ANNOTATION

for dissertation work, Baiseitov Kassymkhan Mukhtaruly
"Kinetic and wave properties of quark-gluon plasma", submitted for the degree of Doctor of Philosophy (PhD) in the specialty "8D05306 - Physics"

The general characteristic of the work. The results of the study of dynamic (kinetic) and wave properties of the quark-gluon plasma based on various models of the representation system are presented in the dissertation.

The relevance of the topic. In nuclear matter under normal conditions, quarks are always kept inside hadrons due to the phenomenon of confinement — they cannot be observed separately. At extremely high temperatures (about hundreds of billions of degrees) and at a very high density of nuclear matter, hadrons "melt" and quarks together with gluons form a collective state. This special state of matter, in which quarks and gluons (fundamental particles of the strong interaction) exist in the composition of hadrons (protons, neutrons, mesons, etc.), but in the form of "free" strongly interacting matter, is called quark-gluon plasma. Such a state of matter was formed in the Universe in the first tens of microseconds after the Big Bang; in modern conditions, quark-gluon plasma (QGP) can be obtained at super-powerful particle accelerators, such as the Large Hadron Collider at CERN.

Thus, the study of the fundamental properties of QGP gives a unique opportunity to reproduce the early stages of the evolution of the Universe and to understand how protons, neutrons and atomic nuclei, which make up the basis of matter, were formed. At the same time, QGP represents a state of matter with high energy density, in which the traditional concepts of particles and fields become less applicable. The study of the properties of QGP can shed light on new aspects of physics and help expand our understanding of the structure and new phases of matter in which the usual properties of particles disappear. For example, in the interior of neutron stars there may be states close to the QGP. Modern collider experiments can also be used to verify quantum chromodynamics - the theory of strong interaction, which predicts such unusual phenomena as deconfinement, phase transitions, etc. at high energies and densities. Since the most powerful unique accelerators (RHIC, LHC), sophisticated detectors, modern methods of analysis of "strongly interacting liquid" are being created for the study of QGP, and these technologies are used in related fields - from medical technologies (proton, ion therapy) to processing of big data in the creation of artificial intelligence. The study of the properties of QGP has an important application in the development of new technologies and materials such as thermonuclear energy, quantum computing, etc. Finally, studying the properties of QGP is extremely important for understanding the eternal philosophical question: what is matter made of what its forms under extreme conditions are, etc.

In general, the results obtained in the presented thesis contribute to the development of fundamental knowledge about the nature of matter and expand our understanding of physical processes in the early period of the evolution of the Universe.

In connection with the above, research and development of models of the interaction of quark-gluon plasma particles, considering the influence of various effects on its dynamic and other physical properties, becomes relevant.

Thus, this thesis is devoted to the study of dynamic (kinetic) and wave properties of quark-gluon plasma.

The purpose of the dissertation is to study the kinetic and wave properties of the quark-gluon plasma based on various interaction models that consider both collisional and hydrodynamic effects.

To achieve the goal, it was necessary to solve the following **tasks**:

1. To analyze analytical expressions for functions of dielectric response (permeability) of plasma and its surface for various models of QGP.
2. Calculate dispersion relations for waves in plasma for different models of QGP.
3. Calculate dispersion relations for waves its surface for different models of QGP.
4. Investigate the propagation of waves in the quark-gluon plasma within the framework of various models of the medium.

Research Object. Quark-gluon plasma at extremely high temperatures and densities.

Research Subject. Kinetic, hydrodynamic, and wave properties of quark-gluon plasma based on various interaction models.

Research Methods. The following methods were used to solve the problems necessary to achieve the stated goal: kinetic equation, linear dielectric response function method, dispersion relations, and numerical methods for solving differential, integral, and algebraic equations. Effective particle interaction models were used to calculate optical characteristics by determining the dispersion relation.

Novelty of the Work. The novelty and originality of this dissertation lies in the fact that it is **the first** to:

- obtain dispersion relations for waves in a collisional and viscous quark-gluon plasma medium;
- analyze the behavior of the dispersion relation for waves in the medium under various model representations in the long-wavelength limit;
- obtain dispersion relations for surface waves in a collisional and viscous quark-gluon plasma;
- Wave propagation in quark-gluon plasma was studied using collisional and viscous models of the medium.

Thesis submitted for defense:

1. Collisions in quark-gluon plasma lead to a decrease in the frequency of longitudinal waves in the medium for collision frequencies from $\nu = 0$ to $\nu = 0{,}4\omega_p$ for wavenumbers from $k = 0$ to $k = 4.0\omega_p$, while viscosity leads to a decrease in the frequency of longitudinal waves in the medium for collision frequencies from $= 0$ to $\nu = 0{,}4\omega_p$ for wavenumbers from $k = 0$ to $k = 4.0\omega_p$.

2. As the collision frequency of particles in the system increases, the frequencies of vibrational modes decrease in the long-wavelength limit, which leads to difficulties in charge separation in the plasma. Collisions in quark-gluon plasma lead to differences in the frequencies of longitudinal waves in the medium in the long-wavelength limit for collision frequencies from $\nu = 0$ to $\nu = 0{,}4\omega_p$.
3. On the surface of the quark-gluon plasma, additional types of oscillations appear due to the inclusion of particle collisions and the viscosity of the medium: in the collisional model, surface waves appear with frequencies from $\omega = 0.6m_D$ to $\omega = 1.4m_D$ for wave numbers from $k = 0$ to $k = 1.0m_D$; inclusion of viscosity leads to the appearance of surface waves with frequencies from $\omega = 1.0\omega_p$ to $\omega = 1.4\omega_p$ for wave numbers from $k = 0$ to $k = 1.0\omega_p$.
4. The phase velocity of waves in collisional and viscous media decreases by a factor of six and ten, respectively, in the range of wavenumbers from $k = 0$ to $k = 1.0\omega_p$. The group velocity of waves in collisional and viscous quark-gluon plasmas is lower in the long-wavelength limit for wavenumbers from $k = 0$ to $k = 2.0\omega_p$, demonstrating strong dispersion phenomena in the long-wavelength limit.

Theoretical and practical significance of the study. The results of this dissertation are valuable for understanding the fundamental properties of matter, modeling the early Universe and astrophysical objects, and for practical applications. Studying the influence of collective effects on the dynamic and wave properties of quark-gluon plasma allows us to adequately determine the physical properties of the medium necessary for modeling the corresponding processes, as well as for understanding the evolution of astrophysical objects such as neutron stars, white and brown dwarfs, and giant planets. Studying the collisions of ultrarelativistic heavy nuclei allows us to improve modern accelerator technologies (LHC, RHIC), which are widely used in medicine, materials science, and nuclear energy. Detector technologies, big data processing, and the development of computer modeling methods, which are integral to experiments at ultrarelativistic accelerators, contribute to progress in artificial intelligence.

Reliability and validity of the obtained results. This dissertation utilized well-known physical models and proven mathematical methods. The reliability and validity of the obtained results are also confirmed by publications in international journals with impact factors and in publications recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, as well as in the proceedings of international scientific conferences in neighboring and non-neighboring countries.

The author's personal contribution consists of the fact that the entire volume of this dissertation, the choice of the research method, the analytical solutions of problems, and the numerical calculations in Python, c++ and Wolfram Mathematica programming languages were completed independently. The formulation of the

problems and the discussion of the results were conducted jointly with scientific advisors.

Dissertation approval. The results obtained in this dissertation were presented and discussed at:

- at the International Conference of Students and Young Scientists "Farabi Alemi" (2020, Almaty, Kazakhstan);
- at the International Conference "Non-ideal Plasma Physics" (2020, Moscow, Russia);
- at the International Conference "47th EPS Conference on Plasma Physics" (2021, Spain);
- at the International Conference of Students and Young Scientists "Farabi Alemi" (2021, Almaty, Kazakhstan);
- at the International Conference "17th International Conference on the Physics of Non-Ideal Plasmas (PNP-2021)" (2021, Dresden, Germany);
- at the International Conference "International Conference on Strongly Coupled Coulomb Systems (SCCS-2022)" (2022, Gorlitz, Germany);

Articles in journals included in the Q3 and Q4 quartiles of the Scopus database with CiteScore percentile.

1. Baiseitov K., Blaschke D., Ramazanov T.S. Collective bulk excitations in the QGP: From the weakly non-ideal case to the strong correlation limit // Contrib Plasma Phys. 2023. V. 63, № 9–10. P. e202300015. doi.org/10.1002/ctpp.202300015. Q3, CiteScore 2.4, percentile 37%.

2. Baiseitov K., Moldabekov, Z.A., Blaschke, D., Djienbekov, N., Ramazanov, T.S. Surface waves in a collisional quark-gluon plasma // Phys Part Nucl Lett. 2020. V. 17, № 6. P. 803–808. doi.org/10.1134/S1547477120060035. Q4, CiteScore 0.7, percentile 27%.

3. Baiseitov K., Blaschke D., Kuanyshbaiuly Ye. Phase and group velocities of waves in medium of Quark-gluon plasma // Phys. Sci. Technol. 2024. V. 11, № 1–2. P. 102–108. DOI: 10.26577/phst2024v11i1a12. Q4, CiteScore 0.7, percentile 24%.

Articles in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Higher Education of the Republic of Kazakhstan.

4. Baiseitov K. Dielectric function of quark-gluon plasma // Bull. NAS RK. 2021. V. 4, № 338. P. 15–24. DOI: 10.32014/2021.2518-1726.61.

5. Байсеитов К. Волны в среде вязкостной кварк-глюонной плазмы // Проблемы эволюции открытых систем. – 2024. – V. 26, №1. – P. 3–9. DOI: 10.26577/JPEOS.2024.v26.i1-i1.

Discussions were held with Professor D. Blaschke (University of Wroclaw, Poland), Professor M. Gazdicki (CERN, Switzerland), and Professor M. Bonitz (Kiel, Germany) as part of international collaboration.

Publications. 11 publications based on the dissertation materials have been published: three in journals included in the List of the Control and Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan for the publication of the main results of PhD dissertations, two articles

in international journals with an impact factor, included in the international information resource Web of Knowledge (Thomson Reuters Clarivate Analytics, USA) and Scopus (Elsevier, the Netherlands); six papers in the proceedings of international scientific conferences.

The connection of the Dissertation with plans for scientific works. The dissertation work was carried out in accordance with the plans of fundamental and applied scientific research (NIR) of Ministry of Science RK "Grant funding of scientific research" on the topic: "The influence of the wake field on the dynamics of strongly correlated heavy particles in classical, quantum and ultrarelativistic plasma" (2020-2022, code AP08052503, state registration); "Comprehensive research on nuclear and radiation physics, high-energy physics and cosmology for the development of competitive technologies" (2021-2023, code BR10965191, state registration); "Research of fundamental and applied problems of plasma physics, plasma-like media for the purposes of solving modern energy problems and obtaining new functional materials" (2022-2024, code BR18574080, state registration).

Scope and structure of the dissertation. The dissertation consists of an introduction, five sections, a conclusion, and a list of 147 references. It contains 101 pages of main computer text, including 24 figures.