Form No. 24

NA61-SHINE PROJECT

Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS (SHINE – SPS Heavy Ion and Neutrino Experiment)

(JINR Participation)

CODE OF THEME: 02-1-1087-2009/2020

Theme: Research on Relativistic Heavy and Light Ion Physics. Experiments at the Accelerator Complex Nuclotron/NICA at JINR and CERN SPS

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	SIGNATURE	DATE
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BY JINR DIRECTOR	______	______
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JINR VICE-DIRECTOR	______	______
CHIEF SCIENTIFIC SECRETARY	______	______
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PROJECT DEPUTY LEADER	[signature]	20.03.2018
ENDORSED PAC FOR PARTICLE PHYSICS	______	______

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Proposal for Extension

Participation of JINR in the NA61/SHINE experiment at the CERN SPS

(theme 02-1-1087-2009/2020)

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2018

Contents

Abstract

This document has been prepared taking into account the recommendations of the 47th session of the Programme Advisory Committee (PAC) of JINR for particle physics and in accordance with the updated "Rules of preparation of the projects", given at the JINR web site http: //www.jinr.ru/docs/.

Experiment NA61/SHINE has been included into the “Seven-year plan of the development of JINR, 2017-2023” , page 17: “Obtaining new results in the energy scan programme in the experiments NA61 (SPS) and STAR (RHIC) – 2017-2023".

It is proposed to continue studying the properties of hadron and nuclear fragmentation in processes with hadron and nuclear beams. Since the draft was discussed at the PAC last year, only a brief overview of the results obtained earlier is given. The results of 2017 on the indication of a new physical phenomenon called “onset of fireball” are described in more detail: the cluster size of the secondary particle radiation area increases during the transition to collisions from light nuclei (Be+ Be) to the heavier ones (Ar+Sc).

The recommendations of the PAC session read: "The PAC appreciates the role of the JINR group in data taking, detector and software maintenance but considers that the impact on physics analyses is not commensurate to the group size and would like to see a larger involvement in leading physics analyses".

In this regard, the number of employees has been optimized. The participation of the JINR team in data analysis was reinforced. Three more of young physicists have joined to analyze the data in the following areas:

- study of the production of light nuclei in nuclear interactions;
- study of the flow of hadrons in nucleus-nucleus collisions;
- the study of hyperon and hypernuclei production in Ar+Sc, Xe+La, Pb+Pb interactions.

Other three young employees have been engaged in the development of the time-of-flight detector based on Multigap Resistive Plate Chambers (MRPC).

The need of using the experience in the NA61 project for the NICA project in JINR was also taken into account. In this connection, a number of other employees have been also involved in the work on the NICA project. An agreement was reached with the leader of the collaboration on the organization of training the young employees on the experience of NA61 for the NICA project. Thus, the NA61 experiment becomes a "forge" of personnel for the NICA project.

Based on the NA61 results three PhD and two doctoral thesis successfully provided scientific degrees for JINR physicists. In 2017 V. I. Kolesnikov, who is currently one of the leaders of the NICA project, defended his doctoral dissertation on the study of the production of light nuclei and antinuclei in nuclear interactions. The subject of this dissertation was the full responsibility of the JINR group and it will be continued.

The team of the Laboratory of High Energy Physics engaged in the study of nucleus-nucleus interactions, calibration of 900 channel time-of-flight wall (constructed at JINR) performs R&D for the new time-of-flight system, based on the Multigap Resistive Plate Chambers (MRPC). These activities require relatively modest resources.

The Laboratory of Nuclear Problems participates in the neutrino program of NA61. This part does not require large expenditures either.

Introduction

The main goal of the heavy-ion program at the CERN Super Proton Synchrotron (SPS) is the experimental investigation of the properties of nuclear matter under extreme conditions. The fixed-target NA61/SHINE experiment at CERN SPS is conducting a rich program on strong interactions, which covers the study of the onset of deconfinement and the search for the QCD critical point. To achieve these goals, the NA61/SHINE collaboration proposed the scan of a broad region of the QCD phase diagram (T−μB) by varying the momentum and size of colliding systems (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb).The obtained results reflect very interesting features which might be related to the onset of deconfinement, as well as to the onset of formation of large clusters of strongly interacting matter, the so called “onset of fireball”. Recently, the experimental setup of NA61/SHINE experiment has been supplemented with Vertex Detector (VD) that was motivated by the importance and opportunity of the first direct measurements of the open charm mesons via registration of D-mesons in heavy ion collisions at SPS energies.

As for the Dubna group principal activity it is related to the following issues:

(i) The study of light nuclei production is important for several reasons. First of all, the mechanism of cluster formation in nucleus-nucleus collisions is not well understood and requires further investigations. On the other side, deuterons and tritons, for example, are not elementary hadronic particles and because of their small binding energy (2.2 and 8.2 MeV, respectively) compared to freeze-out temperatures (the order is about 100 MeV), it is very probable that they will not survive in the repeated collisions.

So, it is likely that the observed deuterons and tritons, as well as the significant fraction of few-nucleon bound states registered near the midrapidity range, are produced in the late stage of the reaction close to the freeze-out point. Thus, the light nuclei, observed in the experiment and formed near the freeze-out, may provide information on the space-time structure of this late stage of the collision.

(ii) The physics objective of the new measurements of Pb+Pb collisions – investigate the charge dependence of particle yields and anisotropic flow harmonics in the forward rapidity region which is sensitive to the effects induced by the strong electric and magnetic fields generated in the heavy ion collision.

The proposed measurements by NA61/SHINE of the charge dependence of anisotropic flow at forward rapidities will bring new experimental information related to electromagnetic effects and the longitudinal expansion of the system formed in the heavy ion collision.

(iii) Relativistic heavy ion collisions provide the unique opportunity of forming and investigating hot and dense matter at the laboratory. The QGP is formed at the initial stage of the reaction while the final stage is driven by the hadronization process and formation of clusters. The capture of the produced hyperons by clusters of nucleons leads to the hypernuclei formation which is a very rare process at strangeness threshold energies. Hypernuclei are unique in their potential of improving our knowledge on the strange particle-nucleus interaction in a many body environment and under the controlled conditions. In its turn, this is essential to derive eventually a more general and self-consistent description of the baryon-baryon interaction.

Strangeness physics adds a new degree of freedom to our understanding of hadrons, their structure, their interactions and the cooperative effects in the many body environment in nuclear systems. In perspective, strangeness physics might be a cornerstone for further extensions into the regions of charm and potentially even higher flavors.

1. Status of research

The key results (Fig.1) obtained on the previous version of the set-up̅ are the energy dependences of the K^+/π^+ ratio and the inverse slope parameter T of the transverse mass spectra of K^+ mesons measured in central Pb+Pb (Au+Au) collisions [1]. These data were the first indication of the onset of the phase transition to the quark-gluon matter in the energy region of about 10 GeV.

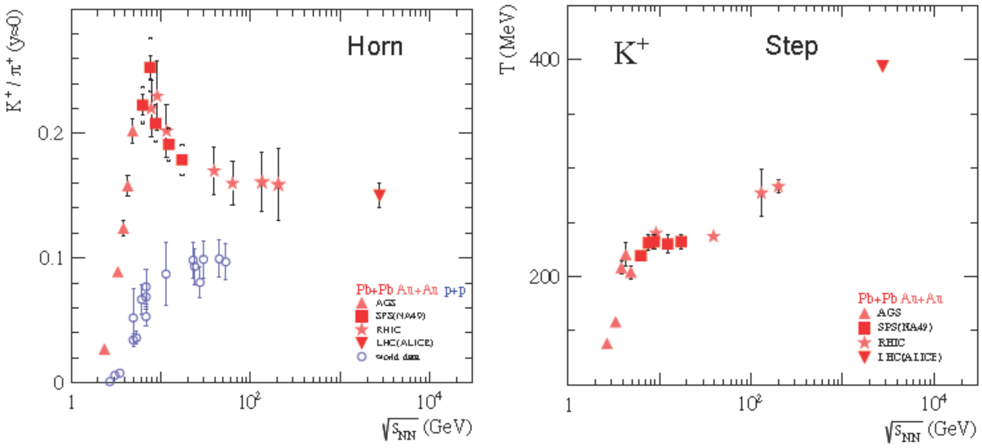

Fig.1. Energy dependence of K^+/p^+ ratio ("Horn") and slope parameter for kaons ("Step") in the central A+A and p+p interactions.

The search for a critical point in the phase diagram of the nuclear matter is carried out in the experiment NA61 by the energy and atomic number scanning of colliding nuclei. Fig. 2 shows a sketch of the phases of strongly interacting matter in the (T, μ_B) plane as suggested by QCD-based considerations. The position of the critical region is uncertain. The latest theoretical estimates based on the lattice QCD calculations localize it at T~158 MeV and μ_B ~360 MeV as indicated in Fig. 2. A characteristic property of the second order phase transition (the critical point or line) is a divergence of the susceptibilities. Consequently an important signal of the second-order phase transition at the critical point is large fluctuations, in particular, the enhancement of fluctuations of multiplicity and transverse momentum are predicted [2].

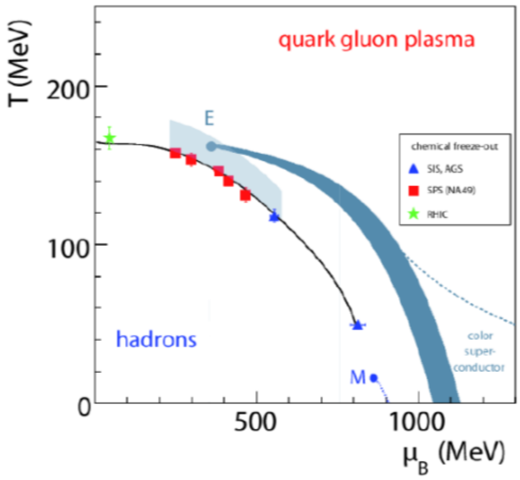

Fig.2. The QCD phase diagram in terms of temperature (T) and baryo-chemical potential (μ_B). E marks the end point E of the first order transition line. The chemical freeze-out points extracted from the analysis of hadron yields in central Pb+Pb (Au+Au) collisions at different energies are plotted by the solid symbols. The region of the estimated phase transition boundary is indicated by the wide band.

Fig.3 shows the expected sketch and present status of fluctuation measurements of NA61 for p+p, Be+Be and Ar+Sc collisions. No indications for critical point have been observed so far. Analysis of Xe+La data of 2017 is expected to continue the investigations.

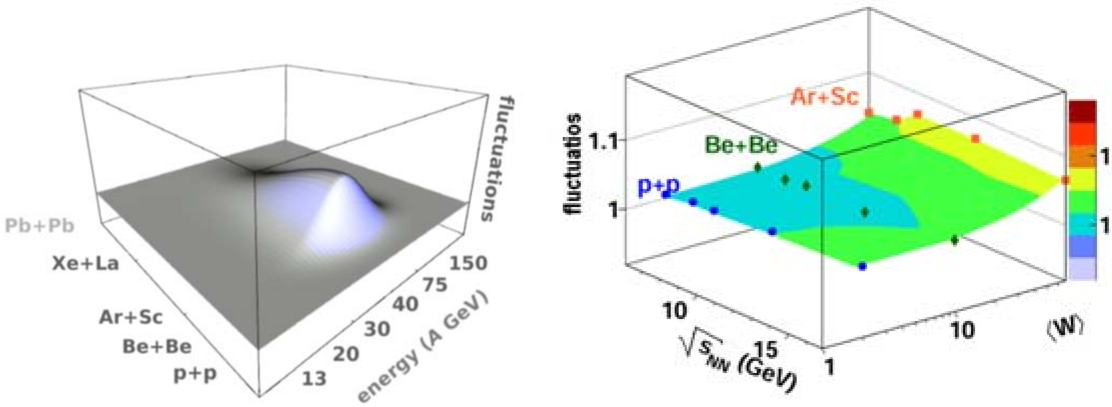

Fig. 3. Left: Sketch of the expected hill of fluctuations which may be observed in the (beam momentum) - (system size) scan of NA61/SHINE. Right: fluctuations measured by NA61/SHINE in inelastic p+p interactions and violent Be+Be and Ar+Sc collisions at the CERN SPS energies. Results refer to negatively charged hadrons at forward rapidity ($0 < y_\pi < y_{beam}$) and $p_T < 1.5$ GeV/c.

In this chapter some new results obtained recently are listed. Since the project was discussed at the PAC last year, below we give a list of publications in References only for 2017-2018 [3-12, 15, 16].

The principal (co)authors from JINR are presented in the following studies:

1. Production of d and ^{3}He nuclei in central Pb+Pb interactions was studied at five collision energies ($\sqrt{s_{NN}}$ = 6.3, 7.6, 8.8, 12.3, and 17.3 GeV) at the CERN SPS by LHEP JINR group [3, 4]. Transverse momentum spectra and rapidity distributions were measured. The light nuclei yields are compared to predictions of statistical models. Phase-space distributions of light nuclei are discussed and compared to those of protons in the context of the coalescence approach. The coalescence parameters B_2 and B_3 for d and ^{3}He were determined at all energies. Coalescence parameters for d and ^{3}He from central A+A collisions are presented in Fig.4.

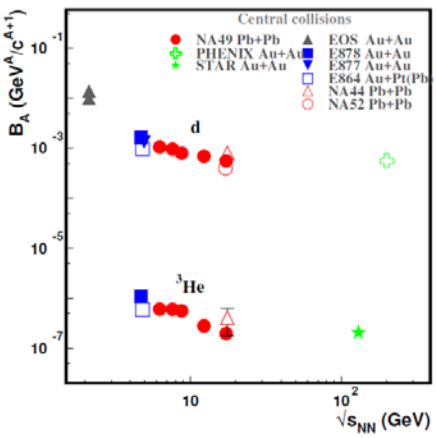

Fig. 4. Coalescence parameters for d and ^{3}He from central A+A collisions.

These results (and a number of the results obtained earlier) were included in V. Kolesnikov's doctoral dissertation "Study of the production of $\pi^{+/-}$, $K^{+/-}$, protons, antiprotons, light nuclei (d, t, ^3He) and anti-deuterons in Pb+Pb collisions at energies from 20 to 158 GeV per nucleon" [4].

2. In the article by G.I. Lykasov and A.I. Malakhov [5] the spectra of secondary pions obtained in the NA61 experiment in pp and AA collisions were well described (Fig.5), obtained in NA61 experiment. The calculations of the spectra were based on the approach using the self-similarity parameter in the four-dimensional velocity space.

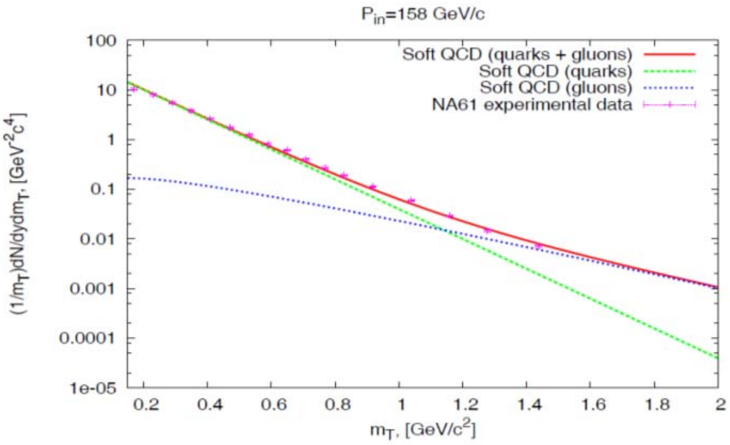

Fig. 5. Results of the calculations of the inclusive cross section of hadron production in pp collisions as function of the transverse mass at the initial momenta 158 GeV/c. They are compared to the NA61 experimental data (A.A.Abgrall et al. Eur. Phys.J., C74 (2014) 2794).

3. A new physics phenomenon was discovered in experiment NA61 in 2017 [6].

The observed rapid change of hadron production properties which appear when moving from Be+Be to Ar+Sc collisions can be interpreted as the beginning of forming large clusters of strongly interacting matter (Fig.6). This phenomenon was referred to as the onset of fireball (the name was proposed by Edward Shuryak at the CPOD 2017 conference).

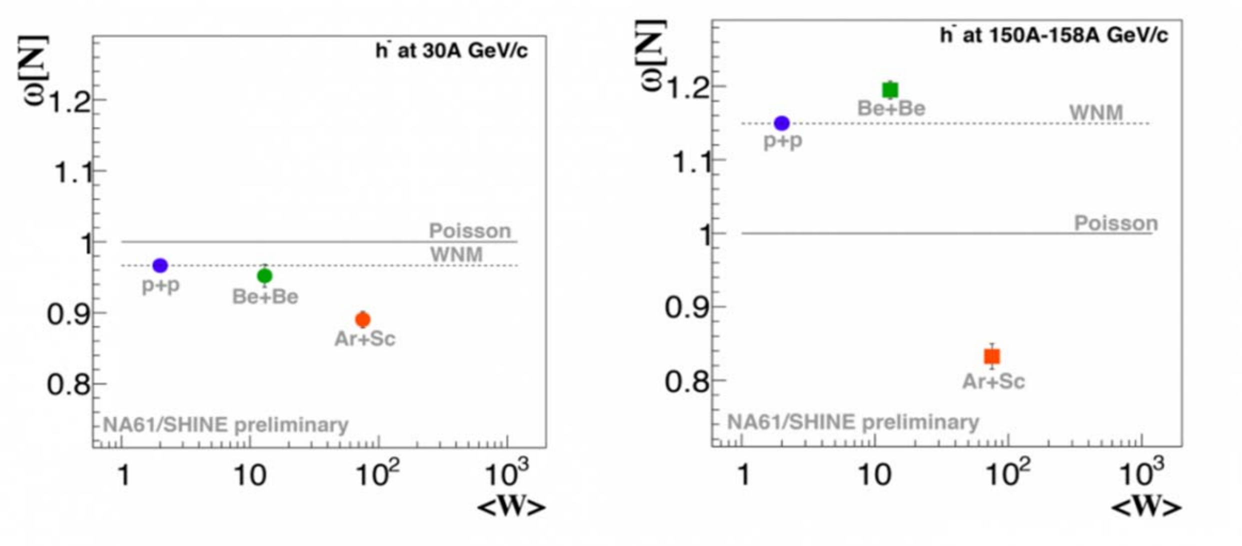

Fig.6. System size dependence of multiplicity fluctuations of negatively charged hadrons at 30 A GeV/c and 158A GeV/c. $\omega[N] = (\langle N_i^2\rangle - \langle N_i\rangle^2)/\langle N_i\rangle$ - scaled variance (multiplicity fluctuations). <W> - according to the "wounded" nucleon model, the number of produced relativistic charged multiplicities (n_{AA}) is scalable to the average number of participant or the "wounded nucleons" (W) with the proton-proton multiplicity (n_{pp}). $n_{AA}(E) = ½ W n_{pp}(E)$.

4. New measurements of $\pi^{+/-}$ emission from the surface of the T2K replica (90 cm-long) carbon target have been recently published [13] from the collected data. Fully-corrected differential yields of $\pi^{+/-}$ - mesons from the surface of the T2K replica target for incoming 31 GeV/c protons were obtained. A possible strategy to implement these results into the T2K neutrino beam predictions has been proposed and the propagation of the uncertainties of these results to the final neutrino flux has been discussed.

Various measurements for neutrino experiments are planned in upcoming data taking 2018. It will be a set of data on precision measurements of hadron yields in proton-nuclear and pion-nuclear interactions using thin targets from beryllium, carbon, aluminum and iron, as well as of the replica target of the NOvA neutrino experiment.

The group of physicists of the Laboratory of Nuclear Problems intends to take an active part in data collection and analysis of these experimental data, as well as in the preparation of scientific publications.

In particular, it is planned to participate in the analysis of the data for the T2K replica target in the configuration with the maximum magnetic field to measure the outputs of hadrons and cross sections in the interactions of protons, pions and kaons with beryllium, carbon and aluminum at the momenta 31, 60 and 120 GeV/c.

2. Description of the proposed research

2.1. The subject of the research and methods

NA61/SHINE [14] is a multi-purpose experiment to study hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron (SPS). The experiment was approved by the CERN Research Board in 2007 based on the request of heavy ion, neutrino and cosmic ray communities. They argued that the opportunities offered by the broad momentum range of beam particles, from pions to lead nuclei, together with the large acceptance and high resolution of the NA61/SHINE detector provide the unique opportunity of urgent performing the needed measurements. The physics data were collected until the end of 2017. This program will be continued in 2018 by data taking on Pb+Pb collisions and hadron-nucleus interactions.

The data have been recorded to

(i) study the properties of the onset of deconfinement and search for the critical point of strongly interacting matter,

(ii) provide precise results on hadron production for improving calculations of the initial neutrino beam flux in the long-base line neutrino oscillation experiments as well as for more reliable simulations of cosmic-ray showers in the air.

Among the most important physics results are as follows:

(i) observation of a rapid change of the system size dependence of hadron production properties - the onset of fireball;

(ii) reduction of systematic uncertainties of the T2K final results by a factor of about 2,

(iii) precise investigation of mechanisms for muon production in ultra-high energy cosmic-ray showers in the air.

Based on the success of the currently running program and motivated by new physics needs the NA61/SHINE collaboration proposes to continue measurements with hadron and ion beams during the period of 2020-2024 in accordance with the Addendum to the NA61/SHINE [15].

The measurements are requested by heavy ion, cosmic ray and neutrino communities and include:
(i) measurements of charm hadron production in Pb+Pb collisions for heavy ion physics,
(ii) measurements of nuclear fragmentation cross sections for cosmic ray physics
(iii) measurements of hadron production in hadron-induced reactions for neutrino physics.

It is necessary to stress that the beam momentum range provided for NA61/SHINE by the SPS and the H2 beam line is highly important for the heavy ion, neutrino and cosmic ray communities. Namely, it covers:
(i) energies at which the phase transition from the matter where quarks and gluons are confined in hadrons to quark gluon plasma, takes place in heavy ion collisions, i.e.,- the onset of deconfinement;
(ii) proton beams of momenta used to produce neutrino beams at J-PARC,(Japan) and Fermilab,(US);
(iii) light nuclei at > 10AGeV/c important for understanding the propagation of cosmic rays in the Galaxy. There is a world-wide effort to construct facilities providing ion and hadron beams in the CERN SPS beam momentum range. These are the fixed-target facilities at FAIR, (Germany) and J-PARC, (Japan) as well as the collider facility NICA, (Russia). They will start operation after the above requested measurements are completed. The second phase of the beam energy scan at RHIC, (US) is planned to run in 2019 and 2020. The data will be taken in the collider and fixed target modes. The fixed target facilities will operate only at energies below the onset of deconfinement. The data from the collider facilities are complementary to the corresponding fixed target results. In particular, the charm hadron measurements in a wide region of the phase space are only possible at the fixed target facilities providing the high collision energy and a rapid data taking rate.

In conclusion, NA61/SHINE is the only experiment which can carry out the requested measurements in the near future. Moreover, the NA61/SHINE operation beyond the LS2 leaves open the opportunity of performing new measurements which are likely to be requested in the future. Moreover, new measurements related to the recent observation of the onset of fireball are sure to be requested soon due to the growing experimental evidence.

2.2 Set-up and facility modifications

The present layout of the detector system is shown in Fig. 7 [15, 16].

The NA61 experiment is a large acceptance hadron spectrometer at the CERN-SPS for the study of the hadronic final states produced in various reactions (from p+p to Pb+Pb). The main tracking devices are four large volume Time Projection Chambers (TPCs), which are capable of detecting 70% of the approximately 1500 charged particles produced in the central Pb+Pb collision at 158A GeV. Two of them, the vertex TPCs (VTPC-1 and VTPC-2), are inside the magnetic field of two superconducting dipole magnets (1.5 and 1.1 T, respectively) and two others (MTPC-L and MTPC-R) are positioned downstream of the magnets. The NA61 TPCs allowed precise measurements of particle momenta p with a resolution of $\sigma(p)/p^2 \cong (0.3 - 7)\ 10^{-4}\ (GeV/c)^{-1}$. The set–up was supplemented by three time-of-flight detector arrays (TOF-F, TOF-L and TOF-R) with a time measurement resolution from 60 to 100 ps and a Projectile Spectator Detector (PSD).

At present, the time-of-flight (TOF-L, TOF-R) system for the NA61/SHINE consists of the two walls of the 900-channel scintillation detectors each, constructed at LHEP of

JINR. This system requires upgrading in order to be in operation for following several years. The unreliable part of the TOF system is the FASTBUS-based readout electronics with a very limited set of spare elements. The proposal is to replace the TOF detector by a modern high-performance MRPC detector. LHEP of JINR has a profound experience in construction and maintenance of these detectors.

Within 2017 the facility upgrades and maintenance listed below were performed:

(i) Forward TPC installation and commissioning. Three Time Projection Chambers (FTPC-1/2/3) were designed to close the gap in the forward acceptance. Now together with the existing GAPTPC they provide momentum reconstruction and particle identification by the ionization energy loss measuring.

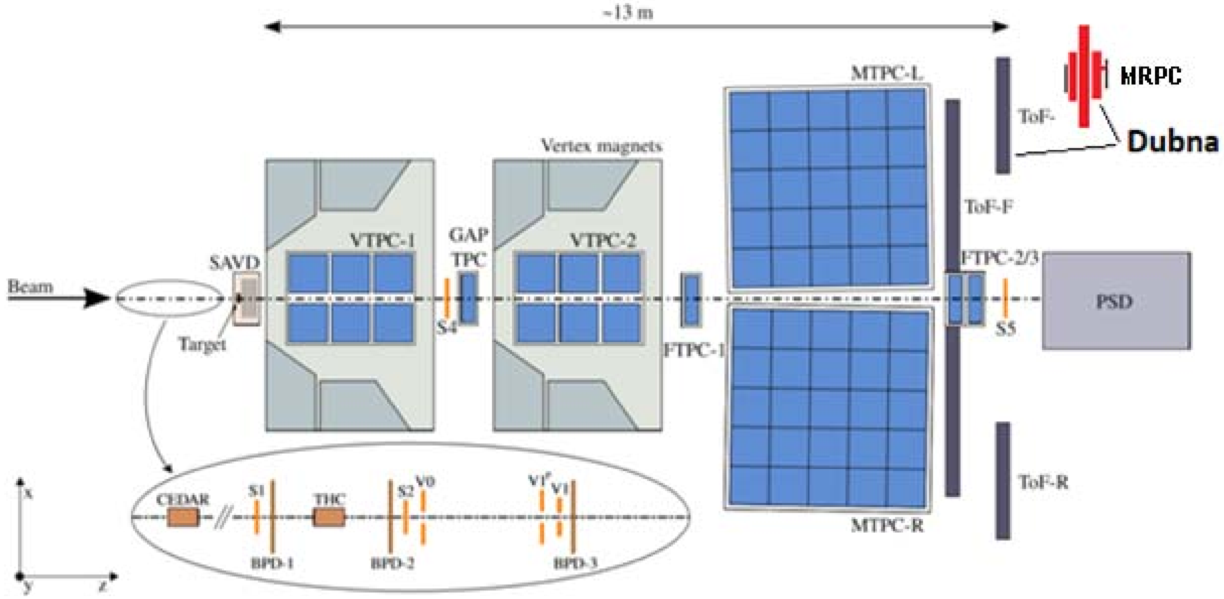

Fig. 7. NA61/SHINE detector layout as of October 2017, horizontal cut, not to scale]. It includes new Vertex Detector, Forward TPCs 1, 2, and 3, four reinstalled ToF-F modules and the TOF system prototype on the MRPC base. TOE-L and MRPC developed at LHEP JINR (Dubna).

(ii) Small Acceptance Vertex Detector (SAVD) tests. The completed SAVD with readout integrated with the NA61/SHINE central DAQ was tested in beam during the Pb+Pb data taking period in December 2016. The reconstruction and calibration algorithms were optimized by using the data.

(iii) Forward Time of Flight with DRS4 based readout. Four (from ten) existing ToF-F modules were installed behind the MTPCs, covering the gap between FTPC-2/3 and TOF-L/R. Signals from 64 photo-multipliers were read out with new DRS4 boards. The system was configured during the data taking campaign and used while measuring the 90 and 120 GeV/c beams in August 2017.

(iv) Projectile Spectator Detector maintenance (PSD). The detector was calibrated and prepared for operation in Xe+La data taking 2017.

(v) Beam tests of MRPC-based TOF detector prototypes (Dubna). A schematic drawing of the proposed MRPC (Multigap Resistive Plate Chamber) module is presented in Fig.8. The detector consists of three stacks of 5 gas gaps each. Float glass was used as resistive electrodes. The outer glass electrodes are 400 μm thick. The internal glass electrodes are 280 μm thick. The fishing line as a spacer defines the 200 μm gap between all the resistive electrodes. The outer part of external glass electrodes is covered by the conductive paint layer with surface resistivity of about 10 MΩ to apply high voltage.

Overall dimensions of the detector (600x300 mm^2) are determined by the size of the glass. 48 pickup electrodes with pitch of 12.5 mm look like strips and made at the inner layer of the PCB. It is necessary for better electrical isolation of strips from the high voltage layer. The differential analog signal is transferred to the front-end electronics (FEE) board by doubled twisted pair cable. FEE based on the NINO ASIC are designed by JINR [17]. The signal is read out from both ends of the strip. It provides a better time resolution and determination of the coordinate of a particle along the strip. Digitizing of the signal is provided by the VME based time-to-digital converter TDC72VHL designed by JINR. The native time resolution of the readout electronics is not more than 20 ps.

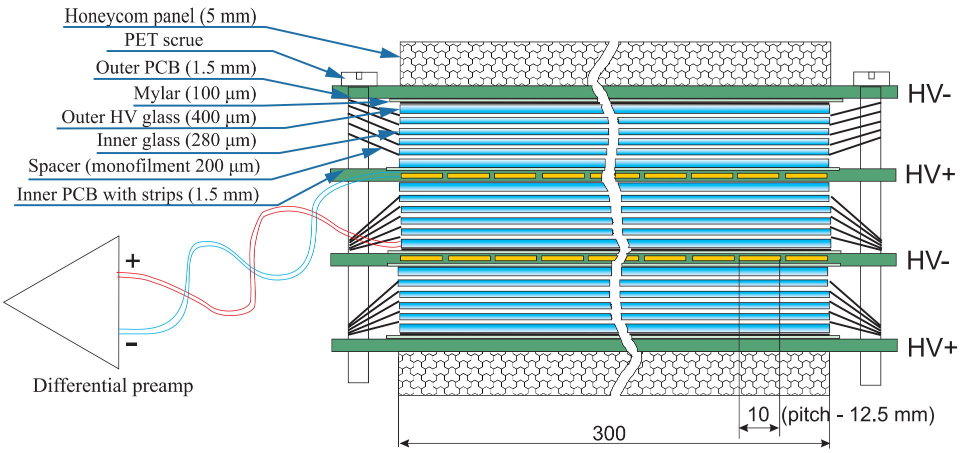

Fig.8. Cut view of the triple-stack MRPC.

A prototype of the proposed MRPC was tested at CERN with the NA61 spectrometer in November 2016. The test setup was located just behind the existing TOF-L wall and registered secondary particles from the Pb-Pb interactions with beam energy of 30 GeV. The first test was performed using a stand-alone data acquisition system with two types of the trigger. The first type of the trigger was coincidence of two scintillator counters located before and after MRPCs. The second type was the central interaction trigger (T2) of the NA61 DAQ. The system of two MRPCs with pad readout [18] was used as a reference to define the time resolution of the tested MRPC.

The time resolution of the tested MRPC was estimated from the time distribution between the tested MRPC and two “start” MRPCs (as demonstrated in Fig.9). If one considers that the time resolution of one pad MRPC is about 62 ps then it can be asserted that the time resolution of the system of two detectors is $equal\ to\ 62/\sqrt{2} \cong 44$ ps. The time resolution of the tested MRPC is $\sqrt{66^2 - 44^2} \cong$ 50 ps.

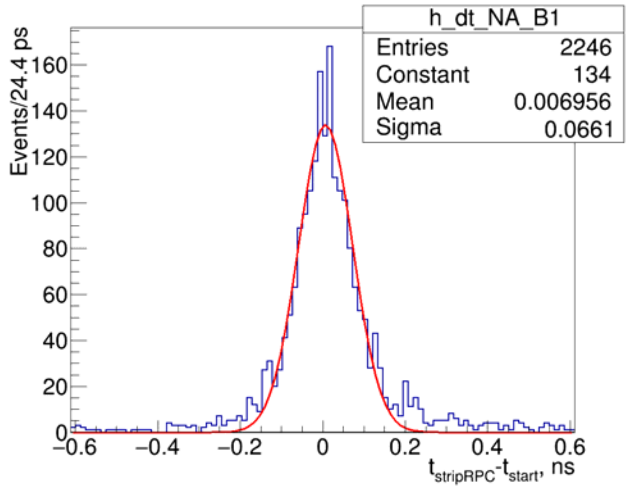

Fig. 9. Distribution of the time difference between the tested MRPC and mean time of two reference MRPCs with pad readout.

2.3. Expected results

The expected results of the JINR group activity based on the experience accumulated by the present time as well as the requested long period of data taking with primary Pb, secondary light ions and hadron beams are well justified by the latest excellent records.

To investigate the main physics issues listed briefly in the introduction by the Dubna group, the following data will be obtained:

- transverse momentum and rapidity spectra for $\pi^{+/-}$, $K^{+/-}$, p, anti-p, deuteron, antideuteron, triton, ^{3}He;
- energy and system size dependence of these particles yields as well as for the coalescence factors for light nuclei production ($\sqrt{s_{NN}}$ = 6.3, 7.6, 8.8, 12.3, and 17.3 GeV; reactions p+p, Be+Be, Ar+Sc, Xe+La);
- charge dependence of the particle yields and anisotropic flow harmonics in the forward rapidity region which is sensitive to effects induced by the strong electric and magnetic fields generated in a heavy ion collision. It will bring new experimental information related to electromagnetic effects and the longitudinal expansion of the system formed in the heavy ion collision;
- 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.
- data analyses for the T2K replica target in the configuration with the maximum magnetic field to measure the hadron yields and cross sections in the interactions of protons, pions and kaons with beryllium, carbon and aluminum at the momenta 31, 60 and 120 GeV/c.

A few million events, at least, will be used to analyze each of the above items.

In addition, the R@D will be completed to use as prototype of the new time-of-flight system based on MRPC.

Being responsible for data taking with 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 three PhD theses using the results obtained in the NA61 experiment and the NICA project.

2.4. Beam time schedule

The 2018 beam request is as follows:

(i) 14 days of h^+ beam at 13-400 GeV/c are needed for the PSD calibration.

(ii) 7 days of p beam at 400 GeV/c are needed for the MRPC test.

(iii) 7 days of K^+ beam at 30 or 60 GeV/c are needed for data taking for the Fermilab neutrino beams.

(iv) 28 days of p beam at 120 GeV/c are needed for data taking for the Fermilab neutrino beams.

(v) 7 days of secondary ^{12}C and ^{16}O beams are needed for the test of fragmentation cross section measurements requested by the cosmic-ray community.

(vi) 60 days of Pb beam at 13A, 19A, 75A and 150AGeV/c are needed to complete data-taking on Pb+Pb collisions.

The Pb beam time will be used as follows:

(a) 20 days Pb beam at 150AGeV/c for open charm, collective effects and fluctuations,

(b) 20 days Pb beam at 75AGeV/c for open charm, collective effects and fluctuations,

(c) 8 days Pb beam at 40AGeV/c for collective effects and fluctuations,

(d) 8 days Pb beam at 19AGeV/c for collective effects and fluctuations.

As a result of these runs, rich experimental data will be obtained for further analysis. Previously, a lot of statistics was obtained for the needed analysis. The NA61/SHINE data recorded within the (beam momentum)-(system size) scan in 2009-2017 and the request for 2021-2024 are presented in Fig10.

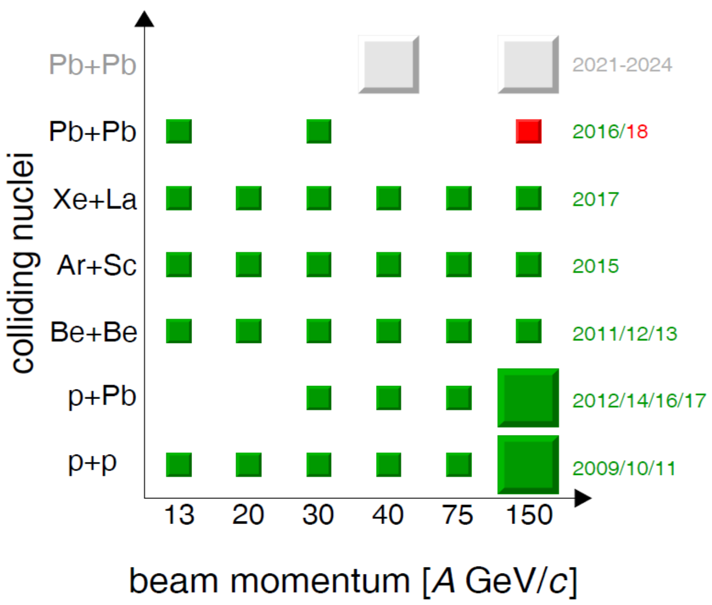

Fig.10. The NA61/SHINE data recorded within the (beam momentum)-(system size) scan in 2009-2017 and the request to 2021-2024 (the upper squares). The size of the squares corresponds to the collected or planned statistics.

2.5. Share of responsibility

JINR contributions/responsibilities:

- Maintenance and operation of TOF-L/R detectors;
- TOF-L/R data calibration;
- R@D for TOF base on MRPC;
- Software developments and maintenance of the software library;
- Raw data reconstruction and DST production;
- Data analysis.

2.6. Scientific experience of authors

The authors of the project have a vast scientific experience. A. Malakhov, G. Melkumov and G. Lykasov possess the Doctor of Science degrees and contribute to study the problems of relativistic nuclear physics. Six young employees have been also actively involved into the Project. Three of them, V. Babkin, M. Buryakov and M. Rumyantsev, have developed a time-of-flight system for the NICA project based on MRPC detectors. They are expected to apply this system for the NA61 experiment. The other three employees, V. Kireyeu, A. Zaitsev, V. Lenivenko, have actively joined to the analysis of the experimental data. They all have publications and plans to prepare PhD theses.

2.7. Publications, PhD theses and presentations at conferences

In general, the JINR participants are the co-authors of more than 100 publications on the NA61/SHINE experiment. As for 2017-2018 years, 11 articles [3-12, 15, 16] have already been published. In three of them, the Dubna group members are the principal co-authors. According to the results of research on the NA61 installation, the JINR employees have defended 3 PhD and 2 doctoral theses. In 2017 V.Kolesnikov has successfully defended a doctoral dissertation on the study of the production of light nuclei and antinuclei in nuclear interactions. He is one of the leading physicists in the NICA project now. During 2017 the members of the JINR group made 5 presentations on the NA61 installation at the international meetings and conferences [8,9].

3. Manpower resources

Tables 1 and 2 show the participants of the NA61 JINR experiment with the directions of the research and share of their participation. Table 3 shows the age of the young employees.

Table 1. LHEP manpower.

№	Name	Category	FTE
1	Babkin V.	MRPC	0.2
2	Buryakov M.	MRPC	0.2
3	Kireyeu V.	Analysis, data taking	0.5
4	Kolesnikov V.	Analysis	0.1
5	Lenivenko V.	Analysis, data taking	0.2
6	Malakhov A.	Analysis, data taking	0.3
7	Melkumov G.	Analysis, data taking	0.8
8	Rumyantsev M.	MRPC	0.2
9	Zaitsev A.	Analysis, data taking	0.8
Σ			3.3

Table.2. LNP manpower.

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

Table 3. The age of young employees.

№	Name	Age (years)
1	Babkin V.	36
2	Buryakov M.	27
3	Kireyeu V.	28
4	Lenivenko V.	27
5	Rumyantsev M.	29
6	Zaitsev A.	26

4. Estimation of the project budget (form No. 26), expenses for 3 years

Form No.26

Proposed timetable and necessary resources for the implementation of the NA61 project (JINR participation)

Expenditures, resources, financing sources			Cost (k$) Resource requirements		Proposal of the Laboratory jn the distribution of finances and resources: 2019		2020		2021	
			Theme 1087	Theme 1124	Theme 1087	Theme 1124	Theme 1087	Theme 1124	Theme 1087	Theme 1124
Expendi-ture	Main units of equipment, work towards its updating, adjustment, etc.		35	-	13	-	13	-	9	-
	Construction /repair of premises		-	-	-	-	-	-	-	-
	Materials		30	-	12	-	12	-	6	-
Required resources	Stan-dart hour	LHEP design bureau	-	-	-	-	-	-	-	-
		JINR Work-shop	-	-	-	-	-	-	-	-
		LHEP Work-shop	-	-	-	-	-	-	-	-
		Nuclotron	-	-	-	-	-	-	-	-
Σ			65	-	25	-	25	-	16	-
Total:			65		25		25		16	
Financing sources	Budget. Theme 1087		65		25		25		25	

Theme 1087 - LHEP.

Theme 1124 -_ DLNP

Project leader A.I. Malakhov

23.03.2018

5. Estimation of expenditures (Form № 29)

Form No. 29

Estimated expenditures for the Project: “Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS (NA61/SHINE – SPS Heavy Ion and Neutrino Experiment)”

№	Name of the items cost	full cost (k$)		2019		2020		2021	
		Theme 1087	Theme 1124	Theme 1087	Theme 1124	Theme 1087	Theme 1124	Theme 1087	Theme 1124
1.	Accelerator (Nuclotron), hour	-	-	-	-	-	-	-	-
2.	Computer communications	15	-	5	-	5	-	5	-
3.	LHEP Design bureau	-	-	-	-	-	-	-	-
4.	LHEP Workshop	-	-	-	-	-	-	-	-
5.	Materials	30	-	12	-	12	-	6	-
6.	Equipment	20	-	8	-	8	-	4	-
7.	Payment research	-	-	-	-	-	-	-	-
8.	Travel allowance, including:	210	12	65	4	60	4	85	4
	(a) to non-rouble zone countries	210	12	65	4	60	4	85	4
	b) in the rouble zone	-	-	-	-	-	-	-	-
	c) protocol-based	24	12	8	4	8	4	8	4
Σ		299	24	98	8	93	8	108	8
Total direct expenses:		323		106		101		116	

Theme 1087 – VBLHEP
Theme 1124 - DLNP

PROJECT LEADER A.I.Malakhov

VBLHEP DIRECTOR V.D.Kekelidze

DLNP DIRECTOR V.A.Bednyakov

VBLHEP CHIEF ENGINEER-ECONOMIST L.M.Nozdrina

DLNP CHIEF ENGINEER-ECONOMIST

6. Strengths, weaknesses, opportunities, threats

The strengths of the project are as follows:
- relevance to the physics program;
- availability of an active experimental facility with unique parameters;
- a large amount of experimental data collected for proton-nuclear and nuclear-nuclear interactions in a wide energy range (from 13 to 158A·GeV)
- extensive experience for experimental data analysis;
- a large number of young employees;
- opportunity for training young people for the NICA project.

Weak points could hardly be found in the Project

The Project has the opportunity of attracting more young physicists to be also trained for the NICA project.

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8. Appendix

8.1 V.V. Burov review

Reference on prolonging project NA61/SHINE in 2019-2021 years (JINR participation)

The offered project is a continuation of successful participation of the JINR group of employees from the Laboratory of High Energy Physics named after V.I.Veksler and A.M.Baldin and from the Laboratory of Nuclear Problems named after B.P.Dzelepov (JINR) in the experiment NA61/SHINE (SPS Heavy Ion and Neutrino Experiment, CERN) at the Super Proton Synchrotron (SPS).

NA61/Shine is a multi-purpose experiment to study hadron-proton, hadron-nucleus and nucleus-nucleus collisions. The broad range momentum of beam particles, from pions to lead nuclei, together with the large acceptance and high resolution NA61/SHINE detector gives a unique opportunity to perform the needed measurements.

This document gives a review of the physics research programme on relativistic nuclei interactions and describes unique experimental results obtained during the previous two years with active participation of the JINR employees in the project NA61. There are also plans of the joint work in the framework of the experiment for a period of 2019-2021 years.

First of all, now it is necessary to carry out analysis of a huge number of the accommodated data, perform modernization of the set-up and provide the performance of the runs in 2018.

The experiment carries out a comprehensive and consequent study of hadron interactions starting from elementary nucleon-nucleon processes till collisions of heavy ions having different atomic numbers and beam energies (20A·GeV-158 A·GeV).

The participants of the project are co-authors of numerous publications and presentations on this topic which are widely quoted in the world literature.

Further participation in experiment NA61 will allow the physicists to continue systematic studying of nucleus-nucleus interactions starting from light nuclei till the heavy ones including the nuclei of the middle sizes. For this programme the studies at the set-up NA61 are extremely valuable and still beyond the competition due to unique parameters of the facility and availability of nuclei beams at SPS in CERN.

The physical programme of the NA61 at SPS, CERN, includes the following main items on experimental data taking and analysis:

• study of energy dependence of hadron properties in p + p и p+A interactions, as well as in nucleus-nucleus collisions to study characteristics of these processes and search for the proof of the critical point existence in the strongly interacting matter;

• study of hadron properties in proton-proton and proton nuclei interactions to understand better the nucleus-nucleus reactions;

• study of hadron production in hadron interactions necessary for neutrino and space experiments.

It is important to emphasize that the beam momentum range provided for NA61/SHINE by SPS is very important for the heavy ion, neutrino and cosmic ray communities. Therefore there is a world-wide effort to construct new facilities providing ion and hadron beams in the CERN SPS beam momentum range. They are: the fixed-target facilities at FAIR, Germany, and J-PARC, Japan, as well as the collider facility NICA, Russia. They will start operation after the results needed for the project are completed. The data from the collider facilities are typically complementary to the corresponding fixed target results. In particular, charm hadron measurements are only possible at the fixed target facilities providing the collision energy and data taking rate to be high enough. NA61/SHINE is the only experiment which carries out the requested measurements in the near future. Moreover, the needed operation of NA61/SHINE beyond Long Shutdown 2 would allow physicists to efficiently extend the programme of new measurements, if necessary.

In addition, JINR group participation in the NA61 experiment is necessary in the framework of training young professionals for the NICA project. On physics close to the NICA programme, in frame of the NA61 project there are two doctoral and two candidate dissertations defended. In 2017 V.Kolesnikov defended his doctoral dissertation on the study of the light nuclei yield in nuclear interactions. Now he is one of the leading physicists in the NICA project.

From the mentioned above it is evident that participation of the JINR group in NA61 experimental data analysis and new measurements on this set-up are considered to be fruitful and should be recommended to prolong the JINR group participation for the next period of 3 years.

Modest financial requests are quite justified to obtain physical results and, as expected, they will be a significant contribution to the research programme of JINR.

It is necessary to stress that JINR participation in the experiment NA61 is very important since the research programme in this experiment lies in the main stream of the long-range programme in the field of relativistic nuclear physics at JINR. It is complementary to the studies being carried out at the Nuclotron (JINR), RHIC (BNL) and the obtained experimental results are needed for planning the research at the acceleration complexes of NICA (JINR) and FAIR (GSI).

Doctor of Phys. and Math. Sciences,
Professor V.V.Burov

20.02.2018

8.2. I.A. Typkin review

Referee report
on the NA61/SHINE project (JINR participation)

A group of physicists from JINR has been actively participating in NA61 experiment for quite a long period of time.

Set-up NA61 operates with heavy ion beams of the Super Proton Synchrotron (SPS) at the energy of 158 A·GeV and uses more light secondary nuclei.

In the due time the group from the Laboratory of High Energy Physics made a time-of-flight detector which has become one of the key detectors to identify charged particles.

The research programme has performed the search for phase transition of the hadron matter to quark-gluon plasma and deconfinement in the hot dense matter in the collisions of relativistic heavy ions.

The key problem was identification of experimental signatures of QGP production. Several of these signatures of forming the transient QGP state during the early stage of the collision have been proposed: enhanced strangeness production and suppression of the open charm. The lately results on the energy dependence of hadron production in central Pb+Pb collisions at 20-158 A·GeV coming from the energy scan program at the CERN SPS can serve as evidence for the existence of transition to the QGP state.

It is necessary to emphasize that the results of the experiment have inspired some theoretical studies, especially those which refer to the proof of the beginning of deconfinement on SPS at the reduced energy. These studies are planned to be continued further.

Besides, they have stimulated measurements at low energies in experiments STAR and PHENIX at RHIC set-up at the Brookhaven National Laboratory (USA) and realization of the priority projects on the programme NICA/MPD at JINR and CBM at GSI.

Project NA61 presents a wide research programme: searching for the critical point in strongly interacting nuclear matter, studies of the deconfinement phenomenon, physics at high transversal momenta and analysis of hadron spectra for neutrino experiments and experiments with cosmic particles.

In the framework of the ion programme the NA61experiment plans to carry out a wide range of two-dimension scanning in dependence on the size of the system and collision energy to search for the critical point. A complex study of the phase diagram of strong interaction of matter to search for the proof of the critical point is an extremely important task.

There is no doubt that the JINR contribution is important for operation of the developed time-of-flight system and construction of a new time-of-flight system based on RPC detectors.

The JINR employees have contributed significantly to measuring and analysis of the processes with light nuclei production. This part of the experiment was totally a responsibility of the LHEP group from data taking, data analysis, and publication of the physical results.

The collaboration in the framework of NA61 is very efficient and simultaneously fruitful for the both institutions: CERN and JINR. In total, according to the experiment NA49/NA61, three candidate and two doctoral dissertations have been defended.

Continuation of this collaboration will provide a deeper understanding of the nuclear matter properties at relativistic energies.

The JINR participation in experiment NA61 is also very important for training the young scientists at JINR for the future project NICA, whose physics programme contains complementary tasks being solved in the framework of project NA61. The experience of work of the JINR team with different detectors on SPS ion beams at CERN can be hardly overestimated as well as their participation in data processing and analysis.

The present project has been prepared taking into account recommendations of the 47-th JINR PAC meeting for Particle Physics, June 26-27, 2017. The optimization of the number of the project members and their participation shares in the project were made, taking into account employment on the NICA project. The participation of the JINR group in the data analysis was increased. Additionally three young employees have been involved in the data analysis. A detailed program R&D for time-of-flight on the MRPC base for the period of 2019-2021 has been presented.

From the mentioned above it follows that participation of the JINR group in experiment NA61 is fruitful. The relatively modest financial requests are fully justified by good physical results which, no doubt, would promote the scientific reputation of JINR. Besides, the expected results are sure to be recognized a significant contribution to the development of the long-term research programmes in the field of heavy ion relativistic physics at JINR, (Dubna).

I would like to recommend approving prolongation of the JINR participation in NA61 experiment in 2019-2021 with the first priority within requested resources.

Doctor of Phys. and Math. Sciences,
Leading Researcher of VBLHEP, JINR

I.A.Tyapkin

19.03.2018

8.3. Extract from the decision of the STC Laboratory

ВЫПИСКА ИЗ ПРОТОКОЛА
заседания НТС ЛФВЭ
от 20 марта 2018 года

Присутствовали на заседании 23 члена НТС из общего числа 40 членов НТС.

НТС ЛФВЭ заслушал отчет и рассмотрел предложение о продлении проекта «**NA61**» темы "Исследования по физике релятивистских тяжелых и легких ионов на ускорительных комплексах Нуклотрон/NICA ОИЯИ и SPS ЦЕРН" (02-1-1087-2009/2020). НТС решил одобрить отчет и рекомендовать ПКК по физике частиц продлить проект до конца 2021 года с первым приоритетом.

Рецензенты: В.В.Буров, И.А.Тяпкин.

Председатель НТС ЛФВЭ — Ю.А.Панебратцев

Ученый секретарь НТС ЛФВЭ — С.П.Мерц

ABSTRACT OF THE MINUTES
OF THE MARCH 20, 2018
VBLHEP STC MEETING

23 STC members were present at the meeting out of a total of 40 STC members.

VBLHEP STC heard the report and considered the proposal on continuation of the NA61 project within the framework of theme (02-1-1087-2009/2020) "Research on Relativistic Heavy and Light ion Physics. Experiments at the Accelerator Complex Nuclotron/NICA at JINR and CERN SPS". STC decided to endorse the report and to recommend that PAC for Particle Physics support continuation of the project until the end of 2021 with first priority.

Referees: V.V.Burov, I.A.Tyapkin.

VBLHEP STC Chairman — Yu.A.Panebratsev

VBLHEP STC Scientific Secretary — S.P.Merts