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Quark-gluon plasma's chaotic dynamics

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Abstract
Within the framework of the approximation of dynamically deterministic chaos the transition of quarks into hadrons, transition of mixed quark and hadronic phases into a quark-gluon plasma and the quark-gluon plasma hadronization's computer simulations have been carried out by the Poincare section method for nonlinear dynamics of the parton distribution function. Parton distributions are compared. The dynamics of the system has been determined by the evolution control parameter. Time derivative of the momentum fraction of a parton at a given time moment is determined by the momentum distribution of partons at previous time moment. Chaotic dynamics in the system takes place for the evolution parameter values. The chaotic state matches the quark-gluon plasma formation. At critical values of the control parameter, bifurcations of phase quark–gluon trajectories take place. As a result of the counteraction of gluon emission and absorption processes, stable attractor quark–gluon structures are formed. Quantum coherence effects follow by dynamic chaos. The change from regular quark–gluon dynamics to irregular chaotic one corresponds to the limit of multiple hadronic processes and emergence of quark–gluon matter in the deconfinement state. Chaotization of the dynamic system occurs with thermalization of the quark–gluon medium.

Keywords: quark-gluon plasma, quarks, parton distribution function, multiplicity

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Кварк-глюондық плазманың хаостық динамикасы

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Түйіндеме
Динамикалық детерминделген хаостық жақындауы шеңберінде партондық үлестіру функциясының бейсызықтық динамикасы үшін Пуанкаре кескіні әдісі арқылы квартардың адрондарға ауысуы үшін, аралас кварктік және адрондық фазалардың кварк-глюондық плазмаға ауысуы үшін және кварк-глюондық плазманың адронизациясы үшін компьютерлік модельдеу іске асырылды. Партондар үлестірулері салыстырылды. Жүйе динамикасы эволюция параметрі арқылы анықталады. Берілген уақыт мезетіндегі партон импульсы үлесі оның алдындағы уақыт мезетіндегі партондар импульсы үлестіруімен анықталады. Жүйедегі хаостық динамика эволюция параметрі мәндері үшін пайда болады. Хаостық күй кварк-глюондық плазманың пайда болуына сәйкес келеді. Басқару параметрінің кризистік мәндері үшін фазалық кварк-глюондық траекториялардың бифуркациялары іске асады. Глюондар шығару мен жұтылу үдерістер қарама-қарсы әсерлері нәтижесінде орнықты аттракторлық кварк-глюондық құрылымдар орнығады. Кванттық когеренттілік эффектілері динамикалық тәртіпсіздік пен қоса жүреді. Ретті кварк-глюондық динамикадан ретсіз хаостық динамикаға ауысу адрондық үрдістердің көптік шегіне және деконфайнмент күйіндегі кварк-глюондық материяның пайда болуына сәйкес келеді. Динамикалық жүйенің тәртіпсіз күйге келуі кварк-глюондық ортаның термализациясы нәтижесінде іске асырылады.

Түйін сөздер: кварк-глюондық плазма, кварктар, партондық үйлестіру функциясы, көптік

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Жаратылыстану ғылымдарының магистрі, «Қазақстан тарихы, жалпы білім беретін пәндер және ақпараттық жүйелер» кафедрасының аға оқытушысы. Л.Б. Гончаров атындағы Қазақ автомобиль-жол институты, Алматы қ, Қазақстан, ORCID ID: https://orcid.org/0000-0001-9097-1828. E-mail: z.work@list.ru

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Хаотическая динамика кварк-глюонной плазмы

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Аннотация
В рамках приближения динамически детерминированного хаоса методом сечений Пуанкаре для нелинейной динамики функции распределения партонов проведено компьютерное моделирование переходов кварков в адроны, смешанных кварковых и адронных фаз в кварк-глюонную плазму и адронизации кварк-глюонной плазмы. Сравниваются распределения партонов. Динамика системы определяется параметром эволюции. Производная по времени от доли импульса партона в данный момент времени определяется распределением импульсов партонов в предыдущий момент времени. Хаотическая динамика в системе имеет место при значениях параметра эволюции . Хаотическое состояние соответствует образованию кварк-глюонной плазмы. При критических значениях параметра управления происходят бифуркации фазовых кварк-глюонных траекторий. В результате противодействия процессов испускания и поглощения глюонов образуются устойчивые аттракторные кварк-глюонные структуры. Эффекты квантовой когерентности сопровождаются динамическим хаосом. Переход от регулярной кварк-глюонной динамики к нерегулярной хаотической соответствует пределу множественности адронных процессов и появлению кварк-глюонной материи в состоянии деконфайнмента. Хаотизация динамической системы происходит как результат термализации кварк-глюонной среды.

Ключевые слова: кварк-глюонная плазма, кварки, функция распределения партонов, множественность

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Introduction

In colliders of heavy relativistic nuclei, SPS, RHIC, LHC, quark-gluon plasma (QGP) is formed under various conditions; extreme substances obtained (for the given colliders) have their own characteristics [1]. Numerical estimates show that the transition to the quark-gluon plasma state occurs as a first-order phase transition at temperature corresponding to the hadron kinetic energy ~ 200 MeV. At temperatures, $T > 150MeV$, and densities, $\rho_0 - 10\rho_0$, here ρ_0 is density of nuclear matter, the average distance between quarks is less than 1 fm, the deconfinement to quark matter and asymptotic freedom take place [2]. The mechanism of QGP hadronization, which is characteristic both for the early Universe and for an extreme matter emerging in collisions of relativistic heavy ions, is discussed in [3, 4].

Interactions of high-energy particles, especially interactions of relativistic hadrons, are proceeding by multiple processes [1]. Multiplicity is an emergence of new particles, which are born in hadron and nuclear collisions. The multiplicity of secondary particles is one of the main characteristics of the interaction process. Multiple births are a combination of many different interaction mechanisms. The multiplicity and jet events are a proof of the complex internal structure of hadrons.

In [5], a Monte Carlo simulation of the phase transition of hadrons in QGP, based on the parton model, during collisions of relativistic heavy ions was performed. The authors suggest that in the case of a first-order phase transition, the formation of a new phase is accompanied by the spontaneous appearance of hadrons from the old state (i. e. QGP). This process is associated with density, energy, and other quantities fluctuations. A non-perturbative process, accompanied by large-amplitude fluctuations, which promotes phase mixing, is possible before reaching the critical temperature. The dynamics is affected by the number of phases to be mixed at the critical temperature. In the case of a large number of miscible phases, the transition is believed to occur through leakage (filtering) of the hadronic phase, otherwise by the non-perturbative process, caused by the fluctuations. During the phase transition the phases can coexist. The coexistence of phases stops at the critical point.

On the base of the hydrodynamic approach, J. Björken found that QGP arises at $T \geq 200 - 300MeV$ and exists for a time about 5 fm/c [6]. The region of low temperatures, when the system is a dilute pion gas, and the region of high temperatures, for which the medium is an ideal liquid of quarks and gluons, are singled out. The phase transition temperature is about 200 MeV.

In [7] on the basis of the QGP transport model J/ψ and ψ(2S) particle fluxes are considered as a result of the deconfinement phase in relativistic collisions of heavy gold ions with energy $\sqrt{S_{NN}} = 200\ GeV$.

The color interaction of quarks and gluons has been described by the quantum chromodynamics (QCD) [8]. The Feynman diagrams show, that in any type of interaction, multiple particle production occurs as a result of the process of quark hadronization in quark and gluon jets. At the present time, a clear idea of confinement associated with nonperturbative effects has not been developed, and there is no explanation for the fluctuations in multiple productions [9].

So, in the process of QGP occurrence and phase transitions in the system, multiple productions of secondary particles take place. The multiplicity is a characteristic of the phase transitions in the QGP-hadrons system.

Methods

Macroparameters of hadronic matter are as follows: density, temperature (energy) and chemical potential [2].

The dimensionless quantities used are as follows [9, 10]:

1) $x = \frac{Q^2}{2M\nu}$ is the Bjorken variable (i.e. the momentum fraction),

M is the nucleon mass, $v = E - E'$, E and E' are energies before and after scattering, Q^2 is the transfer momentum squared;

2) □ is the evolution parameter, $0 < \boldsymbol{\lambda} < 1$. The evolution parameter, i. e. the control parameter, depends on collision energy [11]. An increase of the parameter value is related to the system's energy growth.

Investigation method chosen is the nonlinear dynamics of the Poincaré mapping. A nucleon consists of various types' point QCD partons, both quarks and gluons. The partons can carry the initial nucleon different fractions x of momentum and energy. The structure function can be written as [12]:

$$F_2(x) = \sum_i e_i^2 x f_i(x) \tag{1}$$

Here e_i is interacting with photons i-th parton charge; $f_i(x)$ is the momentum distribution function of partons: $f(x) = q(x) + g(x)$, where $q(x)$ is the distribution function of quarks, $g(x)$ is the distribution function of gluons. An expression (1) is a formal notation of the Bjorken scaling (i. e. an independence of the structure functions on the 4-th momenta Q^2) [6].

The normalization condition should be written as a sum, which includes the momentum fractions of quarks: $\sum_i \int dx \cdot x \cdot q_1(x) = \frac{1}{2}$ [13].

At $x \to 1$, with the i-th parton carrying the nucleon (proton) entire momentum, the parton distribution function (PDF) in accordance with the sums' rule [14] is expressed in terms of $q_i(x) \to (1-x)^{2n_s-1}$ with n_s, being the number of valent spectator quarks, among which the rest part of nucleon (proton) momentum propagates, n_s=2 in the case of nucleons, n_s=4 corresponds to mesons [14, 15].

The QGP nonlinear dynamics equation in vacuum, in the frame of phase representation should be written as follows [15]:

$$\frac{dx}{d\lambda} = xf(x) \tag{2}$$

Here x is an effective value, which corresponds to parton momentum fraction. The normalization condition for the structure function can be defined as $\int_0^1 F_2(x_j)\,dx = 1$. The equation (2) is a renormalization group equation [14]. For completeness of the given consideration PDF in a nucleon (proton) is chosen in nonlinear equation (2).

The dynamics of the system has been determined by means of the evolution control parameter. The control parameter depends on the collision energy [11]. When the collision energy reaches a value of the order of 150-200 GeV, the parameter λ has a magnitude 0,892.

Results

The QGP is considered as a dynamic system, so for it, the concept of a state is unambiguously defined as a set of certain quantities at a given moment of time and a law is set (equation (2)), that describes the change (evolution) of the initial state over time. This law allows predicting the future state of dynamic system from the initial state.

Nonlinear equation (2) has been solved by the Poincaré section method. Compare results at slight difference in the initial approximations for two mappings of eq. (2): x_0=0.6, y_0=0.60001. In figures 1 and 2, iterations numbers are presented along the abscissa axis, relative deviations – along the ordinate axis. Figure 1 corresponds to the growth parameter value of 0.7, figure 2 – to its magnitude, equal to 0.9. The comparison reveals, that with the number of iterations increase (that is time grow) a divergence of values, corresponding to given close initial approximations, grows too. A chaotic behavior in the system takes place.

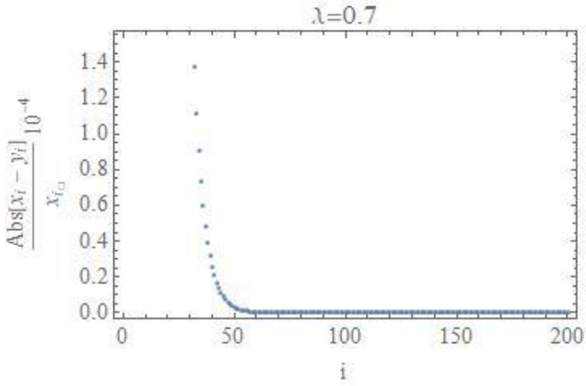

Figure 1. Solution of equation (2), the evolution parameter $\lambda = 0.7$ [author's material]

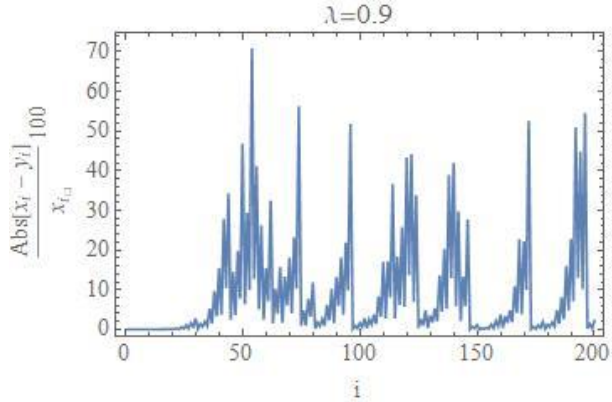

Figure 2. Solution of (2), the evolution parameter $\lambda = 0.9$ [author's material]

At increasing of the control parameter values in the range from 0.7 to 0.98 fluctuations of the momentum fraction of a parton are significant: amplitudes grow on several orders of magnitude. The chaotic dynamics takes place in the system for the evolution parameter values $\lambda \geq 0.89$. The chaotic state matches the quark-gluon plasma formation.

Hadrons are stable states of quarks and gluons. Bifurcation diagram is a geometrical locality of system equilibrium points depending on a given parameter. Bifurcations take place at the evolution parameter ~ 0.62 (Fig. 3). Obviously, the quark system transition to a chaotic regime has been occurred at larger values of □.

The number of bifurcations of phase trajectories in momentum space N_{bf} should be proportional to the multiplicity n_{ch} of secondary hadrons in strong interactions: $N_{bf} \sim n_{ch}$.

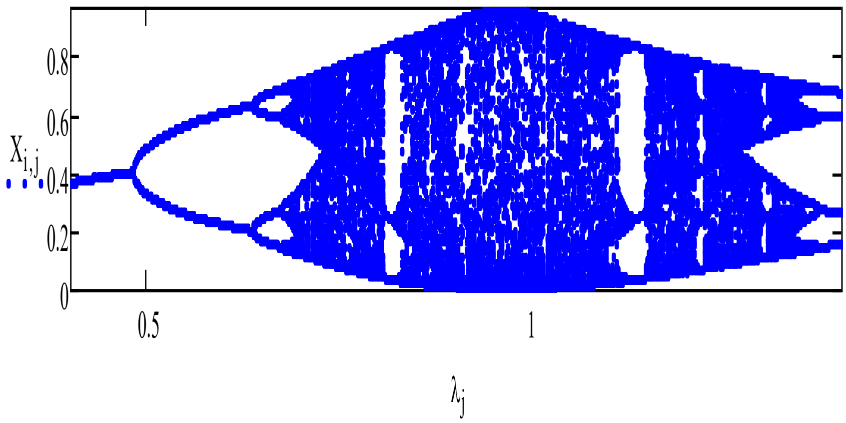

Figure 3. Bifurcation diagram of the quark system [author's material]

With PDF in nucleon, the solutions of (2) are stable attractor structures, which correspond to the fusion of quarks and gluons into steady clusters, i.e. the hadronization of QGP [5, 9, 14].

It is obvious from figure 3, that the hadron-QGP transition takes place with the collision energy increase. In accordance with the assumption that the number of bifurcations is related to the multiplicity, as the collision energy increases, the multiple production of secondary particles is essential, the quantity of quarks and gluons grows, the possibility of intrinsic interactions is higher. In the diagram, in figure 3, bifurcations correspond to phase transition points. At critical energy values, which correspond to the control parameter~1, bifurcation cascade converges, that is bifurcations disappear, as it is seen from figure 3. This situation matches full chaos in the system considered.

It is known, that the rate of convergence of bifurcations is defined by the Feigenbaum constant [11, 15]. According to figure 3, as the energy (or density of colliding nuclei) increases, the limit of cascade processes of multiple hadron production sets in, and hadron clusters have been destroyed with transition to a chaotic state of quarks and gluons.

The reverse transition of the quarks or QGP into hadronic matter takes place, when the QGP cools down. This transition could be associated with a decrease in symmetry.

Discussion

The results obtained provide important insights into the nonlinear dynamics of quark-gluon plasma (QGP) formation and evolution under extreme conditions. The analysis of the nonlinear equation (2) through the Poincaré section method has demonstrated the onset of chaotic behavior in the quark-gluon system. This behavior manifests as a divergence of phase trajectories in momentum space, which is highly sensitive to initial conditions, signifying dynamic instability typical of complex many-body systems.

The dependence of the evolution parameter λ on collision energy has been shown to determine the transition from stable to chaotic regimes. As the energy increases, the number of bifurcations in phase trajectories also increases, corresponding to the higher multiplicity of secondary hadrons, which aligns with experimental observations in high-energy collisions at facilities like SPS, RHIC, and LHC. This highlights the significance of the control parameter as a critical indicator of QGP formation.

A remarkable feature observed is the convergence of bifurcations at critical values of λ, representing the transition to a fully chaotic regime. This finding suggests that the chaotic behavior corresponds to the deconfinement of quarks and gluons and the establishment of a new phase – the QGP. Moreover, the connection between multiplicity and bifurcation structure in the momentum space implies a direct link between observed hadronic spectra and underlying nonlinear dynamics.

The theoretical approach aligns with experimental data, as indicated by the correspondence between the predicted critical values of the evolution parameter and the collision energy levels at which QGP signatures are observed. It also provides a framework to interpret fluctuations in particle production, which are not easily explained by perturbative quantum chromodynamics (QCD) alone.

Importantly, the discussion underscores the need to incorporate chaotic dynamics into models of QGP formation and hadronization, as the deterministic chaos observed offers a plausible explanation for nonperturbative processes involved in these transitions. The link between the Feigenbaum constant and the rate of convergence of bifurcations introduces a universal scaling property, suggesting that similar chaotic dynamics may govern other complex systems in high-energy physics.

Finally, the reverse transition from QGP back to hadronic matter, associated with cooling and potential symmetry restoration, represents an essential aspect of QGP dynamics. This transition, characterized by the reestablishment of confinement and hadronic structures, completes the cycle of matter evolution under extreme conditions and warrants further investigation through both theoretical modeling and experimental validation.

Conclusion

It is of importance to study mechanisms of nonperturbative processes. Chaotic behavior may play a crucial role in the evolution of a large system of quarks and gluons, such as those produced in heavy-ion collisions at high energy.

Within the framework of the approximation of dynamically deterministic chaos the transition of quarks into hadrons, the transition of mixed quark and hadronic phases into quark-gluon plasma and the quark-gluon plasma hadronization's computer simulations have been carried out by the Poincare section method for the nonlinear dynamics of the parton distribution function.

The evolution parameter is chosen as a criterion for chaotic behavior of the system considered, the threshold value of , above which chaotic behavior will definitely occur, is 0.89. The chaotic state matches the quark-gluon plasma formation.

The nonlinear equation of the quark-gluon cascade proposed is a model of the evolution of the momentum distribution of partons due to competing processes of their creation and fusion. As the energy increases, sequential bifurcation (doubling) of phase trajectories occurs, and scale-invariant fractal structures are to create. At sufficiently high interaction energies of hadrons and nuclei, a dynamically determined quark-gluon system, corresponding to QGP, arises in space. There are also hadron-like structures. Quantum coherent effects arise as a result of strong parton correlations in the non-perturbative confinement region. The quarks and gluons merge into stable attractor structures with their subsequent decay into hadrons.

At sufficient energy of nuclear and hadron collisions the growth limit of the multiplicity of secondary hadrons sets in with increasing the collision energy. This corresponds to the limiting Hagedorn temperature, after which quark-gluon plasma arises. The emergence of the quark-gluon plasma in nonlinear dynamics is considered as the limit of a sequence of period-doubling bifurcations with transition to the chaotic quark-gluon state.

Conflict of interests. Correspondent the author states that there is no conflict of interest.

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