**Questionnaire (for projects seeking continuation):**

**A. Scientific merit**

**1.   Goals of the experiment:**

**1a. Give a short description of the goals of the experiment**:

NA61/SHINE experiment is proposed to continue studying the properties of hadron and nuclear fragmentation in processes with hadron and nuclear beams. The search for a critical point in the phase diagram of nuclear matter by scanning the energy and atomic numbers is one of important tasks. Data analysis is also continued in the following areas:

* formation of light nuclei in nuclear interactions;
* hyperon generation in Be+Be, Ar+Sc, Xe+La, Pb+Pb interactions;
* antimatter production in the nucleus-nucleus interactions;
* charm particle production in relativistic heavy ion collisions.

**1b. Explain what the project adds to the international scenario:**

It should be noted that the NA61/SHINE experiment is the flagship experiment for the NICA project.

Unique data on the properties of nuclear matter in the most interesting area of the interaction energies of relativistic nuclei have already been obtained and are planned to be collected further.

1) Search for the second-order **critical end-point** in the temperature versus baryon-chemical potential phase diagram (looking for non-monotonic behavior of critical point signatures, such as transverse momentum and multiplicity fluctuations, intermittency signal, etc., when system freezes out close to the critical point);

2) Study of the properties of the onset of deconfinement (search for the onset of the **horn, kink, step**, and **dale** structures in collisions of light nuclei).

In recent years, the program has been extended by Pb+Pb collisions where the **open charm production,** as well as collective effects is studied. Few years ago, based on the obtained results, NA61/SHINE introduced a concept of two onsets in nucleus-nucleus collisions at the CERN SPS energies: **onset of deconfinement** (beginning of QGP formation – collision energy threshold for deconfinement) and **onset of fireball** (beginning of formation of a large cluster which decays statistically).

**B. Achievements**

**2.   Contributions of the JINR group:**

**2a. List of the specific contributions of the JINR group in hardware (including use of JINR computing resources for the project), software development and physics analyses.**

Dubna group principal activity is concentrated on the following issues:

1. The study of light nuclei production;
2. The study of hyperon and hyper nuclei production in Ar+Sc, Xe+La, Pb+Pb interactions;
3. The study of antimatter production in relativistic nuclear interactions;
4. Analysis of experimental data using the Dubna approach;
5. Measuring the mean number of charm–anti-charm quark pairs produced in the full phase space of heavy ion collisions;
6. Development of the time-of-flight detector based on Multigap Resistive Plate Chambers (MRPC) with high time-of-flight resolution;
7. Neutrino program of NA61;
8. Model independent cluster finding library (was developed and presented to the Collaboration by V.Kireyeu).

**2b. List of the responsibilities of JINR group members within the management structure of the collaboration, if any, giving the name of the JINR member, the managerial role and the appointment period.**

1. Malakhov A.I. – Member of Collaboration Board (2007)
2. Popov B.A. - Co-convener of Neutrino/Cosmic ray working Group (2007)
3. Dmitriev A.V. – Leader of ToF MRPC Group (2020).

**3.   Publications:**

**List the papers published in the refereed literature (no conference proceedings) in which the JINR group had a major contribution (e.g. author of the analysis, promoter of the experiment, corresponding author, realization of a key equipment etc.). Give title of paper, reference and describe in 1-2 sentences the JINR contribution. Only papers published since the last approval of the project should be listed.**

**Mention the total number of papers published by the project in the same time period.**

1. A. Aduszkiewicz,…, V.Babkin, M.Buryakov, A.Dmitriev, V.Golovatyuk, V. A. Kireyeu**,** V.I.Kolesnikov, A.Krasnoperov, V.V.Lyubushkin, A.I.Malakhov, V.Matveev, G.L.Melkumov, B.A.Popov, M.Rumyantsev et al. Measurements of Ξ− and anti-Ξ+ production in proton–proton interactions at √sNN = 17.3 GeV.

The production of Ξ(1321)− and anti-Ξ(1321)+ hyperons in inelastic p+p interactions is studied in a fixed target experiment at a beam momentum of 158 GeV/c.

Results of the simulation by the physicists of the Dubna group are used in this publication (V.Kireyeu et al.)

1. A.I.Malakhov, G.I.Lykasov. Mid-rapidity dependence of pion production in p-p and A-A collisions. Eur. Phys. J. A (2020) 56: 114.

A satisfactory description of the pion rapidity spectra in AA collisions is presented within the self-similarity approach. All the work was done by JINR employees.

1. Gennady Lykasov and Alexander Malakhov. Hadron production in pp and AA collisions at mid-rapidity within self-similarity approach. EPJ Web of Conferences 204, 01022 (2019).

The extension of the self-similarity approach to analyze the pion pt-spectra produced in AA collisions at high and middle energies and mid-rapidity is given. A satisfactory description of experimental data on these spectra in pp and AA collisions within the offered approach is shown. The work was done by JINR employees.

1. A. Aduszkiewicz et al., [NA61/SHINE Collab.] Measurements of hadron production in π+ + C and π+ + Be interactions at 60 GeV/c. Phys. Rev. D 100 no. 11, (2019) 112004, arXiv:1909.06294 [hep-ex].

Hadron production was studied in interactions of π + C at 60 GeV/c and π + Be at 60 GeV/c. These results will enable neutrino flux predictions to be constrained in neutrino experiments. A significant contribution to the work was made by A. B. Popov (processing and analysis of data and preparation of the article).

1. R. R. Prado, [NA61/SHINE Collab.] Recent results from the cosmic ray program of the NA61/SHINE experiment. EPJ Web Conf. 208 (2019) 05006, arXiv:1810.00642 [hep-ex]

In this paper we summarize the results from pion-carbon collisions recorded at beam momenta of 158 and 350 GeV/c. Hadron production measurements in this type of interactions are of fundamental importance to understand the muon production in extensive air showers. B. Popov made a significant contribution to these results.

1. A.I.Malakhov, V.A.Matveev. New results and research perspectives of experiment NA61/SHINE on SPS at CERN. JINR News, No.3, 2020, pp.12-17.

The most recent results of the experiment are presented. Much attention is paid to the results of the research on the search for a critical point in the phase diagram of nuclear matter. The work was done by JINR employees.

1. Georgy Melkumov (NA61 Collaboration). Recent results of strong interaction program from NA61/SHINE experiment at CERN SPS. EPJ Web of Conferences 204, 01010 (2019).

In this article the overview of the latest results of the NA61/SHINE experiment is presented. The publication is fully prepared by G. L. Melkumov.

1. Alexander Malakhov and Gennady Lykasov. Analytical description of hadron production in hadron-hadron and nuclear-nuclear collisions in the mid-rapidity region. EPJ Web of Conferences 204, 01021 (2019).

It is shown that the inclusive spectra of the produced hadrons in hadron-hadron and nuclear-nuclear collisions can be presented as the universal function dependent of the self-similarity parameter in the analytical form. The work was done by JINR employees.

1. Lykasov G. I., Malakhov A. I., Zaitsev A. A. Ratio of cross-sections of kaons to pions produced in pp collisions as a function of √s. Eur. Phys. J. A (2021) 57(3) pp. 1-7.

The given calculation is based on self-similarity approach of the inclusive pT spectra of pions and kaons produced in pp collisions at mid-rapidity in a wide range of initial energies. A satisfactory description of the ratio of cross-sections of K± to π± mesons produced in pp collisions as a function of √s is presented. The work was done by JINR employees.

1. V.Kolesnikov, V.Kireyeu, V.Lenivenko et al. A New Review of Excitation Functions of Hadron Production in pp Collisions in the NICA Energy Range. Physics of Particles and Nuclei Letters, 2020, Vol. 17, No. 2, pp. 142–153.

The data on hadron multiplicities from inelastic proton-proton interactions in the energy range of the NICA collider have been compiled. The compilation includes recent results from the NA61/SHINE and NA49 experiments at the CERN SPS accelerator. The publication has been fully prepared by V.Kireyeu.

The total number of the papers published by the project team is 23 in the same time period.

**4.   PhD theses:**

**List the PhD theses completed within the last 3 years, or expected to be completed within one year, by JINR students within the project, giving the student name, thesis title and graduation year.**

*PhD theses (2019-2021):*

Babkin V. – 2021

“Time-of-flight of particle identification system of multi-purpose detector”.

Zaitsev A. – 2020

“Investigation of the dissociation of relativistic nuclei 10B, 11C and 12C”.

*PhD theses (Plan):*

Dmitriev A. – 2022

" Time-of-flight particle identification system of the NA61/SHINE experiment”.

Buryakov M.- 2022

“Data acquisition system for the NA61 time-of-flight particle identification system”

Kireyeu V. – 2022

“The PHQMD model for the formation of nuclear clusters and hypernuclei in heavy-ion collisions”.

Lenivenko V. – 2023

“Investigation of hyperon generation in nucleus-nuclear interactions”

*Doctoral dissertation:*

Zaitsev A. –2023

“Investigation of the open charm production in the nuclear-nuclear collision”.

**5.   Talks:**

**5a. List the invited plenary talks given by members of the JINR group at international conferences, workshops… since the last approval of the project: give name and date of the Conference, title of talk and speaker name.**

Due to COVID-19, participation in the conferences was limited. However, the following reports were provided:

1. Georgy Melkumov (NA61 Collaboration). Recent results of strong interaction program from NA61/SHINE experiment at CERN SPS. EPJ Web of Conferences 204, 01010 (2019). The XXIVth International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", Dubna, Russia..
2. A. Malakhov. “Analytical description of hadron production in hadronhadron and nuclear-nuclear collisions in the mid-rapidity region”. EPJ Web of Conferences 204, 01021 (2019). The XXIVth International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", Dubna, Russia.
3. A. Dmitriev “Upgrade of the NA61/SHINE ToF system based on a MRPCs for the NICA experiments”. NICA Days 2019 (21-25 October 2019), Warsaw, Poland.

**5b. Give a similar list for parallel talks.**

1. V. Kireyeu. “Parton Hadron Quantum Molecular Dynamics (PHQMD) – a Novel Microscopic N-Body Transport Approach for Heavy-Ion Dynamics and Hypernuclei Production”. The 18th International Conference on Strangeness in Quark Matter (SQM 2019), Bari, Italy.
2. A. Malakhov. “DESCRIPTION RELATIVISTIC NUCLEAR INTERACTION IN FOUR VELOCITY SPACE” LXX International conference NUCLEUS-2020, 11-17 October 2020, Saint Petersburg.
3. Viktar Kireyeu. Prospects for the study of the strangeness production at the NICA experiments. V International Conference on Particle Physics and Astrophysics ICPPA 202, October 5-9, 2020, Moscow
4. Viktar Kireyeu. Parton-Hadron-Quantum-Molecular Dynamics (PHQMD).The NA61/SHINE Collaboration Meeting. Organized by University of Warsaw and Warsaw University of Technology. February 11-15, 2019.

**C. Plans and requests**

**6.   Plans**

**Describe the plans of the JINR group within the project, in physics analysis, data taking, software development. detector R&D, detector operation and maintenance, upgrade activities… for the period of time of the requested extension.**

Extensive statistics already collected at various energies and a wide range of colliding nuclei have enabled us to obtain a large number of planned physical results. The Dubna Group traditionally participates in obtaining data on the following tasks:

* formation of light nuclei in nuclear interactions

(This task is the full responsibility of the Dubna group. V. Kolesnikov defended his doctoral dissertation on deuteron formation in nuclear interactions. The work is continued to study the formation of heavier nuclei);

* hyperon generation in Be+Be, Ar+Sc, Xe+La, Pb+Pb interactions (Identification and reconstruction of Λ-hyperon spectra in Ar+Sc and Xe+La collisions at 30A and 150A∙GeV as the first step to study the hypernuclei formation);
* antimatter production in the nucleus-nucleus interactions;
* open and hidden charm production in heavy ion interaction;
* neutrino program;
* The development of the new time-of-flight system based on MRPC (second wall) will be completed.

Being responsible for data taking with the time-of-flight detector and identification of the secondary particles, the Dubna group actively contribute to the search for the critical point and onset of fireball phenomena in the strong interaction matter.

Reports at the international meetings, conferences and publication of scientific articles are foreseen.

It is planned to prepare 4 PhD theses and one doctor dissertation using the results obtained in the NA61 experiment and the NICA project.

The results obtained by NA61/SHINE and overall progress in physics on strong interactions, neutrinos and cosmic-rays have indicated the necessity to extend NA61/SHINE measurements beyond the ones planned for the period of 2021-2024. New measurements should be carried out after the Long Shutdown 3.

**7.   Group size, composition and budget.**

**7a. List the JINR personnel involved in the project, including name, status (e.g. PI, researcher, post-doc, student, engineer, technician…) and  FTE. Mention the total number of people in the collaboration.**

VBLHEP manpower.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| № | Name | Рosition | Сategory | FTE |
| 1 | Babkin V. | post-doc | MRPC | 0.2 |
| 2 | Buryakov M. | engineer | MRPC | 0.2 |
| 3 | Dmitriev A. | researcher | MRPC | 0.5 |
| 4 | Kireyeu V. | researcher | Analysis, data taking | 0.5 |
| 5 | Kolesnikov R. | engineer | MRPC | 0,3 |
| 6 | Kolesnikov V. | doctor | Analysis | 0.1 |
| 7 | Lenivenko V. | researcher | Analysis, data-taking | 0.1 |
| 8 | Malakhov A. | doctor | Analysis, data taking | 0.3 |
| 9 | Melkumov G. | doctor | Analysis, data taking | 0.8 |
| 10 | Rumyantsev M. | engineer | MRPC | 0.2 |
| 11 | Zaitsev A. | post-doc | Analysis, data taking | 0.8 |
| Σ | | | | 4.0 |

LNP manpower.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| № | Name | Position | Сategory | FTE |
| 1 | Lykasov G. | doctor | Theory | 0.1 |
| 2 | Lyubushkin V. | researcher | Analysis, data taking | 0.2 |
| 3 | Popov B. | researcher | Analysis | 1.0 |
| 4 | Tereshenko V. | researcher | MRPC, data taking | 0.3 |
| Σ | | | | 1.6 |

**7b. Present the JINR group budget for the period of time of the requested extension, specifying the main budget items (equipment, computing, salaries, common funds, travel…)**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| № | Name of the items cost | full cost (k$) | | 2022 | | 2023 | | 2024 | |
| Theme  1087 | Theme  1124 | Theme 1087 | Theme 1124 | Theme 1087 | Theme 1124 | Theme 1087 | Theme 1124 |
| 1. | Accelerator (Nuclotron), hour | - | - | - | - | - | - | - | - |
| 2. | Computer communications | 3 | - | 1 | - | 1 | - | 1 | - |
| 3. | LHEP Design bureau | - | - | - | - | - | - | - | - |
| 4. | LHEP Workshop | - | - | - | - | - | - | - | - |
| 5. | Materials | 270 | - | 140 | - | 110 | - | 20 | - |
| 6. | Equipment | 15 | - | 5 | - | 5 | - | 5 | - |
| 7. | Payment research | - | - | - | - | - | - | - | - |
| 8. | Travel allowance, including: | 178 | 24 | 60 | 8 | 60 | 8 | 58 | 8 |
| (a) to non-rouble zone countries | 150 | 12 | 50 | 4 | 50 | 4 | 50 | 4 |
| b) in the rouble zone | 4 | - | 2 | - | 2 | - | - | - |
| c) protocol-based | 24 | 12 | 8 | 4 | 8 | 4 | 8 | 4 |
| Σ | | 466 | 24 | 206 | 8 | 176 | 8 | 84 | 8 |
| Total direct expenses: | | 490 | | 214 | | 184 | | 92 | |
|  | |  | |  | |  | |  | |

Theme 1087 - VBLHEP.

Theme 1124 - DLNP

**7c. Indicate the use or needs of JINR computing resources for the group and for the project if any.**

There are plans of the Collaboration NA61/SHINE to use JINR computing resources for the data storage and analysis.