in 2018–2020 will be continued. After launching the U-400M cyclotron in 2022, an evaluation of experimental capabilities will be carried on to improve the efficiency of experiments aimed at investigating the ^{7}H structure. Moreover, the researchers will prepare and proceed to the implementation of the experimental programme for studying the structure of more neutron-rich nuclei – ^{10}He, ^{11,13}Li, ^{16}Be, ^{18,19}C, and ^{26}O. Special attention will be given to simulating future experiments with the tritium target at ACCULINNA-2 fragment separator. ^{10}He and ^{16}Be will be investigated in two-neutron transfer reactions after the tritium target is put into operation.

The PAC highly appreciates the work on the development of the NRV web knowledge base on low-energy nuclear physics. The PAC notes that not only the update of the

currently operating base (http://nrv.jinr.ru) is important, but also the development of the upgraded version (http://nrv2.jinr.ru) applying modern Web-technologies is crucial.

The PAC took note on the proposal of the FLNR Directorate for the closure of the project "Construction of a prototype of the initial section of a high-current heavy-ion linear accelerator aimed at producing intense radioactive ion beams for basic research" under the theme "Development of the FLNR accelerator complex and experimental setups (DRIBs-III)". The PAC understands motivations for such decision, but suggests to consider suspension of this project until the funding issues will be resolved.

Recommendation. The PAC recommends that the themes “Development of the FLNR accelerator complex and experimental setups (DRIBS-III)” and “Synthesis and properties of superheavy elements, the structure of nuclei at the limits of nucleon stability” be extended to 2022–2023 with the highest priority.

IV. Project ENGRIN

The PAC heard a proposal to open a new project “Investigation of prompt fission neutron emission in fission” (project ENGRIN) presented by Sh. Zeynalov. The study of spontaneous and near-barrier-energy fission of nuclei is attractive for researchers as the source of new information on the properties of the nuclear system obtained immediately before the neck rupture. The experiments suggested by the authors of ENGRIN project and to be carried out with the use of resonance neutrons assume studying the correlation between the multiplicity and angular distributions obtained for the prompt fission neutrons and the data obtained for the fragment energy and mass spectra. Such challenging experiments are promising for receiving information needed for estimation of the dimension and shape acquired by the nucleus just before the neck rupture.

The PAC notes that the realization of ENGRIN project will offer new prospects for the study of fission dynamics. Its obtained results will undoubtedly become the subject for theory considerations. The setup built for this project can be effective for the experiments aimed at the search for the neutrons emitted at the neck rupture, as well as neutrons emitted at the descent time toward the scission point. The authors of ENGRIN project organized a highly-qualified team of operational expertise in nuclear fission research.

Recommendation. The PAC recommends opening this project for a year starting 2022 with its subsequent extension in case the work on its implementation is successful and the theme financing is approved. The PAC proposes the authors to reconsider the processes of the scattering of fission neutrons in the materials of ionization chamber and neutron

detectors, which might lead to a false identification of the neutron emission angles and energy. The PAC classified the reviewed project in category B.

V. Project MONUMENT

The PAC heard a report on the status of the project “Measurement of ordinary muon capture for testing nuclear matrix elements of 2β decays” (project MONUMENT) presented by M. Shirchenko. The task of the project is to carry out experimental measurements of muon capture at several daughter candidates for 0νββ-decay nuclei. Its obtained results would be crucial for verifying the accuracy of theoretical calculations of the nuclear matrix elements. The JINR group will carry out measurements at the meson factory of the Paul Scherrer Institute (PSI) in Switzerland. The project had been reviewed and approved by the PSI User Committee; the beam time for a preliminary study of ^{136}Ba and ^{76}Se had been officially granted for 2020 plus at least three more years for further measurements, but had been postponed to October-November, 2021, due to COVID-19. As a result, in 2021, the group has brushed up their measurement preparations and analysis of the data in ^{24}Mg obtained in 2019. The JINR group is actively preparing the materials and equipment for the forthcoming measurements. According to the beam schedule, the start of measurements themselves is to be in October 2021.

Recommendation. The PAC recognizes the potential of project MONUMENT and recommends that this project be continued as previously recommended until the end of 2023. The PAC ranks the project in category A.

VI. Project E&T&RM

The PAC heard a report on the project “Study of deep subcritical electronuclear systems and possibilities of their application for energy production, transmutation of radioactive waste and research in the field of radiation material science (E&T&RM)” presented by A. Baldin. The project is dedicated to the development of a new concept of Accelerator-Driven Systems (ADS) based on a high-current accelerator of light nuclei. The prospect of ADS is due to the possibility of creating a closed fuel cycle and the transmutation of radioactive waste. The project includes both theoretical studies and experiments on beams of protons, deuterons, and light nuclei of the JINR accelerator complexes including Phasotron and NICA. The special-purpose nuclear power technology station being created at the NICA accelerator complex extends the frontiers of experimental research on extracted beams of protons and light nuclei. The project is dedicated to studying reactions in various types of targets including depleted uranium and

thorium targets. Experimental measurements of high-energy neutron spectra are required to verify the theoretical models of processes describing the interaction of beams of accelerated ions with extended targets. These results can be used both for solving the problem of spent nuclear fuel transmutation and for studying the radiation resistance of materials. The project has been elaborated and adjusted to the comments made by the members of the PAC at the previous meeting on project underestimation and lack of a detailed work plan. The proposed project presents a workplan for two years and a detailed estimate of the required funds and employed workforce. The PAC rated project E&T&RM to category B at its previous session.

The presentation also included a short reference to two new branches of the project: SINET (Station for Investigation of Nuclear Energy Technologies) and Development and Construction of the Prototype of a Complex for Radiotherapy and Applied Research with Heavy-Ion Beams at the Nuclotron-M.

Recommendation. The PAC recommends extending project E&T&RM until the end of 2023. Furthermore, the PAC considers the two additional branches of extreme interest considering the future availability of high energy beams at the NICA complex. However, a plan concerning the two new branches is missing and it is not clear if they both are thought as part of the same E&T&RM project. Given the wide potential extension of the two new branches, the PAC recommends dividing the project in three branches, and for each it is advisable to present at the next PAC meetings the current status and, if possible, a detailed plan including budget, man-power and institution involvement. The PAC ranks the project E&T&RM in category B.

VII. Next meeting of the PAC

The next meeting of the PAC for Nuclear Physics will be held on 27–28 January 2022. Its tentative agenda includes:

- reports and recommendations on themes and projects to be completed in 2022;
- update on experiments at SHE Factory;
- scientific reports;
- poster presentations of new results and proposals by young scientists in the field of nuclear physics research.

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