IRSTI 27.35.55 https://doi.org/10.26577/RCPh.2022.v82.i3.02

Z. Mazhit*, A.T. Temiraliev

Al-Farabi Kazakh National University, Kazakhstan, Almaty

*email: z.work@list.ru

SIMULATION OF MULTIPLE HADRON PRODUCTION AND TRANSITION TO QUARK-GLUON PLASMAS BASED ON NONLINEAR DYNAMICS

A dynamics of quark-gluon plasmas has been defined by the evolution parameter, which at high energies depends on collision energy of atomic nuclei for appropriate multiplicities of secondary hadrons. The paper is based on the solution of evolution equation for patrons momentum distribution. A transition from regular propagation to irregular chaotic is an indicator of the quark-gluon plasma emerging. Nonlinear renormalization group equation has been solved by the method of Poincaré mappings. The equation 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 energies of quarks and gluons, a dynamically determined quark-gluon system, corresponding to QGP, arises in space. There are also hadron-like structures. Quantum coherence effects follow by dynamic chaos. As a result, quarks and gluons merge into stable attractor structures with their subsequent decay into hadrons. The nonlinear equation introduced for quark-gluon cascade, which comprises dynamical chaos, has include effects of parton recombination. The chaotic dynamics has been connected specifically to the transverse momenta of partons. Clearly, the formation of dynamically determined stable structures should be unknown before, attractor mechanism of quark hadronization.

Key words: quark-gluon plasma, asymptotic freedom, quarks, the color interaction

З. Мәжит,*, А.Т. Теміралиев

Әл Фараби атындағы Қазақ ұлттық университеті, Қазақстан, Алматы қ.

*email: z.work@list.ru

Бейсызықты динамика әдісі арқылы көп адрондар түзулуі мен кварк-глюондық плазмаға ауысуды модельдеу

Кварк-глюондық плазманың динамикасы эволюция параметрімен анықталады, ол жоғары энергияларда екінші реттік адрондардың сәйкес еселігі үшін атом ядроларының соқтығысу энергиясына тәуелді. Партондар импульсінің таралу эволюциясының теңдеуін шешу негізінде бұл жұмыста жүйенің қалыпты динамикадан тұрақты емес хаостық режимге ауысуы кварк-глюондық плазманың пайда болуының көрсеткіші екендігі көрсетілген. Сызықты емес ренорм-тобының теңдеуі Пуанкаре кесінділер әдісімен шешілген. Бұл теңдеу құру мен біріктірудің бәсекелес процестеріне байланысты партондардың импульсінің таралу эволюцияның үлгісі болып табылады. Энергия өскен сайын фазалық траекториялардың бифуркациясы (екі еселенуі) орын алып, масштабты инвариантты фракталдық құрылымдар түзіледі. Кварктар мен глюондардың жеткілікті жоғары энергияларында кеңістікте кварк-глюондық плазмаға сәйкес келетін динамикалық кварк-глюондық жүйе пайда болады, онда адрон тәрізді құрылымдар да болады. Кванттық когеренттілік әсерлері жүйені динамикалық хаосқа келтіреді. Нәтижесінде кварктар мен глюондар тұрақты аттракторлық құрылымдарға қосылады, содан кейін адрондарға ыдырау жүреді. Кварк-глюондық каскадтың енгізілген сызықты емес теңдеуі динамикалық хаосты ескере отырып, партон рекомбинациясының әсерлерін қамтиды. Хаостық динамика ең алдымен партондардың көлденең моменттеріне байланысты. Әбден мүмкін динамикалық тұрақты құрылымдардың қалыптасуы кварк адронизациясының бұрын белгісіз аттракторлық механизмі болып табылады.

Түйін сөздер: кварк-глюондық плазма, асимптотикалық еркіндік, кварктар, түсті әсерлесу

З. Мажит*, А. Т. Темиралиев
Казахский национальный университет им. Аль-Фараби, г. Алматы, Казахстан
*email: z.work@list.ru

Моделирование множественного рождения адронов и перехода в кварк-глюонную плазму на основе нелинейной динамики

Динамика кварк-глюонной плазмы определяется посредством параметра эволюции, который при высоких энергиях зависит от энергии столкновения атомных ядер для соответствующих значений множественности вторичных адронов. В работе на основе решения уравнения эволюции для импульсного распределения партонов показано, что переход системы от регулярной динамики к нерегулярному хаотическому режиму является показателем появления кварк-глюонной плазмы. Нелинейное ренорм-групповое уравнение решалось методом отображений Пуанкаре. Это уравнение представляет собой модель эволюции импульсного распределения партонов за счёт конкурирующих процессов рождения и слияния. С увеличением энергии происходит последовательная бифуркация (удвоение) фазовых траекторий, образуются масштабно-инвариантные фрактальные структуры. При достаточно больших энергиях кварков и глюонов в пространстве возникает динамически детерминированная кварк-глюонная система, соответствующая кварк-глюонной плазме, в которой присутствуют и адроно-подобные структуры. Эффекты квантовой когерентности сводятся к динамическому хаосу. В результате кварки и глюоны сливаются в устойчивые аттракторные состояния с последующим распадом в адроны. Введённое нелинейное уравнение кварк-глюонного каскада с учётом динамического хаоса содержит эффекты рекомбинации партонов. Хаотическая динамика прежде всего связана с поперечными импульсами партонов. Образование динамически детерминированных устойчивых структур представляет, по-видимому, ранее неизвестный аттракторный механизм адронизации кварков.

Ключевые слова: кварк-глюонная плазма, асимптотическая свобода, кварки, цветовое взаимодействие

Introduction

Quark-gluon plasma (QGP), as a state of matter at ultrahigh energies/temperatures and densities, had been discovered in 2000 at CERN (European Center for Nuclear Research) in experiments with relativistic heavy ions of lead and gold [1]. At LHC (the Large Hadron Collider), the formation of QGP in collisions of ions corresponds to an energy of ~ 3.5 TeV. The kinetic energy of the particles being collided had been much higher than their rest energy [2]. The density of the formed matter exceeds the density of nuclear matter (nuclear density) by approximately 10-20 times. QGP formation signals at relativistic heavy ions experiments are as follows: an increased yield of strange mesons, a decrease in the yield of heavy ψ-mesons, suppression of high- energy jets with large transverse momenta, an increase in the yield of photons and dilepton pairs [1].

Quarks and gluons are fundamental particles; they are linked by the color interaction [2]. The color interaction of quarks and gluons has been described by the quantum chromodynamics (QCD). According to the parton model, a proton is composed of a number of point like constituents, named partons (quarks, anti-quarks and gluons). The parton model of hadrons includes the confinement (particles retention within a hadron) and asymptotic freedom. Experiments on deeply inelastic scattering of leptons by nucleons [3], in which the structure function of the nucleon had been measured, were a proof of the parton model of hadrons and QCD as strong interaction theory. Another basis for the parton model of hadrons is the Bjorken scaling, despite that it implements approximately [3, 4].

QCD shows, that the intensity of quarks color interaction changes with distance: it increases with distance growth and decreases with their forthcoming to each other. The asymptotic freedom implies that the quarks interact weakly at small scales. Within hadrons the quarks can be considered as asymptotically free particles. Gluons are the mediators of strong interactions, as well as photons are the mediators of electromagnetic interactions. The quark and gluon densities have not been conserved due to quantum fluctuations [5]. QCD is an essentially nonlinear theory, so approximate research methods, accepted in the quantum field theory, are not quite adequate to determine strong interactions in non-perturbative region [1]. Enforcing the Poincaré symmetry in near equilibrium conditions leads to fractalization of the space-time background [5].

Macroparameters of hadronic matter are as follows: density, temperature (energy) and chemical potential [2]. The dimensionless quantities used are as follows [6]:

1) $x = \frac{Q^2}{2M\nu}$ is the Bjorken variable (i.e. the momentum fraction), M is the nucleon mass, $\nu = E - E'$, E and E' are energies before and after scattering, Q^2 is the transfer momentum squared;

2) λ is the evolution parameter, $0 < \lambda < 1$. The evolution parameter, i.e. the control parameter, depends on collision energy [7].

Methods

Quark distribution

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

$$F_2(x) = \sum_i e_i^2 x f_i(x). \qquad (1)$$

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) [4].

The normalization condition should be written as a sum, which includes the momentum fractions of quarks: $\sum_i \int dx \cdot x \cdot q_i(x) = \frac{1}{2}$. 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 [9] 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 [9]. Figure 1 shows quark momentum distribution within the nucleon (solid line), within a meson (dotted line) and from statistical consideration (dashed line) [8].

QGP nonlinear dynamics equation in vacuum, in the frame of phase representation should be written in a discrete form as follows [5]:

$$x_{j+1} = \lambda x_j f(x_j). \qquad (2)$$

Here j corresponds to iteration number. 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 [5].

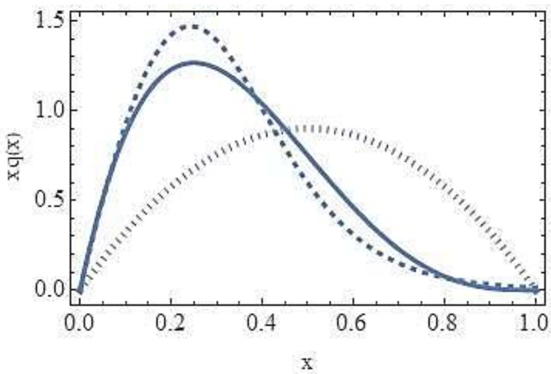

Figure 1 – Quarks momentum distribution. Solid line corresponds to quarks in nucleon [9], dashed line – quark distribution function [8], dotted line – quarks in meson [9].

Results and Discussion

Quark-gluon system modes in dependence on the evolution parameter

The control parameter depends on the collision energy [7]:

$$\lambda \simeq \lambda_\infty - \frac{1}{3\sqrt{s}},$$

λ_∞ is a value, close to 1, $\sqrt{s}$ is the collision energy, measured in GeV. One can see that an increase of the parameter value is connected to a growth of system energy.

In nonlinear equation (2) PDF has been chosen as:

$$\lim_{x \to 1} f(x) = (1-x)^3, \qquad (3)$$

i.e. PDF in a nucleon is in our consideration. The equation (2) has been solved by the Poincaré section method. As the control parameter value changes, a qualitative restructuring of the system takes place. In Fig. 2 the main modes of system restructuring for various values of the control parameter are presented: damping, stationary, periodic and chaotic. An index 'k' growth corresponds to an increase of time.

From dependencies, shown in Fig.2, it follows, that an equilibrium of the quark-gluon system is determined by the control parameter value. In the region of small values of the evolution parameter, for any initial value of the parton momentum x_0 an evolution, that is partons production and recombination, terminates (Fig. 2a). This process corresponds to a damping regime. At increasing the evolution parameter value a transition to a steady state occurs, in which the number of partons does not change (Fig. 2b). Further bifurcations of the parton trajectories occur. The quark-gluon system first passes into a periodic regime, which then changes to a chaotic regime (Figs. 2c and 2d).

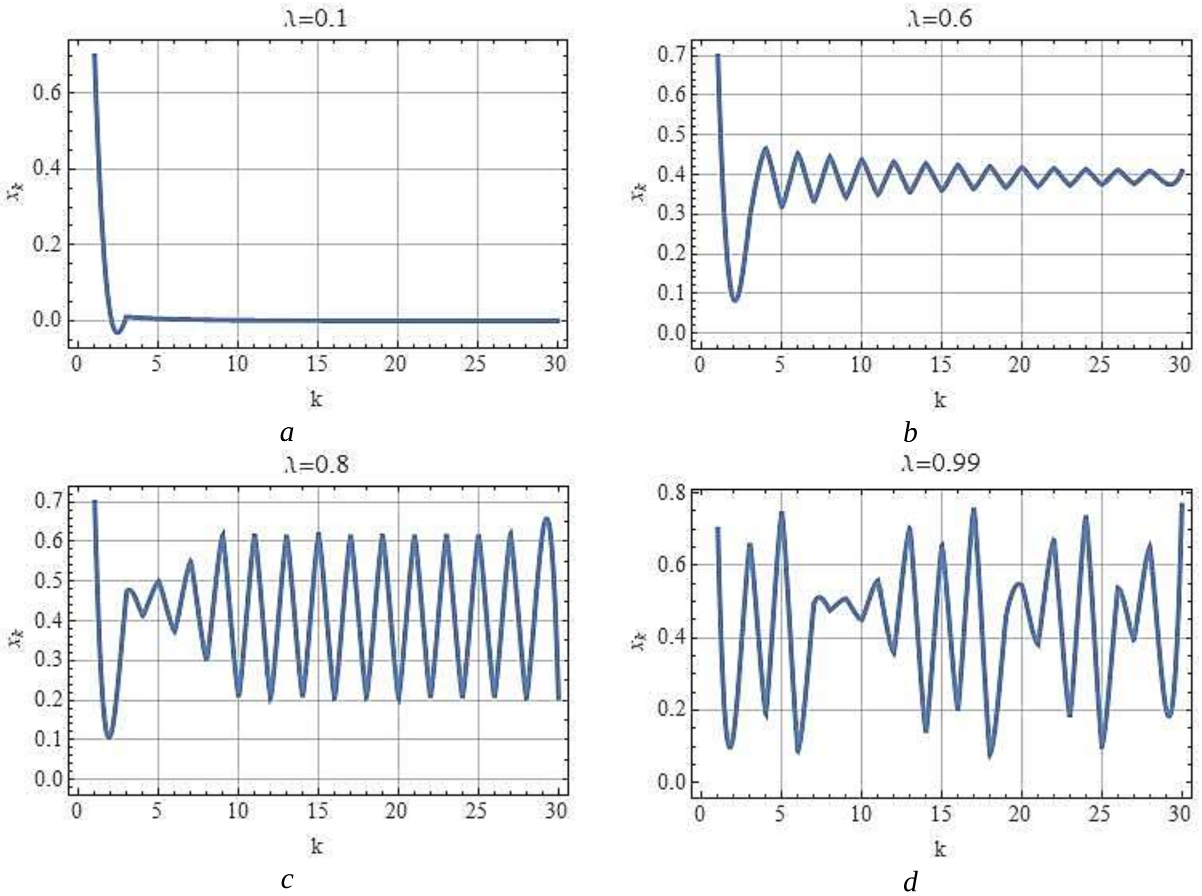

Figure 2 – Different modes in dependence on the control parameter value: damping, stationary, periodic and chaotic: 2a corresponds to $\lambda = 0.1$, 2b – $\lambda = 0.6$, 2c – $\lambda = 0.8$, 2d – $\lambda = 0.99$.

Chaotic dynamics of the quark-gluon system

A bifurcation diagram is a geometrical locality of system equilibrium points depending on a given parameter. A bifurcation takes 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 λ.

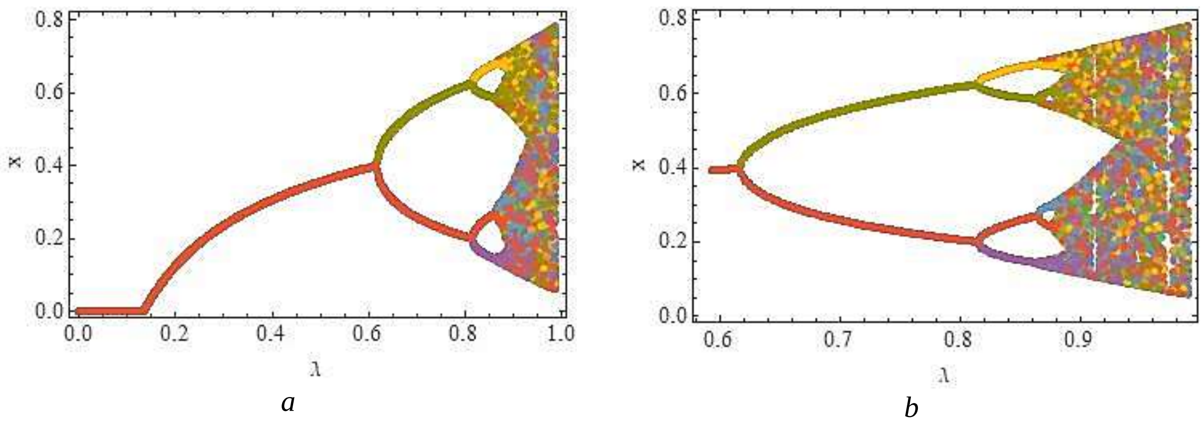

Figure 3 – Bifurcation diagrams of the quark system on different scales of the control parameter: 3a – 0< λ< 1; 3b – 0.6< λ< 1.

The solutions of (2) with PDF in form (3) are stable attractor structures, which correspond to the fusion of quarks and gluons into steady clusters, i.e., the hadronization of QGP [5, 10]. The attractor is a spatial object with fractal structure.

Conclusion

The state of hadronic matter under critical conditions (that is QGP) is defined by macroparameters such as density an order of magnitude greater than the nuclear density ρ_0, ρ_0~1,6 10^{14} g/cm^3, temperature $T \sim 200$ MeV and chemical potential $\mu \neq 0$. The dynamics of the system has been determined by means of the evolution control parameter. In the paper on the basis of nonlinear equation solution with taking into account the distribution of partons over momenta one has presented that chaotic dynamics takes place in the system for the values of the evolution parameter, $\lambda \geq 0.89$. The chaotic state matches the quark-gluon plasma formation.

The nonlinear equation of the quark-gluon cascade (2) 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. As a result, quarks and gluons merge into stable attractor structures with their subsequent decay into hadrons. The introduced nonlinear equation of the quark-gluon cascade, which comprises dynamical chaos, has include the effects of parton recombination. The chaotic dynamics has been connected specifically to the transverse momenta of partons. Clearly, the formation of dynamically determined stable structures should be unknown before, attractor mechanism of quark hadronization.

References

1 Розенталь И.Л., Снигирёв А.М. Гидродинамическая интерпретация взаимодействия частиц высоких энергий и космических γ-всплесков // ФЭЧАЯ. – 2003. – Т.34. Вып.1. – С.142-183.

2 Nopoush M. Non-equilibrium hydrodynamics of quark-gluon plasma. A dissertation for the degree of Doctor of Philosophy // arXiv: 1904.02831v1[hep-ph]. – 2019. – 186 p.

3 Кривохижин В.Г., Котиков А.В. Структурные функции нуклонов и определение константы связи сильного взаимодействия // Физика элементарных частиц и атомного ядра. – 2009. – Т.40. Вып.7. – С.226-298.

4 Bjorken J.D. Highly relativistic nucleus-nucleus collisions: The central rapidity region // Phys. Rev. D. – 1983. – Vol.27, No1. – P.140-151.

5 Темиралиев А.Т., Данлыбаева А.К. Формирование структур в нелинейной кварк-глюонной эволюции // Известия НАН РК. Серия физико-математическая. – 2014. – №2. – С.106-111.

6 Mazhit Z., Temiraliev A.T. Nonlinear dynamics method for studying quark-gluon plasmas // Int. J. Math. Phys. – to be published.

7 Батунин А.В. Фрактальный анализ и универсальность Фейгенбаума в физике адронов // УФН. – 1995. – Т.165, №6. – С.645-660.

8 Sohaily S., Vaziri (Khamedi) M. New approach in the quantum statistical parton distribution // Physics Letters B. – 2017. – Vol.775. – P.172-177.

9 Хелзен Ф., Мартин А. Кварки и лептоны: Введение в физику частиц: Пер. с англ. – М.: Мир, 1987.

10 Goldfain E. Non-equilibrium dynamics as source of asymmetries in high energy physics // EJTP. – 2010. – Vol.7, No.24. – P.219-234.

References

1 I.L. Rozenral, A. M. Snigirev, Phys. Elem. Part. Atom. Nucl., 34 (1), 142-183 (2003). (In Russ).

2 M. Nopoush, Non-equilibrium hydrodynamics of quark-gluon plasma. A dissertation for the degree of Doctor of Philosophy, (Kent State University, USA, 2018, arXiv:1904.02831v1[hep-ph] 2019), 186 p.

3 B.G. Krivozhihin, A.B. Kotikov, Phys. Elem. Part. Atom. Nucl., 40 (7) 226-298 (2009). (In Russ).

4 J.D. Bjorken, Phys. Rev. D, 27 (1), 140-151 (1983).

5 A.T. Temiraliev, A.K. Danlybaeva, RK NASc Habarlary. Phys. and math series, 2, 106-111 (2014). (In Russ).

6 Z. Mazhit, A.T. Temiraliev, Int. J. Math. Phys. – to be published.

7 A.B. Batunin, UFN, 165 (6), 645-660 (1995). (In Russ).

8 S. Sohaily, M. Vaziri (Khamedi), Physics Letters B, 775, 172-177 (2017).

9 F. Helsen, A. Martin, Quarks and leptons: Introduction to Particle Physics, transl. from eng. (Moscpw, 1987). (In Russ).

10 E. Goldfain, EJTP, 7 (24), 219-234 (2010).