Challenges of Compressed Baryonic Matter:
The NICA White Paper

A.S. Sorin
(for the NICA/MPD collaboration)
Ultimate goals:

- Study of the phase transition from hadronic to partonic matter – Quark Gluon Matter
- Search for the critical point
- Study of the in-medium properties of hadrons at high baryon density and temperature
- Study of the phase transition from hadronic to partonic matter – Quark Gluon Matter
“Hilbert Problems”
of Dense Matter Physics:
- which phases?
- which degrees of freedom?
- nature of the nucleon?
- how hadronization proceeds?
- ... 

Challenging questions:
- Character of the transition?
- Signals for 1st order? CP?
The Big Bang vs the Little Bangs

The Universe

- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Inflation
- Quantum Fluctuations

WMAP

1st Stars about 400 million yrs.

Big Bang Expansion

13.7 billion years

Credit: NASA

The Little Bang

1fm/c ~ 3 x 10^-24 s

Credit: P. Sorensen

Collision evolution

Expansion and cooling

Particle detectors

Kinetic freeze-out

QGP phase

Quark and gluon degrees of freedom

Hadronization

Viscous hydrodynamics

Distributions and correlations of produced particles

WMAP

HIC
How can we prove that an equilibrium QGP has been created in central Au+Au collisions?!
Hadron gas
Mixed Phase
Pre-equilibrium
QGM
Freezeout
Time
Space
Initial nuclei
System of maximal net baryon (freeze-out) density is created in A+A collisions at NICA energies \(\rightarrow\) optimum for the compressed baryon matter exploration.

\[ \rho_B \]
Dense QCD Matter Physics

- **Nuclear equation-of-state, new forms of matter at high densities?**
  What are the properties and the degrees of freedom of QCD matter at neutron star core densities?

- **Hadrons in dense matter:**
  What are the in-medium properties of hadrons?
  Is chiral symmetry restored at very high baryon densities?

- **Production of single and double hypernuclei**
  How far can we extend the third (strange) dimension of the nuclear chart?

- **Strange matter:**
  Does strange matter exist in the form of heavy multi-strange objects?
Physics Topics and Observables

The equation-of-state at high $\rho_B$
- collective flow of hadrons
- particle production at threshold energies (multistrange hyperons)

Deconfinement phase transition at high $\rho_B$
- excitation function and flow of strangeness ($K, \Lambda, \Sigma, \Xi, \Omega$)
- excitation function of low-mass lepton pairs

QCD critical endpoint
- excitation function of dynamical event-by-event fluctuations

Onset of chiral symmetry restoration at high $\rho_B$
- in-medium modifications of hadrons ($\rho, \omega, \phi \rightarrow e^+e^-(\mu^+\mu^-)$)

Strange matter
- (double-) lambda hypernuclei
- strange meta-stable objects (e.g. strange dibaryons)
Signals of the phase transition:

- Strangeness enhancement
- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow ($v_1$, $v_2$)
- Thermal dileptons
- Jet quenching and angular correlations
- High $p_T$ suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!

Messengers from the dense fireball...
SEARCHING for a QCD MIXED PHASE at the NUCLotron-Based ION ION COLLIDER FACILITY
(NICA White Paper)
The NICA White Paper addresses the following key topics:

- Phases of dense QCD matter and conditions for their possible realization
- Characteristic processes as indicators of phase transformations
- Estimates of various observables for events
- Comparison to other experiments
**NICA White Paper - Contents**

(111 contributions; 60 prioritized)

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Editorial</td>
<td>(7)</td>
</tr>
<tr>
<td>2</td>
<td>General aspects</td>
<td>(9; 8)</td>
</tr>
<tr>
<td>3</td>
<td>Phases of QCD matter at high baryon density</td>
<td>(16; 10)</td>
</tr>
<tr>
<td>4</td>
<td>Hydrodynamics and hadronic observables</td>
<td>(22; 7)</td>
</tr>
<tr>
<td>5</td>
<td>Femtoscopy, correlations and fluctuations</td>
<td>(10; 4)</td>
</tr>
<tr>
<td>6</td>
<td>Mechanisms of multi-particle production</td>
<td>(9; 3)</td>
</tr>
<tr>
<td>7</td>
<td>Electromagnetic probes and chiral symmetry in dense QCD matter</td>
<td>(9; 8)</td>
</tr>
<tr>
<td>8</td>
<td>Local P and CP violation in hot QCD matter</td>
<td>(8; 5)</td>
</tr>
<tr>
<td>9</td>
<td>Cumulative processes</td>
<td>(3; 3)</td>
</tr>
<tr>
<td>10</td>
<td>Polarization effects and spin physics</td>
<td>(4; 3)</td>
</tr>
<tr>
<td>11</td>
<td>Related topics</td>
<td>(5; 1)</td>
</tr>
<tr>
<td>12</td>
<td>Fixed Target Experiments</td>
<td>(9; 6)</td>
</tr>
</tbody>
</table>

List of Contributors (188)
NICA White Paper - International Effort

Statistics of White Paper Contributions

104 contributions: 188 authors from 70 centers in 24 countries

SEARCHING for a QCD MIXED PHASE at the NUCLotron-based ION COLLIDER FACILITY
(NICA White Paper)
NICA White Paper prioritization Team

**THEORY**
- J. Aichelin (SUBATECH Nantes, France)
- D. Blaschke (JINR & Univ. Wroclaw, Poland)
- E. Bratkovskaya (Univ. Frankfurt, Germany)
- J. Randrup (LBNL Berkeley, USA)
- V. Toneev (JINR)
- O. Teryaev (JINR)

**EXPER.**
- V. Friese (GSI Darmstadt, Germany)
- M. Gazdzicki (Univ. Frankfurt, Germany & Univ. Kielce, Poland)
- O. Rogachevsky (JINR)
Fixed Target Experiments at the Nuclotron

→ Ideally suited for exploration of reaction mechanisms & in-medium properties
→ Energy range formerly not accessible or of limited experimental information
→ Expectation of a rich structure of the QCD phase diagram at high densities

TOOL:
→ Subthreshold production of (multi-)strange hadrons: Φ, K*, K*, Λ, Σ, Ξ, Ω-
→ Extend studies at SIS18, observe Ω^- as result of multi-step production here
→ Extract information about densities reached in the collision → EoS

Important:
→ Systematic study of production mechanisms by measurement of excitation functions for hadron production in p+p, d+p
→ High enough statistics for multi-dimensional analysis (centrality, y, p_T)

Production of hypernuclei: → study recommended!
→ Two mechanisms: (1) Absorption of produce Λ by spectator nuclei  
(2) Coalescence of Λ nucleons at midrapidity
→ Important for hypernuclei spectroscopy: extract Y-N, Y-Y interactions
Collider Experiments at MPD

First round of MPD/NICA experiments:

→ diagnostic observables of beam energy scan programs at SPS, RHIC
→ MPD detector to be optimized to study fluctuations an correlations
→ excitation functions of fluct./corr., dependence on centrality & system size

Observables:

→ EBE fluctuations of multiplicity and $p_T$ of charged and identified part. $(p,K,\pi)$
→ long-range angular correlations like $v_1$, $v_2$ of $(p,K,\pi,\Lambda)$ and light clusters
→ three-body correlations (for CME) and short-range two-particle corr. (size)
→ coverage in rapidity and $p_T$ shall be large, low $p_T$ extremely important!
→ measurements as function of collision energy for following systems:
  – $p+p$ collisions
  – $d+d$ collisions with possibility of off-line event selection of reactions with $(p,p)$, $(p,n)$, $(n,n)$ spectators
  – $d+Pb$ collisions
  – collisions of identical heavy nuclei, such as $Pb+Pb$ (later also smaller A)
→ second stage: open-charm hadrons, di-leptons, di-photons at NICA
Satellite Meetings:


Email: sqm@jinr.ru
Website: http://sqm.jinr.ru
There's two possible outcomes: if the result confirms the hypothesis, then you've made a discovery. If the result is contrary to the hypothesis, then you've made a discovery.

(Enrico Fermi)
Welcome to the collaboration!

Thank you for attention!
QCD phase diagram: prospects for NICA

Energy Range of NICA
unexplored region of the QCD phase diagram:

- Highest net baryon density
- Onset of deconfinement phase transition
- Discovery potential:
  a) Critical End Point (CEP)
  b) Chiral Symmetry Restoration
  c) Hypothetic Quarkyonic phase
- Complementary to the RHIC/BES, NA61/CERN, CBM/FAIR and Nuclotron-M experimental programs

Comprehensive experimental program requires scan over the QCD phase diagram by varying collision parameters: system size, beam energy and collision centrality. NICA provides capabilities for studying a variety of phenomena in a large region of the phase diagram.
### Experiments on superdense nuclear matter

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Energy range (Au/Pb beams)</th>
<th>Reaction rates Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR@RHIC BNL</td>
<td>$\sqrt{s_{NN}} = 7 – 200$ GeV</td>
<td>$1 – 800$ (limitation by luminosity)</td>
</tr>
<tr>
<td>NA61@SPS CERN</td>
<td>$E_{kin} = 20 – 160$ A GeV</td>
<td>$80$ (limitation by detector)</td>
</tr>
<tr>
<td></td>
<td>$\sqrt{s_{NN}} = 6.4 – 17.4$ GeV</td>
<td></td>
</tr>
<tr>
<td>MPD@NICA Dubna</td>
<td>$\sqrt{s_{NN}} = 4.0 – 11.0$ GeV</td>
<td>$\sim 7000$ (design luminosity of $10^{27}$ cm$^{-2}$s$^{-1}$ for heavy ions)</td>
</tr>
<tr>
<td>CBM@FAIR Darmstadt</td>
<td>$E_{kin} = 2.0 – 35$ A GeV</td>
<td>$10^5 – 10^7$ (limitation by detector)</td>
</tr>
<tr>
<td></td>
<td>$\sqrt{s_{NN}} = 2.7 – 8.3$ GeV</td>
<td></td>
</tr>
</tbody>
</table>
# Experiments on superdense nuclear matter

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Observables for high baryon density region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hadrons</td>
</tr>
<tr>
<td>STAR@RHIC BNL</td>
<td>yes</td>
</tr>
<tr>
<td>NA61@SPS CERN</td>
<td>yes</td>
</tr>
<tr>
<td>MPD@NICA Dubna</td>
<td>yes</td>
</tr>
<tr>
<td>CBM@FAIR Darmstadt</td>
<td>yes</td>
</tr>
</tbody>
</table>

**Advantage of collider experiments:** Uniform phase-space coverage when measuring excitation functions.