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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. THEORY

Recent Progress in Experiments with Relativistic Ions at the Nuclotron[1]

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Abstract—Progress in realization of the NICA project in JINR is outlined with special attention paid to results of the latest Nuclotron upgrades. The most important of them are (1) renewal of the polarized deuteron beam with kinetic energy up to $T_{\rm kin}$ ~ 5 GeV/nucleon, now available for experiments with fixed targets, and (2) successful acceleration in the Nuclotron (and extraction from it) of relativistic polarized protons.

Keywords: relativistic heavy ions, nuclear matter, equation of state, phase diagram, phase transitions, few nucleon systems, polarization phenomena, polarized deuterons, polarized protons

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1. INTRODUCTION

Nuclotron-based Ion Collider fAcility (NICA) comprises a set of instruments (including superconductive collider of heavy nuclei), based on modern technologies, which are necessary in order to investigate such specific collisions between heavy nuclei, when nuclear matter is highly compressed: to densities much higher than the density of "normal" nuclei.

It is the international project, now being under realization at JINR (see Ref. [1]). The physical program of the NICA project is outlined in Ref. [2, 3].

The ultimate aims of research at the NICA facility are to understand (see Fig. 1):

• How a "proto"-matter of the Universe was formed in few μs after the "Big Bang" event?

• What properties and forms (phases) had this "proto"-matter?

• What phase transitions (see Fig. 2) the "proto"-matter had during its evolution (if had)?

• How elementary particles and atomic nuclei emerged in the "proto"-matter?

• How the "proto"-matter evolved into the present matter of the Universe?

Another part of the NICA physical program is related with study of polarization phenomena at intermediate energies (see Ref. [4]), namely:

• spin structure of nucleons as well as the phenomenology of the *NN* interaction;

• few nucleon systems at short distances, where sub-nucleonic aspects, effective multi-nucleon forces etc. may be essential.

Also, more traditional "flavor" physics studies, related with the problem of possible changes of particle properties in baryonic matter (cold and normal, hot and dense), are included in the NICA physical program.

2. RECENT PROGRESS WITH NUCLOTRON BEAMS

Significant progress in development of instrumental basis for physics of polarization phenomena within the NICA project was achieved during last two years.

In the first half of the 2016 year the new source of polarized ions (SPI, Fig. 4) was commissioned and set into exploitation. (Details about the SPI operating and its characteristics can be found in Ref. [5] and references therein.) Simultaneously with this work, the new fore-injector for LU-20 (see Fig. 4 capture) was mounted and set into exploitation. Commissioning, tests and tunings of the new injection chain elements (including the SPI) before LU-20 were successfully fulfilled in the 1-st half of the year 2016; at the same time the modernized polarimetric system at the Nuclotron(which includes the low energy polarimeter after LU-20, polarimeters at the accelerated internal beam and at the slow extracted beam) was successfully prepared and used during the run.

In the second half of the 2016 year the Nuclotron had physical run. Its ultimate goals were optimization of the SPI settings (in order to increase its perfor-

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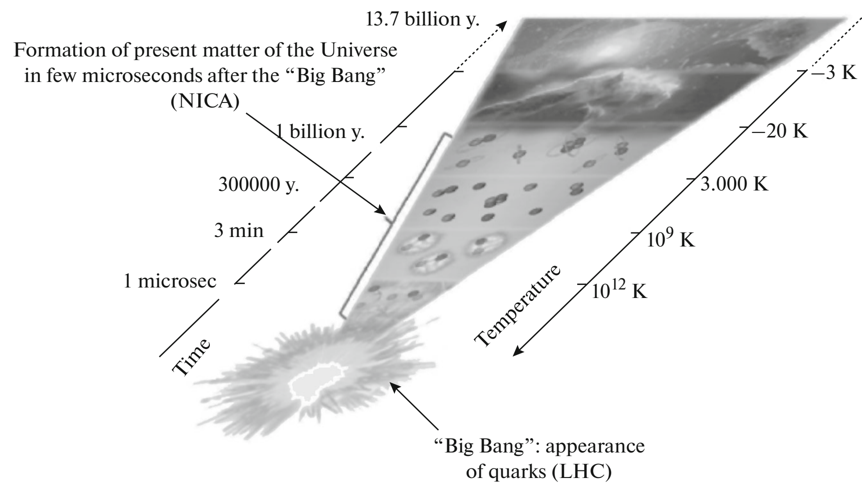

Fig. 1. Where research at NICA complex are aimed to.

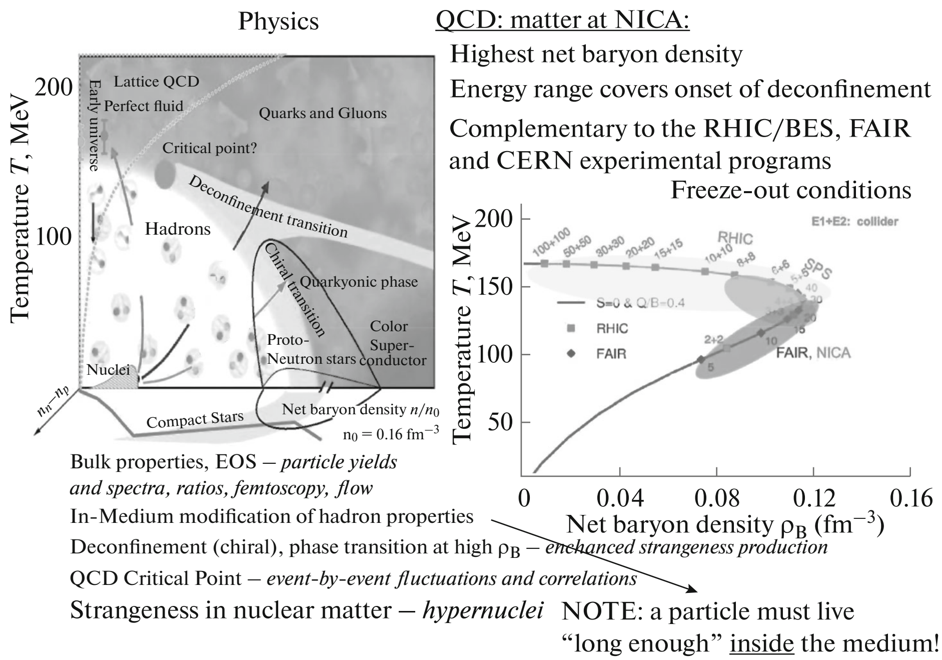

Fig. 2. Theoretical predictions for the phase diagram of the QCD matter (left panel) and for the energy regions, where the highest net baryon density can be reached (right panel).

mance) and "physics with polarized deuteron beam", namely: (1) with vector polarized deuteron beam: measurements of analyzing powers for polarized protons and neutrons in the multi-GeV energy region (within the ALPOM-2 project); (2) with the tensor polarized deuteron beam: measurements of cross sections and analyzing powers of deuteron scattering at CH2 and C targets (within the DSS project). Results of that run were quite successful and some new data were obtained at first time in the world, in particular – with polarized quasi-monochromatic neutron beam up to the neutron momenta of 3.75 GeV/c.

The most significant result of the Nuclotron runs in 2016 year is that the JINR has again, at the LHEP Nuclotron, the polarized deuteron beam with kinetic energy up to 5 GeV/nucleon, available for physical experiments.

In the begin of the 2017 year the work, started in the previous Nuclotron run, was continued in order to:

• increase taken statistics and complete the started programs (within the ALPOM-2 and DSS projects);

• increase the SPI performance further;

• perform tests of possibility to accelerate polarized protons in the Nuclotron and extract them.

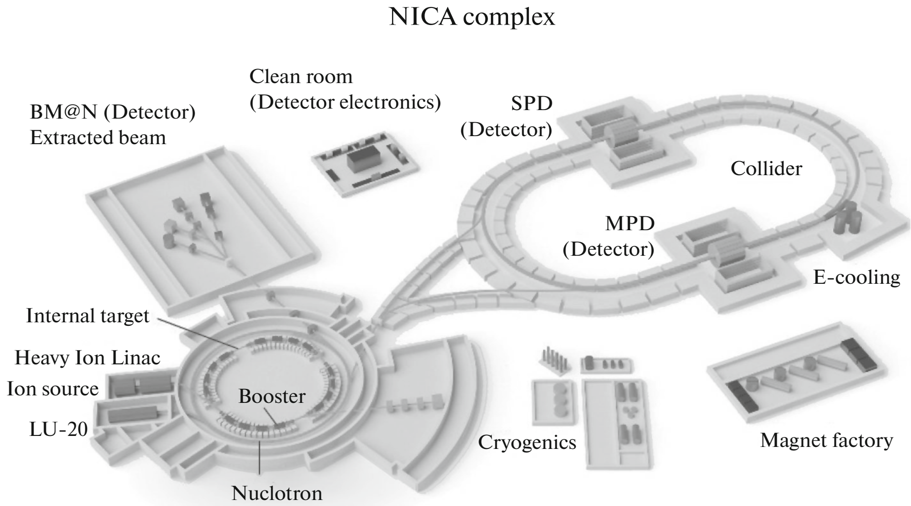

Fig. 3. Schematic layout of the Nuclotron-NICA complex.

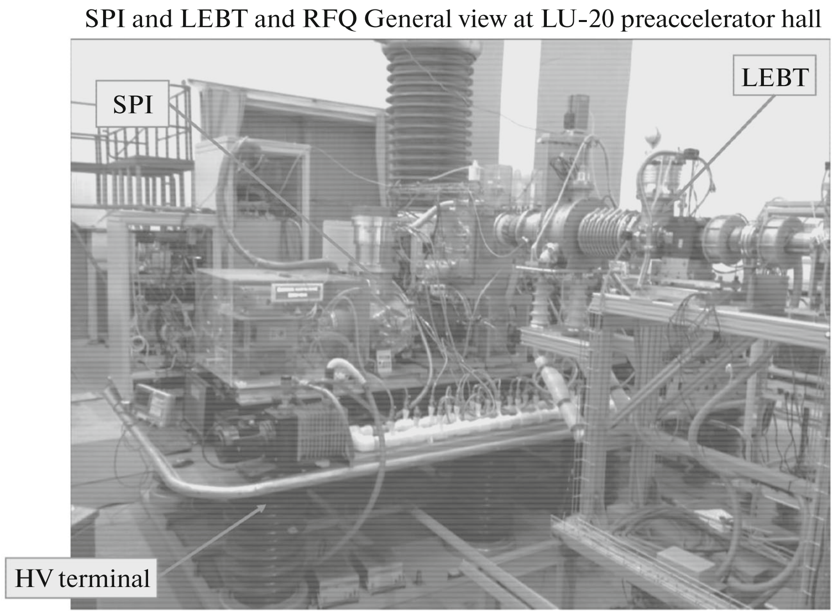

Fig. 4. Schematic layout of the SPI with the new fore-injector consisting from the LEBT, RFQ and MEBT. Here LEBT stands for the "Low Energy Beam Transport" line between the SPI and 4 wanes RFQ; the beam from RFQ is being transferred to the linear accelerator LU-20 by the 'Medium Energy Beam Transport" line (MEBT), not shown here. The LEBT, RFQ and MEBT were assembled in place in March – May of the year 2016.

Preliminary results of those runs were reported at the XVII Workshop on High Energy Spin Physics (DSPIN-17), held in Dubna (Russia) in September 11–15, 2017: see Refs. [6–8]. In particular, new physical results were obtained, which are of high importance and value for intermediate energy polarimetry of neutrons (above pion production threshold): see Ref. [6] and Fig. 5. It is necessary to emphasize that results, reported in Ref. [6], are very important for **polarimetry of secondaries** (i.e., for example, of scattered particles) when their polarization must be measured.

SPI performance for production of polarized deuterons was investigated. In particular, the settings of the SPI in the "mixed" mode with tensor and vector polarizations were studied (results are quoted in Ref. [7]) as well as an optimization of settings for mode of the pure vector polarization of deuterons (see Ref. [8]) was done.

The capability of the Nuclotron to accelerate polarized protons was investigated at first time in JINR. Polarization of the internal beam of polarized protons was measured at 500 MeV (see Ref. [7]) and after slow extraction at 1 and ~2 GeV (see Ref. [8]).

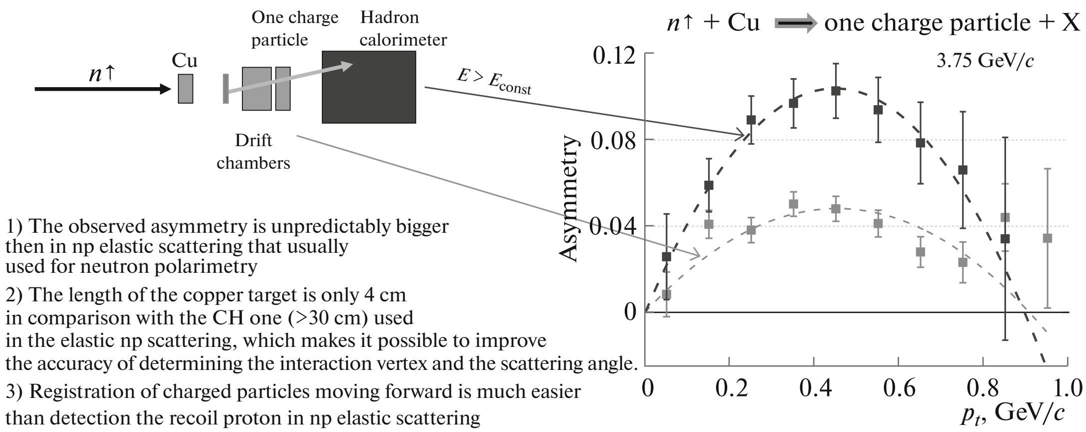

Fig. 5. Preliminary results for inclusive $n_{\text{polarized}} + \text{Cu} \to p + X$ reaction (see Ref. [6]).

The most important result is that at first time in the JINR history, it now has not only the polarized deuteron beam, but the relativistic polarized proton beam as well, accelerated for energies above 1 GeV. Despite experiments can already be carried out with such a beam, additional works must be (and can be!) done in order to effectively pass through the known depolarizing resonances for the proton beam in the Nuclotron (in order to accelerate protons to higher energies) and to avoid losses of polarization at the injection and extraction stages.

This result will definitely have rather important impact on the very conception of the NICA Storage Rings as well as on the "Spin Physics" program for the Nuclotron-NICA complex.

There is quite remarkable progress in other aspects of the NICA project, especially in development of its ifrastructure, but only aspects, related with physics, are briefly outlined in this talk.

3. CONCLUSIONS

The most impressive progress in experiments with relativistic ions at the Nuclotron during 2016-2017 years was achieved in development of the instrumental base for the "Physics of polarization phenomena at intermediate energy region", namely in directions, listed below.

• Restoration of the accelerated polarized deuteron beam with kinetic energy up to 5 GeV/nucleon. It is very important result for the NICA project in its spin physics part. It is of a great importance as for experiments in the "collider" mode, as in the "fixed target" mode.

• Acceleration of polarized protons in the Nuclotron. It is another very important result for the NICA project, as concerns its spin physics part: both for experiments in the "collider" mode and in the the "fixed target" mode.

It should be taken into account, that interest to the intermediate energy physics problems is being renewed and new experimental opportunities are being opened for polarization phenomena studies (at JINR, first of all) or are motivated (see, for example, Ref. [9] for meson beams at future machines). It should be noted that an interesting new opportunities are being opened in China, within the "High Intensity Heavy Ion Accelerator Facility" (i.e. the "HIAF" project).

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