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Technical Report

Physics of hot and dense quark-gluon matter

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1 Executive summary

This technical report describes the work done under the DOE grant DE-FG-88ER41723 (final award number DE-SC0005645), "The physics of hot and dense quark-gluon matter", during the year of 12/01/2010 through 11/30/2011. As planned in the proposal, the performed research focused along two main thrusts: 1) topological effects in hot quark-gluon matter and 2) phenomenology of relativistic heavy ion collisions. The results of research are presented in 11 papers published in reputable refereed journals (Physical Review Letters, Physical Review, Physics Letters and Nuclear Physics). All of the performed research is directly related to the experimental programs of DOE, especially at the Relativistic Heavy Ion Collider. Much of it also has broader interdisciplinary implications - for example, the work on the non-dissipative chiral magnetic current is directly relevant for quantum computing.

2 Results of the research

Topological effects in hot quark-gluon matter

Much of the work in this direction has been carried out together with Stony Brook postdocs Ho-Ung Yee (who has recently accepted a tenure-track offer from UIC and RIKEN-BNL Center) and Gokce Basar.

Together with Ho-Ung Yee, we have identified a novel collective gapless excitation – the "Chiral Magnetic Wave" – that appears in all plasmas containing relativistic fermions in the presence of an external magnetic field as a consequence of axial anomaly [1]. The Chiral Magnetic Wave (CMW) is the carrier of chiral magnetic current in strongly coupled plasma.

At finite baryon density, the CMW leads to a spectacular new effect - the permanent electric quadrupole moment of the plasma [2]. This has a directly observable consequence for heavy ion collisions – the elliptic flow of negative pions should exceed the one for positive pions at energies of the RHIC beam energy scan, when the baryon density is relatively large. Such an effect was predicted in [2], and observed during the beam energy scan at RHIC. The possibility of alternative interpretations is currently investigated by several groups.

The existence of novel phenomena caused by quantum anomalies in relativistic fluids motivated us to undertake a systematic and rigorous study of second order relativistic hydrodynamics [3]. We have classified all terms caused by triangle anomalies in the presence of external magnetic and electric fields. The resulting theory – the Chiral MagnetoHydroDynamics – has broad applications, including those far outside the field of nuclear physics (topological insulators, Weyl semi-metals, quantum computing, etc) [4].

As it was pointed out in our paper [5], the quantum anomalies lead to interesting effects not only in hot quark-gluon plasma, but also in the structure of hadrons in external magnetic fields – we have found that the neutron in an external magnetic field develops a new type of a quadrupole moment. This leads to a new component in the precession of the neutron's spin in magnetic fields, with possible implications for neutron stars.

Together with the ITEP lattice theory group, I continued the studies of an intriguing

effect that we have observed earlier – namely, the QCD vacuum begins to conduct electric current in the presence of a sufficiently strong external magnetic field [6, 7]. One possible explanation is that in strong magnetic field the QCD vacuum becomes a superconductor.

These intriguing lattice observations motivated us to perform a first principles study of the QCD instanton in an external magnetic field [8]. In the limit of a strong magnetic field, we were able to find an exact solution for the quark zero modes. We also demonstrated that in magnetic field the instanton develops an electric dipole moment, providing an explicit and analytically treatable example of the chiral magnetic effect.

These studies were extended to the case of sphaleron processes in [9]. This study is a necessary step in a quantitative treatment of the chiral magnetic effect in heavy ion collisions. We have used the holographic approach and obtained an explicit analytical answer for the sphaleron rate.

Topological effects in magnetic fields were investigated further in [10], where we have identified the instability leading to the chiral magnetic current in the systems of chiral fermions at finite chiral chemical potential. This work relied on the holographic approach as well (so-called D3/D7 brane formulation).

Phenomenology of heavy ion collisions

The work directly aimed at the support of the DOE’s experimental programs was a very important component of the performed research.

In the paper [11], we have extended our previous KLN (Kharzeev-Levin-Nardi) approach to multiparticle production in high energy nuclear collisions that has been tested at RHIC and have produced detailed predictions for the LHC experiments.

In the paper [12] we have devised a new approach to high energy hadron scattering based on the ideas of holography. We have used so-called Witten metric that accounts for confinement in the boundary field theory, and have constructed a soft Pomeron responsible for most of the hadron-hadron cross section.

Recently, the LHC experiments have observed a puzzling similarity between the jet fragmentation functions in heavy ion and pp collisions. Together with my Stony Brook student Frasher Loshaj, we have proposed an explanation of this phenomenon [13].

Finally, in a series of papers [14, 15, 16] we have continued the systematic studies of the initial state effects on heavy quarkonium production in pA and AA collisions at RHIC and LHC.

3 Organizational issues

The DOE award has allowed me to perform a smooth transition into the Stony Brook University environment. At present I am a Co-PI on the Stony Brook Nuclear Theory grant (PI: Prof. Edward Shuryak). I actively work with my Stony Brook students Frasher Loshaj

and Joshua Ilany on various aspects of high energy nuclear physics.

4 Publications

The results of the research are described in 12 papers published in refereed journals (Physical Review Letters, Physical Review, Physics Letters and Nuclear Physics), 2 proceedings contributions, and 2 papers that are in the process of refereeing (three of the recent papers were submitted after 11/30/2011 but are based on the work much of which was carried out during the grant period).

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