Strongly interacting matter at RHIC: experimental highlights

V. A. Okorokov

Physics Department, National Research Nuclear University “MEPhI”
(Moscow Engineering Physics Institute),
Moscow, 115409, Russia
E-mail: VAOkorokov@mephi.ru; Okorokov@bnl.gov

Recent experimental results obtained at the Relativistic Heavy-Ion Collider (RHIC) will be discussed. Investigations of different nucleus-nucleus collisions in recent years focus on two main tasks, namely, the detailed study of sQGP properties and the exploration of the QCD phase diagram. Results at top RHIC energy provide important information about event shapes as well as transport and thermodynamic properties of the hot medium for various flavors. Heavy-ion collisions are a unique tool for the study of topological properties of theory. Experimental results obtained for discrete QCD symmetries at finite temperatures are discussed. These results confirm indirectly the topologically non-trivial structure of the QCD vacuum. Most results obtained during phase-I of the RHIC beam energy scan (BES) program show smooth behavior vs initial energy. However, certain results suggest the transition in the domain of dominance of hadronic degrees of freedom at center-of-mass energies between 10-20 GeV. Future developments and more precise studies of features of the QCD phase diagram in the framework of phase-II of RHIC BES will be briefly discussed.

Keywords: quark-gluon plasma; RHIC.

1. Introduction

Investigation of strongly interacting matter under extreme conditions is of value for various fields of fundamental physics, namely for quantum chromodynamics (QCD), cosmology and relativistic astrophysics. The Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory was designed and was built for investigations in the field of strong-interaction physics specially. The data samples taken since 2000 are shown in Table II. The main result of the first stage of the heavy-ion program at RHIC is the demonstration that new state of nuclear matter—strongly coupled quark-gluon plasma (sQGP)—has been observed in nucleus-nucleus collisions at top RHIC energy and mid-rapidity. Subsequent experimental goals focus on studying the properties of the sQGP and exploring features of the phase diagram of strongly interacting matter.

2. Probing of the sQGP at high RHIC energies

During recent years the study of event shapes at higher RHIC energies ($\sqrt{s_{NN}} \geq 62.4$ GeV) is focused on measurements of $v_2$ up to high $p_T$, higher-order harmonics, comparisons of various collisions, investigation of scaling behavior of $v_2$ on num-
Table 1. Data samples obtained during RHIC runs.

| Species     | √s_{NN}, GeV |
|-------------|--------------|
| p+p         | 22.0\(^{a}\), 62.4, 200, 410\(^{b}\), 500, 510 |
| d+Au        | 200          |
| He\(^{3}\)+Au | 200         |
| Cu+Cu       | 22.4\(^{b}\), 62.4, 200 |
| Cu+Au       | 200          |
| Au+Au       | 7.7, 9.2\(^{b}\), 11.5, 14.5, 19.6, 27.0, 39.0, 55.8\(^{b}\), 62.4, 130, 200 |
| U+U         | 193          |

*Note:* \(^{a}\) with unpolarized (√s = 62.4 GeV) and with longitudinal / transverse polarized beams; \(^{b}\) run with small integral luminosity.

The particle production is dominated by parton recombination in the central collisions at top RHIC energy and intermediate \(p_T\), but recombination is not the dominant mode in noncentral collisions at \(p_T > 2\) GeV/c and some other mechanisms – parton-energy loss, jet chemistry, and different fragmentation functions – may contribute to generating the observed azimuthal anisotropy of particle emission. The \(v_2\) of \(\pi^0\) and \(\eta\) mesons with high \(p_T\) exhibit the possibility of the combined influence of initial-geometry fluctuations of collisions and finite viscosity on space-time evolution of created matter. Finite \(v_2\) found for direct \(\gamma\) in the thermal region supports the hypothesis of early thermalization and small viscosity for hot matter created in central Au+Au collisions at √s_{NN} = 200 GeV. The \(v_2\) in d+Au at RHIC agrees qualitatively both with results for \(v_2\) in p+Pb at the LHC and with hydrodynamics.

Dihadron azimuthal correlations as a function of the trigger particle’s azimuthal angle relative to the event plane at top RHIC energy with additional comparison of small (d+Au) and large (Au+Au) systems show the presence of path-length-dependent jet quenching. This conclusion is confirmed by both the results for \(\pi^0\) azimuthal anisotropy and the azimuthal correlations in \(h^\pm - \pi^0\) pairs as a function of the neutral trigger’s orientation with respect to the reaction plane. Study of the three-particle azimuthal correlations for various systems at top RHIC energy signals conical emission of charged hadrons correlated with high \(p_T\) trigger particles in central Au+Au collisions with emission angle to be independent of the associated particle \(p_T\). The observation allows the exclusion of the hypothesis of Cherenkov gluon emission as the dominant mechanism of production of away-side peak structure in back-to-back jet configurations at RHIC. Multihadron correlations show the conversion of energy lost by associated particles with higher \(p_T\) into production of softer hadrons. Direct \(\gamma\)-hadron correlations confirm both conclusions for path-length dependence of the strength of jet quenching and for redistribution of missing energy resulted in an increasing of production of soft particles.

Spectra for identified charged particles exhibits experimental evidence for differ-
ent contributions of gluon jets and quark jets to hadron production in the high-\(p_T\) domain at top RHIC energy as well as the absence of the Casimir effect for parton energy loss in sQGP. Spectrum on \(p_T\) of direct \(\gamma\) in central Au+Au collisions at top RHIC energy shows the inverse slope \(T_{\text{eff}} = 221 \pm 19^{\text{stat}} \pm 19^{\text{syst}}\) MeV for \(p_T > 1\) GeV/c, which can be considered an estimation of the initial temperature of the final state created in heavy-ion collisions. This temperature is significantly higher than that predicted by calculations in lattice QCD for the phase transition from hadronic matter to sQGP and is in qualitative agreement with hydrodynamical models. The study of both the spectra and the nuclear modification factor \((R_{AA})\) for \(\pi^0\) mesons confirms the strong dependence of parton energy loss \((\Delta E)\) on length of path \((L)\) passed by them in hot strongly interacting matter and allows the establishment the relation \(\langle \Delta E \rangle \propto \langle L \rangle^3\) with help by a hybrid model utilizing pQCD for the hard scattering and AdS/CFT correspondence for the soft interactions. Spectra exhibit the significant suppression of heavier mesons with open / hidden strangeness; furthermore, results for non-strange and for strange particles are complementary in the high-\(p_T\) domain in some cases. Smooth behavior of strangeness yields, different particle ratios and corresponding \(R_{AA}\) dependencies on \(\sqrt{s_{\text{NN}}}\) at higher RHIC energies \((\sqrt{s_{\text{NN}}} \geq 62.4\) GeV) allows the estimation of parameters of the chemical freeze-out. Dilepton mass spectra, in particular, give the indication in favor of theoretical models with in-medium broadened contributions in the case of Au+Au collisions at top RHIC energy. Studying of charged particle spectra as a function of pseudorapidity for various collision types and \(\sqrt{s_{\text{NN}}}\) results in the following relation for total multiplicity of secondary charged particles: \(N_{\text{ch}} \propto \ln^2 s_{\text{NN}}\) for the wide range \(\sqrt{s_{\text{NN}}} = 2.7 - 200\) GeV.

The \(R_{AA}\) of \(J/\psi\) with low and intermediate \(p_T\) in Cu+Cu and Au+Au is evidence in favor of models of charmonium production that take into account the color screening and regeneration and exclude the model of hydrodynamic flow. Measurements of \(J/\psi\) production at \(\sqrt{s_{\text{NN}}} = 200\) GeV in the high-\(p_T\) domain show increasing \(R_{AA}\). In the case of Cu+Cu, this observation contradicts with calculations in the framework of model of quarkonium dissociation in a strongly coupled liquid using an AdS/CFT approach, whereas the growth of \(R_{AA}\) for collisions of mean nuclei are described reasonably by a two-component model with finite \(J/\psi\) formation time. As well as for light flavors the significant suppression is observed for yields of \(J/\psi\) integrated over transverse momentum in central Au+Au collisions at the highest RHIC energy. Values of \(v_2\) for \(J/\psi\) at \(p_T = 2 - 10\) GeV/c are consistent with zero within statistical errors. Finite \(v_2\) observed for electrons with \(p_T = 1.3 - 1.8\) GeV/c and \(p_T > 2.4\) GeV/c from heavy-flavor decays supposes that heavy quarks interact with the environment at higher RHIC energies \((\sqrt{s_{\text{NN}}} \geq 62.4\) GeV) but their degree of thermalization with the medium may depend on \(\sqrt{s_{\text{NN}}}\). Significant suppression is observed for open charm mesons with intermediate and large \(p_T\) in Au+Au collisions at the highest RHIC energy which suggests that coalescence can be considered as mechanisms of hadronization. The first results were
obtained for $J/\psi$ suppression in collisions of asymmetric beams $Cu+Au$ and for bottomonium production in various collisions at $\sqrt{s_{NN}} = 200$ GeV. The behavior of $R_{AA}$ in nuclear collisions exhibits the complete suppression of excited-state $\Upsilon$ mesons and agrees with model calculations that include the presence of a sQGP.

Results in the field of correlation femtoscopy show that the space-time extent of the charged kaon source is smaller than that for charged pions. Investigation of azimuthally-sensitive femtoscopy correlations at top RHIC energy indicate that the oscillations of femtoscopy parameters with respect to the 3rd-order event plane are largely dominated by the dynamical effects from triangular flow. Estimations of the space-time extent of the pion emission source in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of kinematic observables show similar patterns in $Au+Au$ collisions and indicate similarities in expansion dynamics in collisions of various systems at RHIC. The scaling results for some radii indicate that hydrodynamic-like collective expansion is driven by final-state rescattering effects. Study of short- and long-range multiplicity correlations on pseudorapidity at top RHIC energy established qualitative agreement with the dual partonic model and pointed to the presence of multiple parton interactions in $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Measurements of three-particle coincidence in pseudorapidity between trigger particle with $p_T > 3$ GeV/$c$ and two lower $p_T$ associated particles within small azimuthal separation in $d+Au$ and $Au+Au$ collisions at top RHIC energy found no correlation between production of the ridge and production of the jetlike particles, suggesting the ridge may be formed from the bulk medium itself. This result, as well as the persistence of the ridge structure over at least $\eta \approx 4$, indicate that the models attributed the ridge to the medium itself seem more preferable than the models attributed the ridge to jet-medium interactions. Accounting for soft particles results in observation of the ridge in central $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV that agrees qualitatively with discovery of similar features of event structure in small system collisions at the LHC. Thus the measurements at RHIC and LHC are complementary to each other. System-size dependence of widths of charge balance functions at $\sqrt{s_{NN}} = 200$ GeV agrees with the hypothesis of limited diffusion which corresponds with, in turn, the creation of matter with a very small viscosity, which requires a small mean free path in $Au+Au$ collisions. Investigations of the correlation function of transverse momentum allow one to confirm the small viscosity of matter formed in central $Au+Au$ collisions at top RHIC energy and get the following range of estimations for ratio of the shear viscosity to entropy density: $\eta/s = 0.06 - 0.21$. It was also found that transport-based model calculations show better quantitative agreement with the measurements compared with models which incorporated only jet-like correlations. On the other hand the anomalous evolution of two-particle angular correlations on centrality was observed. This result does not allow one exclude the alternative scenario in which the heavy-ion collisions in domain, at least, of high RHIC energies are dominated by minijet structure and the early stage of space-time evolution of collisions is described by pQCD.
with modified fragmentation without such specific properties of created matter as opacity for few-GeV partons and very small viscosity. It is important to note that the representation of relativistic heavy-ion collisions with the creation of matter characterized by opacity for hard partons and very small viscosity was confirmed by a wider set of observables than the approach based on minijets. At present, the former case is the dominant paradigm for the study of the sQGP.

3. Fundamental symmetries of QCD at finite temperatures

During recent years important progress has been achieved in both theoretical and experimental studies of fundamental discrete symmetries of QCD, in particular, $\mathcal{P}/\mathcal{C}\mathcal{P}$ invariance, in hot strongly interacting matter. The interplay between the external Abelian magnetic field with extremely large intensity (peak $B \sim 10^{15}$ T) and the sQGP created in the heavy-ion collisions makes local topologically induced violation of $\mathcal{P}/\mathcal{C}\mathcal{P}$ invariance in strong interactions possible – lTIP effect. One of the possible mechanisms for manifestation of this effect experimentally is the phenomenon of electric charge separation along the axis of the applied magnetic field in the presence of fluctuating topological charge – the so-called chiral magnetic effect – CME. RHIC provides a good opportunity to study this fundamental physics. Experimentally, first indication on the CME effect was observed with charged hadron correlations in high-energy nuclear collisions. Then high statistics study confirmed the existence of the charge separation effect, and found that the separation of charge is predominantly orthogonal to the reaction plane, as expected for the CME. The collision energy dependence of the charge separation shows the remarkable feature that when the energy is lower than 11 GeV the charge separation approaches zero. This implies the dominance of hadronic interactions over partonic ones at lower collision energies and indicates that the onset of such dominance is in the range $\sqrt{s_{NN}} = 11.5–19.6$ GeV. There is no model without CME which can describe all experimental results simultaneously, especially the centrality dependence of same-sign correlations. Thus most of corresponding experimental results confirm indirectly the non-trivial topology of QCD vacuum. But results for multiplicity asymmetry correlations in Au+Au collisions at top RHIC energy show $p_T$-dependence which is unexpected in the framework of CME. These data will stimulate further developments for background estimations.

4. Scan of collision energy and future plans

Detailed exploration of the phase diagram of strongly interacting matter and its features is the main goal of the beam energy scan (BES) program at RHIC. Most results obtained during the first phase of the program (BES-I) for Au+Au collisions show either a smooth dependence or absence of the visible changing of corresponding physical quantities on collision energy. The set of these results can point on weak changing of contribution of soft processes, at least, in heavy nuclei
collisions at initial energies $\sqrt{s_{NN}} = 39 - 200$ GeV. However, it should be mentioned that at the same time some features observed in Au+Au collisions,\textsuperscript{40,43-45} for example, significant difference in the $v_2$ values for particles and their corresponding antiparticles,\textsuperscript{44} allow one to suggest that the transition occurs at initial energies $\sqrt{s_{NN}} = 10 - 20$ GeV in the domain of dominance of hadronic degrees of freedom over those of quark and gluons. Precise measurements are planned at top RHIC energy, which will provide, as expected, new information on the sQGP thermodynamic and transport properties. For the phase-II of the BES program the proposed upgrades to RHIC will increase the luminosity for future low energy runs by a factor of 2 to 20 for $\sqrt{s_{NN}} = 7.7 - 20$ GeV, depending on beam energy. The upgrades to the PHENIX and STAR detector systems will significantly improve the quality of the measurements. PHENIX has proposed a new more conventional collider detector, s(uper)PHENIX, based on a thin-coil superconducting solenoid while, STAR has proposed two new subsystems, the event plane detector (EPD) and the inner Time Projection Chamber (iTPC), which will improve the capabilities of all STAR. Furthermore, STAR plans down to $\sqrt{s_{NN}} \approx 3$ GeV and reach to region of compressed baryonic matter in the framework of the fixed target part of the phase-II.

5. Summary

In this review some of the main experimental results obtained at RHIC during the last 5 years have been discussed. The elliptic flow of charged particles scaled by the initial-state eccentricity follow a common trend with multiplicity for RHIC and the LHC in collisions of small systems as well as for large systems. Results for heavy mesons at top RHIC energy exhibit significant energy loss by heavy-flavor quarks in hot matter and also indicate intensive interactions of such quarks with the environment. The space-time evolution of the ellipticity and triangularity is observed in angular dependent HBT measurement for Au+Au collisions at the top RHIC energy. Experimental indications of the local topology-induced parity violation in strong interactions are observed in nucleus-nucleus collisions at higher RHIC energies. The deviation from the sQGP signals in the lower energy collisions indicates the onset of the hadronic degrees of freedom. The proposed upgrades to RHIC and large experiments (PHENIX, STAR) will offer the unique opportunity for precise study of the properties of the sQGP as well as for detailed exploration of the phase structure of strongly interacting matter. Therefore one can say that at present the investigation of QCD matter passed from the “discovery stage” to “precision science” studies.

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