ФИЗИКА

PHYSICS

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MONTE-CARLO SIMULATION OF THE 1ST ORDER HADRON-QGP PHASE TRANSITION IN HEAVY ION COLLISIONS USING A PARTON MODEL

Abstract. Quark gluon plasma (QGP) is a special state of nuclear matter where quarks and gluons behave like free particles. Recently, a number of investigations of this state with high temperature and/or density have been conducted using collisions of relativistic and ultra-relativistic heavy nuclei. It is accepted that depending on the temperature and density, 1st or the 2nd order phase transitions take place in hadron matter during the formation of QGP. Herein, we have modeled heavy ion collisions using a HIJING Monte-Carlo generator, taking into account the description of the 1st order phase transition as a probabilistic process. We analyzed the behavior of the fluctuations of the total ($N = N_+ - N_-$) and resultant ($Q = N_+ - N_-$) electric charges of the system. Different phases were introduced using the BDMPS (Baier – Dokshitzer – Mueller – Piegne – Schiff) model of parton energy loss during crossing through a dense nuclear medium.

Keywords: high energy physics, Monte-Carlo simulation, heavy ion collisions, fluctuations, quark-gluon plasma, HIJING, phase transitions

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МОНТЕ-КАРЛО МОДЕЛИРОВАНИЕ ФАЗОВОГО ПЕРЕХОДА АДРОНЫ-КГП В СТОЛКНОВЕНИЯХ ТЯЖЕЛЫХ ИОНОВ С ПОМОЩЬЮ ПАРТОННОЙ МОДЕЛИ

Аннотация. Кварк-глюонная плазма (КГП) является особым состоянием ядерной материи, при котором кварки и глюоны ведут себя как свободные частицы. В настоящее время проводятся исследования этого состояния вещества с высокими температурой и/или плотностью с помощью столкновений релятивистских и ультрарелятивистских тяжелых ядер. Считается, что адронная материя испытывает (в зависимости от температуры и плотности) фазовый переход первого или второго рода при образовании КГП. В данной статье были промоделированы столкновения тяжелых ионов с помощью Монте-Карло генератора HIJING с учетом описания фазового перехода первого рода как вероятностного процесса и проанализировано поведение флуктуаций полного ($N = N_+ - N_-$) и результирующего ($Q = N_+ - N_-$) электрических зарядов системы. Разные фазы были заданы с помощью BDMPS (Baier – Dokshitzer – Mueller – Piegne – Schiff) модели потери партонной энергии при прохождении через плотное ядерное вещество.

Ключевые слова: физика высоких энергий, Монте-Карло моделирование, тяжелые ионы, столкновения, флуктуации, кварк-глюонная плазма, HIJING, фазовые переходы

Introduction. The search for quark gluon plasma (QGP) has been one of the key targets of high energy experiments for the last decade. Its existence comes from the asymptotic freedom – the fundamental property of QCD. However, since it is hard to theoretically calculate the properties of QCD matter for finite resultant baryon densities, the burden of finding and determining the order of the QGP phase transition falls on the experiment. Also, we need observables that are sensitive to the phase transition (namely, to its order) and can be experimentally measured. In 2005 four international collaborations announced the results of their measurements and the discovery of QGP (for example, [1]). Still, there are dozens of yet open questions (strangeness production, order of the phase transition, location of the critical point etc.). Some of the observables behavior can be explained without implementing QGP or appear in pp or pA collisions (where the formation of QGP is still an open question) [2–5]. So, to explore this produced state of QCD matter, different experiments are being conducted (NA61, BES) or planned (NICA, FAIR). The last two are especially interesting since they are scanning the part of the phase diagram, in which both 1st and 2nd order phase transitions are possible.

One of the experimental observables for the phase transition is fluctuations (for example, critical opalescence in liquids – the result of the density fluctuations – is a signal for the critical point of the liquid/gas phase transition). In this paper we will focus on the fluctuations of the electric charge (both full and resultant). For simulations, we will use the HIJING v.1.411 [6] model, since it operates with microscopic parameters, and we can implement different phases by, for example, using a parton energy loss formula from Baier et.al. [7]. Moreover, it is freely accessible (unlike hijing 2.0 and hijing ++).

We will also simulate the first order phase transition as a probabilistic process that depends on the collision c. m. energy, where fluctuations show nonlinearities or other non-typical behavior in the 50% probability point. The goal of this paper is to analyze the behavior of the total and resultant electric charge cumulants in terms of the applied models with respect to kinematic cuts.

The results of this work can be used for describing the experimental data of heavy ion collisions.

1. QCD Phase Diagram. Quantum chromodynamics (QCD) is the theory that describes strong interaction. According to it, hadrons consist of quarks (3 for baryons, quark-antiquark for mesons). But unlike Quantum electrodynamics, in which the potential between charged particles decreases with increasing the distance between them, QCD has a very important feature – asymptotic freedom. It means that hot/dense matter must be weakly coupled [8]. This feature provides the idea of the new form of nuclear matter – quark gluon plasma. This is only a high temperature feature ($T \geq 105$–200 MeV). At low temperatures, quarks are locked inside hadrons via a basic property of the QCD vacuum – confinement [9]. So, in the experiment we can observe only hadronic matter.

Figure 1 shows the QCD phase diagram. Each point of the diagram presents a stable thermodynamic state. The thermodynamic parameters are the temperature and the baryon-chemical potential, which expresses the net-baryon density of the system. The basic theory, which is used to build such diagrams, is lattice QCD. It is worth saying that lattice QCD works only in the $\mu_B \approx 0$ area. As it can be seen, with vanishing baryo-chemical potentials lattice QCD predicts a smooth crossover between hadronic matter and QGP. However, with increasing μ_B the sign problem appears, which makes the usage of lattice QCD impossible. This area of the phase diagram is very important: it contains the 1st order phase transitions and critical points. To map the phase diagram, various $\mu_B \approx 0$ extrapolation and approximation techniques are used. So, the precise boundaries of phases are not known experimentally [10].

Therefore, its exploration and clarification falls on experiments, and to be more specific – on nucleon-nucleon, nucleon-ion, and ion-ion collisions. QGP, for example, is expected to be not produced in nucleon-nucleon collisions (and nucleon-ion, too). The general evolution of heavy ion collisions is as follows. Two nuclei in the center-of-mass system look like two Lorentz-contracted 'pancakes' with a longitudinal extent smaller by a factor $\gamma \sim \sqrt{S_{NN}}/2$ for high energy collisions. After the collision, at a proper time $\tau = \sqrt{t^2 - z^2} = 0$ fm/c two nuclei hit. The first processes that occur at this time are hard ones, involving a large momentum transfer, $Q \geq 10$ GeV/c. Hard particles (the transverse momenta are of the order of Q) are born during this stage. After that, the bulk of the partonic constituents begin to interact. They form a dense medium, which is not in a thermodynamic equilibrium. After that, there are 2 scenarios: the produced partons interact or not (or the interaction is negligible). The second one implies
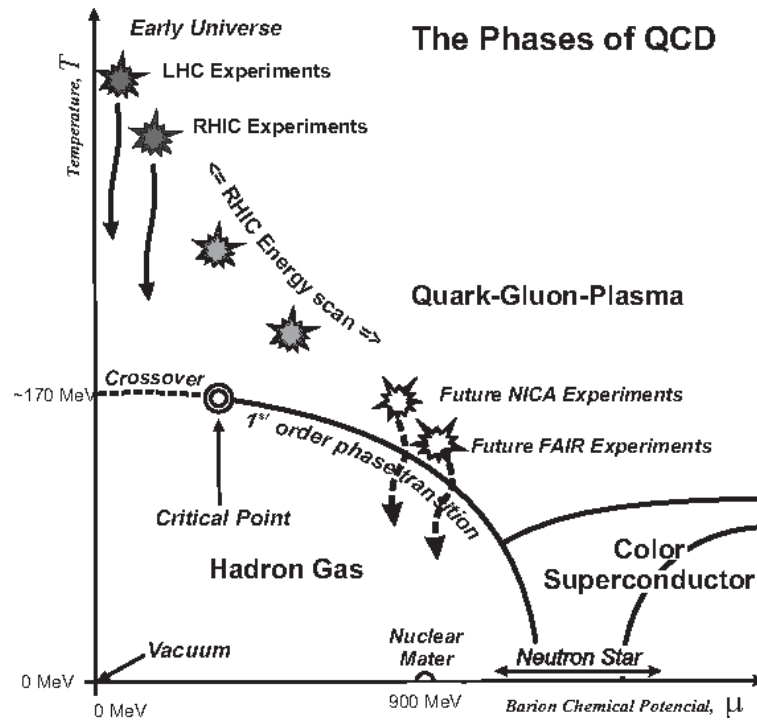
Fig. 1. The QCD Phase Diagram

Рис. 1. Фазовая диаграмма КХД

rapid separation from each other and hadronization (this would be in nucleon-nucleon or nucleon-ion collisions). The first one implies that there is thermalization and, as a result, quark-gluon plasma, having a local equilibrium, is produced. As will be seen below, it means that if we know how this stage of collision goes, we can tell whether QGP is produced or not. After that, the matter becomes less and less dense, cools to the phase transition temperature, and eventually hadronizes and freezes out [11].

We need to point out, in such experiments we can control 2 parameters: the beam energy (which is connected to the collision energy in the c.m.s. system, $\sqrt{S_{NN}}$) and the number of participating nuclei (A). Currently, the connection between the experimental parameters and the ones used in the phase diagram is given by freeze-out parametrization [12].

To find out whether QGP is produced or not, there are lots of observables to look at: elliptic flow, jet quenching, ratios of particle abundances, strangeness enhancement, etc. Among them, fluctuations are the experimental observables that are sensitive to the existence of the phase transition and its type and can provide information about the effective degrees of freedom in a system.

2. Fluctuations and phase transitions. As is pointed out, the phase transition from QGP to hadrons can be crossover, 1st order or 2nd order, depending on the control parameters of the QCD phase diagram.

During the 1st order phase transitions, the new phase can be formed by a spontaneous emergence of these phase (hadron) nuclei inside the old state (QGP). This emergence arises from the fluctuations of density, energy, and associated quantities. Depending on the thermodynamic properties and evolution of the system, the nuclei of the new phase can grow into the new phase or just disappear. In certain cases, it is possible to have nonperturbative large-amplitude fluctuations before the critical temperature is reached, which promotes phase mixing [13]. System dynamics will be sensitive to the amount of the phase mixing at the critical temperature. For the large phase mixing scenario, the transition takes place through the percolation of the hadronic phase, for the lower – as is shown above. During the 1st order phase transitions the phases can coexist along the 1st order transition curve, which ends with the critical point.

Summarizing the above statements, we can assume that:

1. The closer the system is to the critical point, the smoother the distribution of the fluctuations of observables is.

2. If the phases have the same probability for existence during the 1st order phase transition, the fluctuations of observables show it.

One of such observables is the fluctuations of conserved quantities (electric charge (Q), baryon number (B), and strangeness (S). According to [14] and the cited literature there, to construct the fluctuation measures, we need to construct the cumulants of quantities distributions with respect to the linear response relation:

$$M_q = \langle N_q \rangle = VT^3\chi_1^q, \quad C_2^q = \langle (\delta N_q)^2 \rangle = VT^3\chi_2^q,$$

$$C_3^q = \langle (\delta N_q)^3 \rangle = VT^3\chi_3^q, \quad C_4^q = \langle (\delta N_4)^4 \rangle - 3(C_2^q)^2 = VT^3\chi_4^q, \tag{1}$$

$$S_q = \frac{C_3^q}{(C_2^q)^{3/2}}, \quad \kappa_q = \frac{C_4^q}{(C_2^q)^2},$$

where $q = B, Q, C$, N_q are the number of particles carrying the corresponding charge, χ^q is the susceptibility of the corresponding charge, $\delta N_q = N_q - \langle N_q \rangle$, κ_q is the kurtosis, S_q is the skewness, V is the system (fireball) volume, and T is the system temperature. During the phase transition, C_2^q has the peak, and C_3^q changes the sign.

After that, we construct the following ratios of the cumulants:

$$\frac{C_2^q}{C_1^q} = \frac{\chi_2^q}{\chi_1^q}, \qquad \frac{C_3^q}{C_2^q} = \frac{\chi_3^q}{\chi_2^q},$$

$$\frac{C_4^q}{C_2^q} = \frac{\chi_4^q}{\chi_2^q}, \qquad \frac{C_4^q}{C_3^q} = \frac{\chi_4^q}{\chi_3^q}. \tag{2}$$

Constructing the ratios of the cumulants cancels the volume fluctuations. In this paper, we focus only on the electric charge cumulants and susceptibilities ($q = Q$).

Now we assume that centrality, required for the 1st order phase transition, is achieved, the phase equilibrium c.m.s. energy is 120 GeV, and the probability of the transition (ω) versus $\sqrt{S_{NN}}$ has the following distribution:

$$\omega_i(x_i) = \frac{1}{\sqrt{2\pi \langle x^2 \rangle}} \exp\left(-\frac{x_i^2}{2\langle x^2 \rangle}\right),$$

$$x_i = \left(\sqrt{S_{NN}}\right)_i - \langle \sqrt{S_{NN}} \rangle, \tag{3}$$

$$\langle x^2 \rangle = \frac{\sum_{i=1}^{N}\left[\left(\sqrt{S_{NN}}\right)_i - \langle \sqrt{S_{NN}} \rangle\right]}{N},$$

where $\left(\sqrt{S_{NN}}\right)_i$ is the c.m.s. energy in the i-th event, N is the number of events, $\langle \sqrt{S_{NN}} \rangle$ is the binodal c.m.s. energy among all N events, and $\langle x^2 \rangle$ characterizes the intensity of the fluctuations that arise in the system (density, temperature e.t.c) (Fig. 2).

3. Simulation and results. As been said before, the production of QGP depends on the properties of the medium emerging during heavy ion collisions. If the medium is cold, then there is no QGP production at the later stages. In [15] the properties of a QCD medium, such as λ, $\frac{dE}{dz}$, are calculated and used in this analysis. The results, obtained in [14], are taken by us with the following simplifications: we ignore the dependence of the parton energy loss $\frac{dE}{dz}(\alpha_s)$, and assume that $\alpha_s = 1/3$ for the hot QCD matter and $\alpha_s = 1/2$ for the cold QCD matter, the plasma temperature $T = 250$ MeV, and the length of the QCD medium $L = 10$ fm. In further works these simplifications will be removed. Simulations are made in
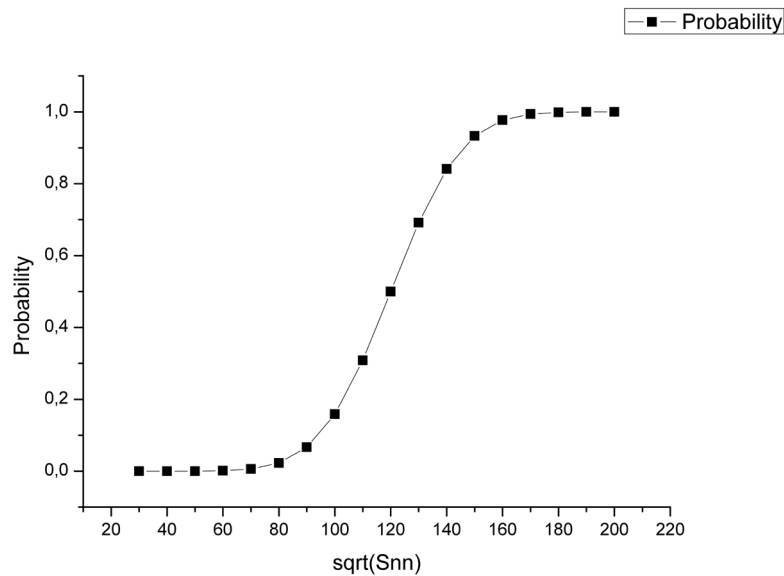
Fig. 2. The probability distribution of the 1st order phase transition in event-by-event collisions versus $\sqrt{S_{NN}}$

Рис. 2. Распределение вероятностей фазового перехода первого рода по $\sqrt{S_{NN}}$ при пособытийных столкновениях

HIJING since this generator allowed us to specify the necessary quantities as free parameters, able to be calculated with the implied simplified model.

Thus, for the hot QCD matter we have the following parameters: the gluon energy loss $\frac{dE}{dz}$ is 6 (the energy loss of a quark is half of that in a gluon), and the mean free path λ is 1.

For the cold QCD matter the gluon energy loss is 0.4, and the mean free path is 6.

The general simulation features: a and b are the parameters of the symmetric Lund fragmentation function $a = 2.2$, $b = 0.5$ [16], the K factor is taken default (2), the jet quenching is turned on, the initial and final state radiation is turned on for both cases. Moreover, for the total charge the rapidity cut is $-1 \leq y \leq 1$ and p_T cut is $0 \leq p_T \leq 2$ GeV/c and only $K^{\pm}$, $p^{\pm}$, $\pi^{\pm}$ are used for the analysis

Firstly, we will explore the total charge $N = N_+ - N_-$ where N_+ is the number of positive and negative charged particles, respectively. Although it is not a conserved quantity, it is still worth to study its cumulant behavior since it is related to the system entropy and, moreover, its "conservation" is described in [17].

The results of the simulations are given in the Figs., where the following designations are used: Hadron is the simulation with the cold hadron matter parameters, QGP is the simulation with the hot matter parameters, Gauss is the simulation with respect to the probability distribution (3)). Figure 3 shows the dependence of the mean number of charged particles vs. the collision energy in the c.m.s with respect to the probability of the phase transition during the collision. In this and the following ones the hadron probability is 0, the QGP probability is 1 and the Gauss is according to the distribution (4). As can be seen, there is a linear dependence consistent with the theoretical predictions.

Figure 4 shows the dependence of the cumulant (susceptibilities) ratios vs. the collision energy. Although the ratios are different for hadron and QGP matter (but linear in both cases), they show non-linear behavior in the phase equality region. And yet, these results are consistent with the predictions for the 1st order phase transitions made above.

The fluctuations of the resultant electric charge ($Q = N_+ - N_-$) are analyzed, but without any kinematic cuts and for all charged particles. Figure 5 shows the dependence of the resultant charge cumulant relations of the c.m.s. collision energy. As can be seen, HIJING with the parameters described above doesn't show any changes in the cumulant behavior (since droplets do not produce any additional resultant charge [17]).
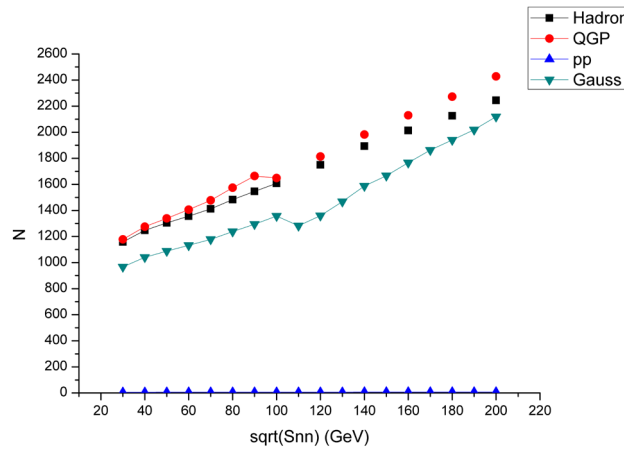
Fig. 3. The mean multiplicity of the charged particles produced in heavy ion collisions vs. the collision energy

Рис. 3. Зависимость средней множественности заряженных частиц, образованных в столкновениях тяжелых ионов, от энергии столкновения
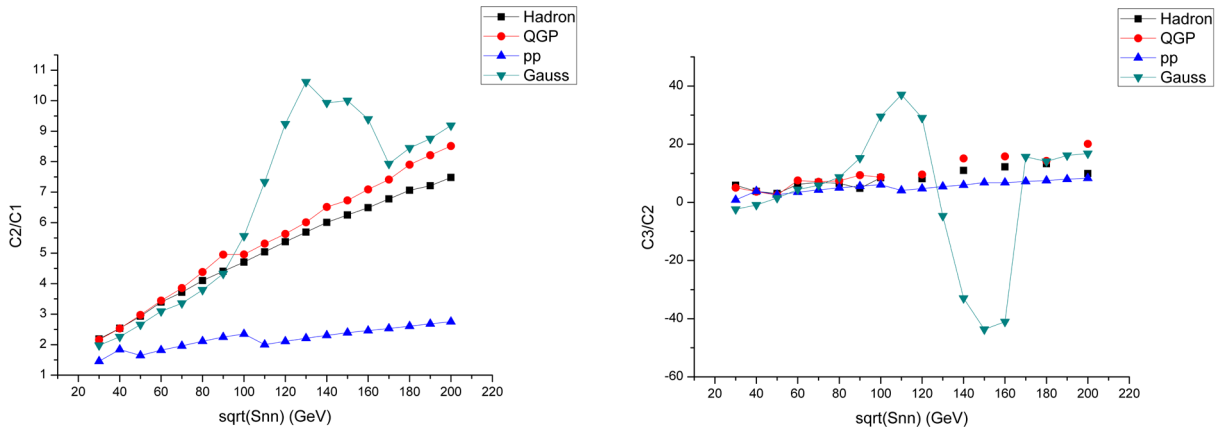

Fig. 4. The dependence of the ratios of the total charge cumulants of the system on the collision energy if we do and don't take into account the phase transient in the kinematic region described above

Рис. 4. Зависимость соотношений кумулянтов полного заряда системы с учетом и без учета фазового перехода от энергии столкновений в описанной выше кинематической области
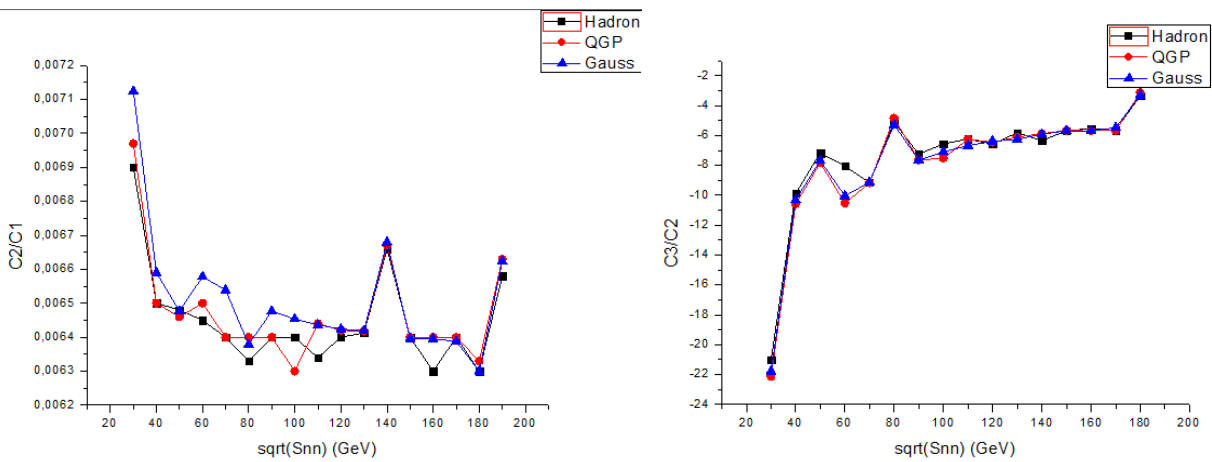

Fig. 5. The dependence of the ratios of the resultant charge cumulants of the system on the collision energy if we take into account and don't take into account the phase transitions.

Рис. 5. Зависимость соотношений кумулянтов результирующего заряда системы с учетом и без учета фазовых переходов от энергии столкновений

Conclusions. In this paper, we implemented extra fluctuations due to the 1st order phase transition to QGP using HIJING. To imply different phases, we used partonic jet energy loss and mean path calculations by Baier et. al. We used a simplified model, as the full model will be implemented later. After the implementation, we analyzed the fluctuations of the resultant and total electric charge for different probabilities of the phase transition. Simulations for the total charge were made with the following kinematic cuts: $-1 \leq y \leq 1, \quad 0.2 \leq p_T \leq 2$ GeV.

The results are the following:

1. The total charge cumulants behave according to the theoretical expectations.

2. HIJING with the mentioned parameters and the used approach doesn't reproduce any changes in the resultant charge cumulants behavior, independently of the type of the produced matter during the collision.

Thus, this study will proceed in the following directions:

1. Increasing statistics for using further cumulants.

2. Implying the full model for parton energy loss in the medium.

3. Analyzing the cumulants of other conserved quantities (resultant strangeness, net baryon charge) and the cumulants of total quantities.

4. Comparison with the experimental data with respect to efficiency corrections [14].

References

1. Adams J. Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions. *Nuclear Physics A*, 2005, vol. 757, pp. 102–183.

2. Blume C. Open questions in the understanding of strangeness production in HIC – Experiment perspective. *Proceedings for the Strange Quark Matter 2017 conference.* Utrecht, Netherlands, 2017. https://doi.org/10.1051/epjconf/201817103001

3. Biswarup P. Charmonium production in p-Pb collisions with ALICE at the LHC. *European Physical Society Conference on High Energy Physics, Italy, 5–12 July 2017.* Venice, 2017. https://doi.org/10.22323/1.314.0182

4. Shuryak E. Strongly coupled quark-gluon plasma in heavy ion collisions. *Reviews of Modern Physics*, 2017, vol. 89, no. 3, pp. 61. https://doi.org/10.1103/RevModPhys.89.035001

5. Koch, P., Muller. B., Rafelski J. From strangeness enhancement to quark gluon plasma discovery. *International Journal of Modern Physics A*, 2017, vol. 32, no. 31, pp. 1730024. https://doi.org/10.1142/S0217751X17300241

6. Xian Nian Wang, Gyulassy M. HIJING 1.0: A Monte-Carlo Program for Parton Parton and Particle Production in High Energy Hadronic and Nuclear Collisions. *Computer Physics Communications*, 1994, vol. 83, no. 2–3, pp. 307–331. https://doi.org/10.1016/0010-4655(94)90057-4

7. Baier R., Dokshitzer Yu. L., Mueller A. H., Piegne S., Schiff D. Radiative energy loss of high energy quarks and gluons in a finite volume quark-gluon plasma. *Nuclear Physics B*, 1997, vol. 483, no. 1–2, pp. 291–320, https://doi.org/10.1016/S0550-3213(96)00553-6

8. Shuryak E. V. Theory of Hadronic Plasma. *Journal of Experimental and Theoretical Physics*, 1978, vol. 74, pp. 408–420.

9. Bass S. A., Gyulassy M., Stoecker H., Greiner W. Signatures of Quark-Gluon-Plasma formation in high energy heavy-ion collisions: A critical review. *Journal of Physics G: Nuclear and Particle Physics*, 1999, vol. 25, no. 3, pp. R1–R57. https://doi.org/10.1088/0954-3899/25/3/013.

10. Fukushima K., Hatsuda T. The Phase Diagram of dense QCD. *Reports on Progress in Physics*, 2010, vol. 74, no. 1, pp. 014001. https://doi.org/10.1088/0034-4885/74/1/014001

11. Lancu E. *QCD in heavy ion collisions.* 2012. Available at: https://arxiv.org/abs/1205.0579v1

12. Cleymans J., Oeschler H., Redlich K., Wheaton S. Comprasion of Chemical Freeze-out Criteria in Heavy Ion Collisions. *Physical Review C*, 2006, vol. 73 no. 3, 15 p. https://doi.org/10.1103/PhysRevC.73.034905

13. Mohanty A. K., Shukla P., Gleiser M. Pre-transitional effects in rapidly expanding quark gluon plasmas. *Physical Review C*, 2002, vol. 65, no. 3, 7 p. https://doi.org/10.1103/PhysRevC.65.034908

14. Luo X., Xu N. Search for the QCD Critical Point with Fluctuations of Conserved Quantities in Relativistic Heavy-Ion Collisions at RHIC: An Overview. *Nuclear Science and Techniques*, 2017, vol. 28, no. 8, 42 p. https://doi.org/10.1007/s41365-017-0257-0

15. Baier R., Schiff D., Zakharov B. G. Energy loss in perturbative QCD. *Annual Review of Nuclear and Particle Science*, 2000, vol. 50, no. 1, pp. 37–69. https://doi.org/10.1146/annurev.nucl.50.1.37

16. Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, Subrata Pal. A Multi-Phase Transport Model for Relativistic Heavy Ion Collisions. *Physical Review C*, 2005, vol. 72, no. 6, 33 p. https://doi.org/10.1103/PhysRevC.72.064901

17. Heiselberg H. Event-by-event physics in relativistic heavy ion collisions. *Physics Reports*, 2001, vol. 351, no. 3, pp. 161–194. https://doi.org/10.1016/S0370-1573(00)00140-X

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