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AN ANALYSIS OF φ MESON PRODUCTION IN THE COLLISIONS OF PROTON BEAMS WITH ALUMINUM AND GOLD NUCLEI AT ENERGIES OF 200 GeV

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In the paper, φ meson production in the relativistic collisions at energies of 200 GeV measured by the PHENIX experiment (RHIC) has been studied. Phi mesons' nuclear modification factors were calculated for the mentioned interactions under conditions identical to the experimental ones, using different theoretical models, the results being compared. The accounting for the formation phase of quark-gluon plasma (QGP) in simulation was established to agree well with experiment for the p + Au collisions and disagree for the p + Al ones. This result could indicate an insufficient size of the interaction system of the latter to form QGP at an energy of 200 GeV and the sufficiency of the created minimum conditions for its formation in the former interaction system.

Keywords: quark-gluon plasma, cold nuclear matter effect, nuclear modification factor

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АНАЛИЗ РОЖДЕНИЯ φ-МЕЗОНОВ В СТОЛКНОВЕНИЯХ ПУЧКОВ ПРОТОНОВ С ЯДРАМИ АЛЮМИНИЯ И ЗОЛОТА ПРИ ЭНЕРГИЯХ 200 ГэВ

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В работе изучено рождение φ-мезонов в релятивистских столкновениях пучков протонов с ядрами алюминия (p + Al) и золота (p + Au) при энергиях 200 ГэВ, в области малых быстрот. Исследование проведено с помощью детекторной системы «ФЕНИКС» на коллайдере RHIC. С помощью различных теоретических моделей рассчитаны факторы ядерной модификации φ-мезонов в указанных взаимодействиях при условиях, идентичных экспериментальным, проведено сравнение результатов. Установлено, что учет фазы образования кварк-глюонной плазмы (КГП) при моделировании дает хорошее согласие с экспериментом для взаимодействия p + Au и не дает его для p + Al, что может говорить о недостаточности размера системы взаимодействия последнего при энергии 200 ГэВ для формирования КГП, а также достаточности созданных минимальных условий для ее формирования в первом случае.

Ключевые слова: кварк-глюонная плазма, эффект холодной ядерной материи, фактор ядерной модификации

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Introduction

Computations in lattice quantum chromodynamics predict a phase transition of hadron gas into such a state of matter as quark-gluon plasma (QGP) at a temperature $T \approx 150$ MeV $\approx 10^{12}$ K (Fig. 1 [1]). QGP is matter consisting of strongly interacting elementary particles, where quarks and gluons are deconfined and can move like quasi-free particles.

Systematic study of collisions of relativistic nuclei presents a unique opportunity to explore the phase transition of quantum chromodynamics (QCD) in laboratory conditions. The experimental program of the PHENIX detector [2] at the Relativistic Heavy Ion Collider (RHIC [3]) includes a wide range of colliding nuclei systems: from basic interactions of proton beams to heavy ion collisions. This allows analyzing different aspects of the conditions necessary to produce QGP.

Experimental signatures of QGP were previously obtained in collisions of such systems as heavy ions of gold (Au + Au) [4], copper and gold (Cu + Au), with the nuclei accelerated to relativistic energy $\sqrt{s_{NN}} = 200$ GeV, and with uranium (U + U) nuclei accelerated at $\sqrt{s_{NN}} = 192$ GeV [5]. As for the dynamics of proton interactions ($p + p$), it is well described by perturbative QCD [1].

Study of elliptical and triangular fluxes of charged hadrons in small interaction systems, such as proton beams with gold nuclei (p + Au), deuterium nuclei with gold nuclei (d + Au), helium-3 nuclei with gold nuclei (^{3}He + Au), made it possible to formulate the hypothesis that the energy density in such collisions is sufficient for producing hot and dense QGP matter [6, 7]. Further experiments are necessary to gain deeper insights into the evolution of the system.

Investigations into the peculiarities of light hadron production are widely carried out for studying the process of QGP generation in the interactions of relativistic nuclei [5].

While there is a wide variety of light hadrons, the φ meson holds particular interest [8], since it contains (anti)strange quarks ($s\bar{s}$), its yields are measurable up to large transverse momenta, and it has a relatively small cross section for hadron interaction, as well as a longer lifetime than that of QGP (~46 fm/c, compared to ~5 fm/c, where c is the speed of light in vacuum [1]).

Study of light hadron production in interactions of relativistic nuclei makes it possible to observe various effects of hot (assuming the generation of QGP) [1] and cold (reflecting the initial and final conditions of interaction) [9] nuclear matter. Phenomena pointing to production of hot and dense matter include collective effects such as increased strangeness yield [10] and the jet quenching effect [11]. The effects of cold nuclear matter include the Cronin effect [12], multiple parton scattering [13], modification of the initial distribution functions of partons in the nucleus [14], etc.

Thus, multiple effects of different nature, indicating either production or absence of QGP, are capable of influencing the production of the φ meson in the interaction of relativistic nuclei. Simulating the interactions under the conditions matching the experimental ones allows obtaining, via different theoretical models, the expected influence from hot and cold nuclear matter on the production of φ mesons.

The minimum conditions for QGP production can be understood by interpreting the experimental data based on comparison with simulation.

The goal of this study consisted in exploring the evolution of collisions of proton beam systems with aluminum and gold nuclei at an energy $\sqrt{s_{NN}} = 200$ GeV by simulating the φ meson production in such collisions and comparing the simulated results with the experiment.

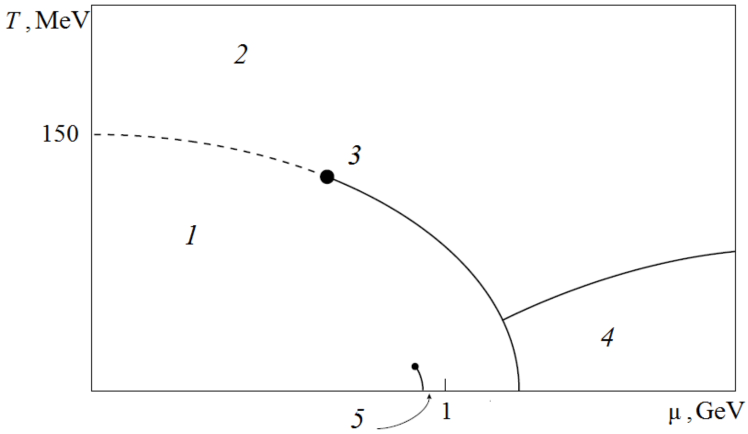

Fig. 1. Theoretical phase diagram of nuclear matter as function of temperature T and baryonic chemical potential μ:
hadron gas *1*, quark-gluon plasma *2*, critical point *3*, color superconductivity *4*, normal nuclear matter *5*.
The dashed line indicates the second-order phase transition

The PYTHIA [15] and AMPT [16] software packages with default parameters were used to simulate the evolution of the system without the QGP phase. The AMPT model with string melting was used to consider collective effects (QGP effects).

Measurement method and models used

The experimental datasets used in the analysis were obtained in the PHENIX experiment at RHIC at $\sqrt{s_{NN}} = 200$ GeV in (p + Al) and (p + Au)-interactions near midrapidity ($|\eta| < 0.35$). The production of φ mesons was considered in the decay channel into two unlike-sign K mesons. The values of the φ meson mass, its mean lifetime, and the probability of decay in a given channel (Br) are listed in Table [14].

According to Glauber's model [17], the interaction of relativistic nuclei in the absence of collective effects can be represented as a superposition of elementary nucleon-nucleon interactions. However, various effects of both hot and cold matter can influence the evolution of a system of colliding nuclei. For this reason, nuclear modification factors RAB are used to study the collective effects governing particle production in collisions of ultrarelativistic nuclei [18]. This quantity is calculated as the ratio of invariant hadron yields in $A + B$ collision to the invariant yield of the same hadrons in proton beam collisions ($p + p$) at the same energy, normalized to the number of inelastic nucleon-nucleon collisions (N_{coll}) in $A + B$ system.

The value of Ncoll in Glauber's model is estimated using Monte Carlo simulation.

For deeper analysis of the experimental data obtained, we used the PYTHA and AMPT software packages to simulate the p + Al and p + Au interactions at $\sqrt{s_{NN}} = 200$ GeV, similar to the interactions carried out experimentally. Lund's model of string fragmentation is widely used to describe the hadronization process of ($p + p$) collisions and to perform QCD computations [19].

Table

Main characteristics of φ meson decay

Decay channel	Mass, MeV/c^2	Mean lifetime, fm/c	Br, %
$\varphi \to K^+K^-$	1019.455 ± 0.020	46.3 ± 0.4	48.9 ± 0.5

The PYTHIA software package was created in 1997 based on this model: its purpose is to simulate the interaction of protons at high energies. We used the latest version of the software package, PYTHIA 8, in our study. However, the computational results related to φ meson production in interactions of proton beams at $\sqrt{s_{NN}}$ = 200 GeV deviate from the experimental data [20]. A new hybrid PYTHIA/Angantyr model was constructed based on PYTHIA to describe the interactions of heavy (heavier than a proton) relativistic nuclei [21]. The interaction of $A + B$ nuclei is described within the framework of this model as a superposition of elementary nucleon-nucleon interactions of different types (elastic, diffraction, absorptive).

Nuclear modification factors of the φ meson were calculated in this study based on the simulated interactions in the PYTHIA software package in accordance with the same procedure that was applied to the experimental data. The values of the nuclear modification factor RAB were calculated as the ratio of invariant φ meson yields in p + Al or p + Au interactions, obtained using the PYTHIA/Angantyr software package, to similar invariant φ meson yields in the interactions of proton beams at the same energy $\sqrt{s_{NN}}$ = 200 GeV, obtained using the standard PYTHIA 8 package. This ratio is normalized to the experimental number of inelastic nucleon-nucleon collisions (N_{coll}) in the p + Al or p + Au system, respectively. This procedure for calculating the nuclear modification factors eliminates the aforementioned discrepancy between the experimental and the calculated data for invariant φ meson yields in proton beam interactions, performed using the PYTHIA 8 package.

Another theoretical model widely used for describing the evolution of relativistic ion collisions is the Multi-Phase Transport Model (AMPT). The software package based on this model makes it possible to comprehensively study the process of potential QGP production. The AMPT model with default parameters describes the evolution of relativistic nuclei interaction without QGP production. This AMPT model configuration includes the following stages:

initial conditions,
parton cascade accounting for the confined state of quarks and gluons;
transition from parton to hadron matter based on Lund's model of string fragmentation;
hadronic interactions.

The extended configuration of the AMPT software package with string melting accounts for the production of the QGP phase: the parton cascade is simulated, followed by partons combining into hadrons by the quark coalescence model [16]. In this case, the nuclear modification factors of the φ meson were calculated as the ratio of their invariant yields in the given interactions, obtained using the AMPT software package, to the experimental value of the similar invariant yield in the interaction of proton beams ($p + p$) at the same energy [22], normalized to the experimental number N_{coll} of inelastic nucleon-nucleon collisions p + Al or p + Au, respectively.

Experimental results and discussion

Fig. 2,*a*,*b* compares the nuclear modification factors of φ mesons in p + Al and p + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, obtained in the PHENIX experiment, and nuclear modification factors of φ mesons in similar interactions, calculated using the PYTHIA software package. Evidently, the nuclear modification factors of φ mesons calculated with the PYTHIA software package are in good agreement with the experimental results in p + Al collisions at $\sqrt{s_{NN}}$ = 200 GeV. However, the values of RAB calculated using the PYTHIA model turn out to be less than R_{AB} obtained in the experiment in p + Au interactions at $\sqrt{s_{NN}}$ = 200 GeV. Notably, the discrepancy grows with increasing transverse momentum p_T.

Fig. 2,*c*,*d* shows the distributions of the nuclear modification factors R_{AB} over transverse momentum, measured for φ mesons in (p + Al) and (p + Au)-interactions at the same energy $\sqrt{s_{NN}}$ = = 200 GeV at the PHENIX experiment using the AMPT software package. The AMPT model with default parameters describes the experimental results in (p + Al) interactions fairly well, while the

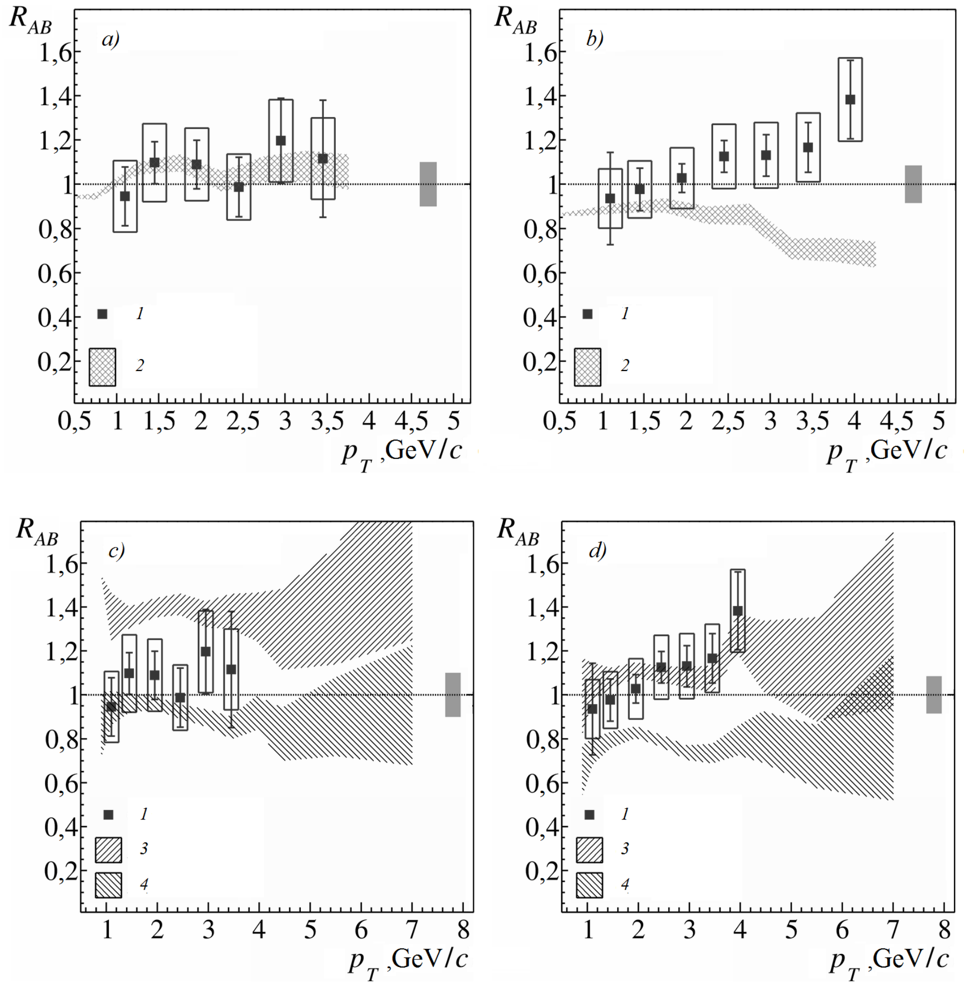

Fig. 2. Distributions of nuclear modification factors of φ mesons over transverse momentum in (p + Al)- (a,c) and (p + Au)- (b,d) interactions at $\sqrt{s_{NN}}$ = 200 GeV; data obtained experimentally (1), using PYTHIA software package (2), AMPT software package, configuration with string melting (3) and with default parameters (4). Bars and boxes correspond to statistical and systematic uncertainties, shaded boxes on the right correspond to normalized uncertainty

AMPT configuration with string melting yields smaller R_{AB} values in (p + Au) interactions. than the experiments. On the other hand, the values of nuclear modification factors of φ mesons calculated using the AMPT model configuration with string melting exceed the experimental ones in (p + Al) interactions, but agree well with those in (p + Au) interactions.

Conclusion

We have analyzed the production of φ mesons in collisions of proton beams with aluminum and gold nuclei at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity. The interactions were simulated under the conditions matching the experimental ones using the PYTHIA and AMPT software packages and comparing the obtained experimental results with the data of theoretical computations.

The distribution of nuclear modification factors of φ mesons in (p + Au) collisions at $\sqrt{s_{NN}}$ = = 200 GeV near midrapidity coincides with the computed results obtained using the AMPT model with string melting, within the uncertainty, while the nuclear modification factors obtained in the

PYTHIA and AMPT software packages with default parameters turned out to be smaller than the experimental values.

Conversely, the distribution of nuclear modification factors of φ mesons in (p + Al) collisions at $\sqrt{s_{NN}}$ = 200 GeV near midrapidity coincides with the computed results obtained using the the PYTHIA and AMPT software packages with default parameters, with the uncertainty, while the nuclear modification factors obtained using the AMPT model with string melting turned out to be larger than the experimental values.

The result obtained may indicate that the mechanism governing the φ meson production at $\sqrt{s_{NN}}$ = 200 GeV in interactions of proton beams with aluminum nuclei is considerably different from that in interactions of proton beams with gold nuclei. The minimum conditions (temperature and baryon density) necessary for QGP production may be achieved in the interactions of proton beams with gold nuclei at $\sqrt{s_{NN}}$ = 200 GeV, while no signatures for QGP production are observed in the interactions of proton beams with aluminum nuclei at the same energy.

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