Status of the Experiments at the Megascience Complex RHIC

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Abstract. The Relativistic Heavy Ion Collider at Brookhaven National Laboratory (BNL) is a megascience complex that is dedicated to study the properties of nuclear matter at extreme temperatures and baryon chemical potentials, and to study the spin structure of the proton. In these proceedings, the current status and future developments of the megascience complex RHIC are presented.

1. Introduction
The building principles of the periodic table were revealed in 20th century using quantum mechanics. With increasing technical capabilities various detectors and facilities were build that allowed to shed light on atomic, nuclear, and particle physics. To study properties of the nuclear matter and particles the particle accelerators were developed and more than 40 complexes were constructed during the last 90 years. Since then, the it was revealed that atomic nuclei composed from protons and neutrons, which are themselves consist from the quarks (u and d). The quarks are held together by gluons, the quanta of the strong interaction. In order to describe the strong interaction a theory called Quantum Chromodynamics (QCD) was developed in 1983. With the introduction of the quark model and QCD, discussion began on the possibility of creating a form of matter which will consist of quarks and gluons called Quark-Gluon Plasma (QGP). An international physics community got interested in the possibility of creating and studying QGP by colliding heavy nuclei at high energies.

2. Relativistic Heavy Ion Collider
Brookhaven National Laboratory (BNL) is a National Laboratory funded by the U.S. Federal Government, and located on Long Island about 100 km east of New York City. It was founded in 1947 to promote basic research in physics, chemistry, biology, and engineering. BNL provides a construction and operation of large scientific machines that individual institutions could not afford to develop on their own. In December 1983 DOE/NSF Nuclear Science Advisory Committee (NSAC) considered a high-energy heavy-ion collider as a part of a long-range plan for nuclear science. In August 1984, after a series of discussions at several workshops and international conferences, and with the cooperation of accelerator design experts from many laboratories throughout the U.S. and Europe, BNL submitted to the DOE a proposed design for a Relativistic Heavy Ion Collider. A Conceptual Design Report (CDR) with a detailed construction plan and cost estimate was presented in May 1986 [1]. The RHIC facility is be
a complex set of accelerators and beam transfer equipment connecting them. RHIC itself is a collider with two independent rings (called “Blue” and “Yellow”) of superconducting magnets that operate at 3.45 T [2]. The length of the ring is 3834 m. The operations started in the year 2000 with the four experiments STAR, PHENIX, BRAHMS, and PHOBOS taking data. Figure 1 shows a view of the Relativistic Heavy Ion Collider.

Figure 1. The accelerator complex at Brookhaven National Laboratory.

RHIC has six interaction points where particles circulating in the two rings cross, allowing the particles to collide. The interaction points are enumerated by clock positions. The design of the accelerator complex provides possibility to collide different particle species that allow to reveal various physics aspects. The types of particle combinations studied at RHIC are p+p, p+Al, p+Au, d+Au, 3He+Au, Cu+Cu, Cu+Au, Zr+Zr, Ru+Ru, Au+Au and U+U. Figure 2 shows species combinations, collider luminosities and collision energies that were achieved from 2001 to 2019.

For Au+Au collisions the center-of-mass energy can vary from 3 to 200 GeV per nucleon pair. An average luminosity of $2 \times 10^{26}$ cm$^{-2}$s$^{-1}$ was targeted during the planning. The current average Au+Au luminosity of the collider has reached $87 \times 10^{26}$ cm$^{-2}$s$^{-1}$. The heavy ion luminosity is substantially increased using stochastic cooling [3]. Figure 3 shows the nucleon-pair luminosity for ion collisions. The nucleon-pair luminosity is defined as $L_{NN} = A_1 A_2 L$, where $L$ is the luminosity, and $A_1$ and $A_2$ are the number of nucleons of the ions in the two beam, respectively.

PHOBOS, BRAHMS and PHENIX completed their programs in 2005, 2006, and 2016, respectively. The STAR experiment is only experiment that will run till 2025. STAR is fully utilizing RHIC capabilities in the Beam Energy Scan II program that is aimed to study Au+Au collisions in the broad energy range of $\sqrt{s_{NN}} = 3$–27 GeV. Collisions at $\sqrt{s_{NN}} = 3$–7.7 GeV will occur in the fixed-target mode, while at higher energies collisions will happen in the collider mode. In addition, RHIC will use other ion species to address physical aspects, such as chiral magnetic effect, vorticity, fluctuations of the conserved quantum numbers, and influence of the initial conditions on the QGP.

A new detector sPHENIX is under construction in the old PHENIX hall and is expected to being taking data in 2023–25.
Figure 2. RHIC energies, species combinations and luminosities.

Figure 3. Nucleon-pair luminosity for ion collisions at different colliders.

RHIC will have a major upgrade and will be turned to the Electron-Ion Collider (EIC) with the addition of a 18 GeV high intensity electron beam facility. At least one new detector will have to be built to study the collisions [4]. The BNL eRHIC design has been selected for the future Electron-ion collider (EIC) in the United States. It was announced by undersecretary of the US Department of Energy Office of Science on January 9th, 2020.

3. RHIC Physics Scope
QCD is the fundamental theory of the strong interaction between quarks and gluons. At ordinary temperatures/nuclear densities strong interaction confines the quarks into composite hadrons. But when the temperature or nuclear density rises to the point where the inter-quark separation is less than 1 fm, the hadronic matter under extremely conditions undergoes a phase transition to form the QGP in which quarks and gluons are no longer confined to the size of a hadron [5,6].
The QGP was discovered at RHIC, and announced on April 19, 2005. However the results at RHIC indicated that instead of behaving like a gas of free quarks and gluons, the matter created in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV appears to behave like a liquid. This was discussed by the STAR, PHENIX, BRAHMS and PHOBOS experiments [7–10]. Later, theorists called this new type of matter strongly interacting QGP (sQGP) [11].

To understand the properties of sQGP, physicists started making measurements of multiple observables over a large range of collision energies and systems. In addition, the STAR and PHENIX experiments passed multiple detector upgrades in order to increase the precision of the measurements. Due to the space limitation, here we list some observables that allow to address various key aspects of the sQGP. For more detailed reviews see Refs. [12–14] and references therein.

3.1. Anisotropic Flow
Emission of the huge number of soft particles produced in relativistic heavy-ion collisions is not isotropic but exhibits an asymmetry in the azimuthal distribution. Measurements of these anisotropies relative to the so-called flow symmetry planes can be characterized by Fourier coefficients ($v_n$):

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)],$$

where $\phi$ – azimuthal angle of a produced particle, and $\Psi_n$ – azimuthal angle of the $n^{th}$-order event plane [15]. Values of $v_n$ as a function of collision energy, centrality, particle species and transverse momentum provide valuable information about the shear and bulk viscosities of the system, as well as give some insights on the initial-state fluctuation importance when forming the sQGP. For example, hydrodynamic calculations [16,17] suggested the presence of a minimum in the net-baryon directed flow slope of $\sqrt{s_{NN}}$ excitation function as a signature of the first-order phase transition between hadronic matter and QGP. Figure 4 shows a measurement of $dv_1/dy$ of various particles species as a function of collision energy performed by the STAR experiment [18], which hints to a change of the phase transition type.

3.2. Correlation femtoscopy
A technique that allows one to measure spatial and temporal timescales ($10^{-15}$ m and $10^{-22}$ s, respectively) of the hot expanding system. Selecting different momentum components relative to the colliding-beam axis, one can get a three-dimensional picture of the particle-radiating volume at the moment of freeze-out. Figure 5 shows a world data on a lifetime ($\tau$) dependence of system created in heavy-ion collisions [19]. It clearly shows that the sQGP leaves longer at high collision energies. Correlation femtoscopy results reveal important insights into the dynamic evolution of the expanding system and provide constraints on the theoretical models of heavy ion collisions. Some additional ideas about the measurements that can be performed at RHIC for large (e.g. Au+Au and Cu+Au) and small (e.g. d+Au and $^3$He+Au) colliding systems can be found in Refs. [20,21].

3.3. Identified particle spectra and yields
Measurement of Identified particle spectra and yields allow us to infer the temperature ($T$) and baryon chemical potential ($\mu_B$) values at particle production time. Particle ratios, and freeze-out properties may provide insight into the particle production mechanisms. The chemical ($T_{ch}$) and kinetic ($T_{kin}$) freeze-out temperatures are extracted by STAR from a thermal and a blast-wave model fits to the data [22] at midrapidity, respectively, and shown in Fig. 6.

$T_{kin}$ decreases from peripheral to central collisions suggesting a longer lived fireball in central collisions. An average transverse radial flow velocity ($<\beta>$) decreases from central to peripheral
Figure 4. Directed flow slope \( (d\nu_1/dy) \) of (anti)protons, \( \Lambda, \bar{\Lambda}, \phi \) meson, and kaons versus beam energy for midcentral \((10-40\%)\) Au+Au collisions measured by STAR \[18\].

Figure 5. The lifetime, \( \tau \), of the system as a function of beam energy for central Au+Au collisions assuming a temperature of \( T=0.12 \) GeV at kinetic freeze-out \[19\].

Collisions suggesting stronger expansion in central collisions. The difference between \( T_{ch} \) and \( T_{kin} \) increases with increasing \( \sqrt{s_{NN}} \). It suggests the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies. The systematic study of these bulk properties may reveal the evolution and change in behavior of the system formed in heavy-ion collisions as a function of collision energy.
3.4. Global hyperon polarization

Several theoretical models suggest that in non-central heavy-ion collisions the large angular momentum carried by two colliding nuclei can be transferred to the created system. Because of the spin-orbit coupling, this will lead to a global spin polarization of produced particles along the direction of the system angular momentum. Experimentally, the global polarization can be measured with baryons that contain strange quark (such baryons are known as hyperons) via parity-violating weak decays. In weak decays of the daughter baryon is preferentially emitted in the direction of the hyperon spin. In case the hyperon is antiparticle (that has the same mass as a particle but opposite quantum charges) then daughter baryon is emitted in the direction which is opposite to the antihyperon spin.

The angular distribution of daughter baryons in the hyperon decays can be expressed as:

$$\frac{dN}{d\cos \theta^*} = 1 + \alpha_H P_H \cos \theta^*,$$  (2)
where $P_H$ is a hyperon polarization, $\alpha_H$ – hyperon decay parameter, and $\theta^*$ – angle between the polarization vector in hyperon rest frame and the momentum of daughter baryon. The lightest and most abundant hyperons are $\Lambda$ and their antiparticles $\bar{\Lambda}$. Figure 7 shows the global polarization of $\Lambda$ and $\bar{\Lambda}$ as a function of $\sqrt{s_{NN}}$ for the 20-50% central Au+Au collisions [23].

![Figure 7](image.png)

**Figure 7.** Global polarization of $\Lambda$ and $\bar{\Lambda}$ as a function of the collision energy ($\sqrt{s_{NN}}$) for 20-50% central Au+Au collisions [23].

At top RHIC energy ($\sqrt{s_{NN}} = 200$ GeV) no significant difference between $\Lambda$ and $\bar{\Lambda}$ polarization within the uncertainties. The global hyperon polarization increases with decreasing collision energy. The $\sqrt{s_{NN}}$-averaged polarizations indicate a vorticity of $\omega \approx (9 \pm 1) \times 10^{21} \text{ s}^{-1}$. This opens new directions in the study of the hottest, least viscous and now, most vortical fluid ever produced in the laboratory.

4. Summary
The current status of the experiments at the megascience complex RHIC was presented. RHIC increased the number of operating modes to 11 total, that clearly shows the unmatched flexibility of the machine. The 11 modes, all with Au beams, consisted of five colliding modes, four fixed target modes, and two modes for the commissioning of bunched electron beam cooling. We demonstrated several recent results that show new opportunities and directions of relativistic heavy-ion physics. The current status of the experiments at RHIC and future transition of RHIC to Electron-Ion Collider were discussed.

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