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Report on the habilitation thesis of Dr. Viktor Begun

This thesis of Dr. Viktor Begun, entitled *Statistical and thermodynamics properties of systems created in high energy collisions*, was prepared for the habilitation based on his series of studies listed below:

1. V. Begun, "Fluctuations as a test of chemical non-equilibrium at the LHC," Phys. Rev. C **94**, no. 5, 054904 (2016).
2. V. Vovchenko, V. V. Begun and M. I. Gorenstein, "Hadron multiplicities and chemical freeze-out conditions in proton-proton and nucleus-nucleus collisions," Phys. Rev. C **93**, no. 6, 064906 (2016).
3. V. Begun and W. Florkowski, "Bose-Einstein condensation of pions in heavy-ion collisions at the CERN Large Hadron Collider (LHC) energies," Phys. Rev. C **91**, 054909 (2015).
4. V. V. Begun, M. I. Gorenstein and K. Grebieszkow, "Strongly Intensive Measures for Particle Number Fluctuations: Effects of Hadronic Resonances," J. Phys. G **42**, no. 7, 075101 (2015).
5. V. Begun, W. Florkowski and M. Rybczynski, "Transverse-momentum spectra of strange particles produced in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in the chemical non-equilibrium model," Phys. Rev. C **90**, no. 5, 054912 (2014).
6. V. Begun, W. Florkowski and M. Rybczynski, "Explanation of hadron transverse-momentum spectra in heavy-ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV within chemical non-equilibrium statistical hadronization model," Phys. Rev. C **90**, no. 1, 014906 (2014).
7. V. V. Begun, M. Gazdzicki and M. I. Gorenstein, "Hadron-resonance gas at freeze-out: Reminder on the importance of repulsive interactions," Phys. Rev. C **88**, no. 2, 024902 (2013).
8. V. V. Begun, V. P. Konchakovski, M. I. Gorenstein and E. Bratkovskaya, "Strongly Intensive Measures for Multiplicity Fluctuations," J. Phys. G **40**, 045109 (2013).
9. V. V. Begun, M. I. Gorenstein and O. A. Mogilevsky, "Modified Bag Models for the Quark Gluon Plasma Equation of State," Int. J. Mod. Phys. E **20**, 1805 (2011).

10. V. V. Begun, M. I. Gorenstein and O. A. Mogilevsky, "Pion Number Fluctuations and Correlations in the Statistical System with Fixed Isospin," Phys. Rev. C **82**, 024904 (2010).

11. V. V. Begun, M. Gazdzicki and M. I. Gorenstein, "Semi-Inclusive Distributions in Statistical Models," Phys. Rev. C **80**, 064903 (2009).

12. V. V. Begun, M. I. Gorenstein and W. Greiner, "Crossover to Cluster Plasma in the Gas of Quark-Gluon Bags," J. Phys. G **36**, 095005 (2009).

13. V. V. Begun and M. I. Gorenstein, "Bose-Einstein Condensation in the Relativistic Pion Gas: Thermodynamic Limit and Finite Size Effects," Phys. Rev. C **77**, 064903 (2008).

14. V. V. Begun, M. Gazdzicki and M. I. Gorenstein, "Power Law in Micro-Canonical Ensemble with Scaling Volume Fluctuations," Phys. Rev. C **78**, 024904 (2008).

The scientific accomplishments consist of four parts,

- Relativistic gas of hadrons and resonances
- Fluctuations in a hadron resonance gas
- Power law spectrum in a micro-canonical ensemble with volume fluctuations
- Bose-Einstein condensation in relativistic reactions

and each of which is briefly summarized below.

Relativistic gas of hadrons and resonances: It is often approximated that particles produced at chemical freeze-out are described as a non-interacting gas of the ground-state hadrons and the resonances, known as the hadron resonance gas (HRG) model. A set of thermal parameters included in the partition function is determined with fitting multiplicities of the particles measured in experiments.

In Ref. [2] the HRG model was utilized to analyze the particle yields in the experiments performed for the p+p, Au+Au and Pb+Pb reactions in a wide energy range of the collisions. In Ref. [7] a non-vanishing volume of the hadrons is introduced to illustrate how the maximum baryon density is affected depending on the collision energy.

In Ref. [12] a phase transition from a gas of hadrons to the quark-gluon plasma (QGP) was illustrated in the context of the HRG combined with the bag pressure of massless and non-interacting quarks and gluons. The bag volume depends on temperature with two characteristic exponents, γ and δ. It was shown that in a wide range on the γ-δ plane a crossover takes place.

In Ref. [9] the thermodynamics in this line was further extended to parameterize the QCD equation of state observed in lattice simulations. The bag pressure which depends on temperature reasonably reproduces the interaction measure and the speed of sound, in spite of its simplicity in modeling the QCD phase transition.

Although the QGP bag turns out to be expanding at higher temperature which is counter-intuitive, this may be the consequence of the somewhat oversimplified treatment for the non-perturbative physics.

Fluctuations in a hadron resonance gas: In Ref. [10] the thermodynamics consequences of charge conservation were examined in the system of charged and neutral pions. Conservation of isospin and electric charge was imposed to quantify the fluctuations of the particle number, and their different characteristics is nicely demonstrated with selected observables.

In Ref. [8], as key observables in relativistic nucleus collisions, strongly intensive variables associated with the ratio of the multiplicity of pions and kaons produced in the same volume were considered, and their dependence of the collision energy was examined.

In Ref. [4] the influence of resonance decays over those variables was examined in the HRG model with a canonical and a grand-canonical ensembles. It is shown that, depending on the rapidity window, the strongly intensive variables obey different ensembles, i.e. conservation of charges for *each* micro state is ensured only when the rapidity window is large enough.

Power law spectrum in a micro-canonical ensemble with volume fluctuations: In Refs. [11,14] the HRG model was appropriately extended in order to describe the momentum distribution of the particles in the presence of the volume fluctuations, and applied to systems with different size. The momentum and probability distributions were studied in various statistical ensembles, and it was given analytically how the volume scaling comes in to the micro canonical ensembles.

Bose-Einstein condensation in relativistic reactions: There exists an anomalous increase of the particles (protons and pions) in low transverse-momentum p_T measured in Pb+Pb collisions at the LHC, known as the *proton puzzle*. In Refs. [1,3,5,6] the Bose-Einstein condensation of pions as a phenomenological option considered in Ref. [13] was revisited to possibly resolve the aforementioned puzzle.

The HRG model was extended accordingly, and the relevant thermal parameters (the temperature and the pion chemical potential), were extracted from the fit to the observed multiplicities [3,5,6]. The best observable to verify this scenario is the fluctuations of the pion number as proposed in [1], and it is to be examined in the experiments near future.

Assessment of the scientific achievements

The selected 14 papers, published from high-standard international journals, contain the results highly relevant in analysing the experimental data performed in relativistic heavy-ion collisions to obtain an insight into the physics of strongly interacting QCD matter. The system-size dependence, volume fluctuations and the consequence of conserved quantum charges are of great significance in the current and up-coming experiments and the beam-energy scan program. The issue discussed in Refs. [1,3,5,6] is about a potential resolution of the proton puzzle, which has been standing since 2012, thus quite timely.

It is particularly impressive that Dr. Begun has collaborated with his local colleagues at each host institution since 2007, and produced a few publications as a series of some specific issue(s). This apparently shows his scientific initiative and adaptation in the research collaborations as well as his strong dedication to the subjects. Also, the paper [1] is his single-authored publication and he gave a strong prediction of the scenario developed previously in [3,5,6] as a testable signature in high-energy heavy-ion collisions. I therefore conclude that he is an independent researcher with advanced skills of theoretical physics and strong capability in a wide range of heavy-ion phenomenology.

Assessment of other achievements and activities

Dr. Begun has produced 39 publications (29 excluding conference/workshop proceedings) from international peer-reviewed journals, the total number of citations 629 (479 excluding self-citations) and the h-index 16 which is pretty good. Note that 22 publications came out after his PhD.

He has given 49 oral presentations in major conferences and workshops since 2004. In particular, last 5 years, he gave 4 talks (2 invited ones) per year as the average, which indicates his activity being kept quite high and furthermore well appreciated by the community.

Given the fact that he has also had teaching since 2016, I see that he keeps a high standard both in his scientific and didactic activities. In particular in 2017, he conducted a number of exercises and lectures, altogether 7.

He has been in close contact with the experimentalists as well. In fact, his 3 papers [7,11,14] and additional 2 papers were coauthored by Prof. M. Gazdzicki who is one of the leading physicists in the heavy-ion community. It is certainly nontrivial to integrate what comes out both from experiments and theoretical study to build a unified picture, and Dr. Begun has the capability to handle such involved tasks in a pragmatic way.

Conclusions

The scientific accomplishments summarized in Dr. Begun's habilitation thesis and his other achievements clearly comply with all the requirements. I would like to strongly support his application for the habilitation.

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