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MEASUREMENT OF φ-MESON'S NUCLEAR MODIFICATION FACTORS IN THE COLLISIONS OF PROTON BEAMS WITH ALUMINUM NUCLEI AT AN ENERGY OF 200 GEV

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The φ-mesons production in the relativistic collisions of proton beams with aluminum nuclei (p + Al, small system) at $\sqrt{s_{NN}}$ energy of 200 GeV has been studied. The PHENIX experiment was carried out at the RHIC. The φ-mesons' invariant transverse momentum spectra and their nuclear modification factors were measured in four centrality bins of the range of transverse momentum (%): 0 – 20, 20 – 40, 40 – 72, 0 – 72. The obtained results were compared with similar data on the π^0-mesons production. The experimental data analysis led to the conclusion that the φ-mesons' nuclear modification factors were equal to one (within the measurement uncertainties) over all available ranges of centrality and transverse momenta. The findings of the work testified that quark-gluon plasma did not produce in the performed collisions.

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

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ИЗМЕРЕНИЕ ФАКТОРОВ ЯДЕРНОЙ МОДИФИКАЦИИ φ-МЕЗОНА В СТОЛКНОВЕНИЯХ ПРОТОННЫХ ПУЧКОВ С ЯДРАМИ АЛЮМИНИЯ ПРИ ЭНЕРГИИ 200 ГЭВ

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В работе изучено рождение φ-мезонов в релятивистских столкновениях пучков протонов с ядрами алюминия (p + Al, малая система) при энергии $\sqrt{s_{NN}}$ = 200 ГэВ, проведенных в эксперименте PHENIX на коллайдере RHIC. Измерены инвариантные спектры φ-мезонов по поперечному импульсу и их факторы ядерной модификации для четырех классов событий по центральности, %: 72 – 0 ,72–40 ,40 – 20 ,20 – 0. Проведено сравнение полученных результатов с аналогичными данными по рождению π^0-мезонов. Анализ полученных экспериментальных данных привел к заключению, что во всех доступных диапазонах по центральности и поперечному импульсу факторы ядерной модификации φ-мезонов равны единице в пределах неопределенностей измерения. Полученный результат свидетельствует в пользу того, что в рассматриваемых столкновениях кварк-глюонная плазма не образуется.

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

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Introduction

Quantum chromodynamics predicts the existence of a state of matter known as quark-gluon plasma (QGP), where quarks and gluons are deconfined. Ultrarelativistic heavy ion collisions provide an opportunity for studying the behavior of nuclear matter at temperatures and pressures sufficient for QGP production [1]. Exploring the properties of QGP produced in controlled conditions and its evolution into hadron gas is the main purpose of the PHENIX experiment [2] at RHIC (Relativistic Heavy Ion Collider located at Brookhaven National Laboratory, USA) [3].

One method for studying the properties of QGP experimentally is measuring final-state particle yields. In particular, φ mesons have a range of distinctive properties, such as small cross section for interaction with non-strange hadrons and much longer lifetimes (42 fm/*c*) than those of QGP [4]. Thanks to these properties, hadron interactions have less effect on φ meson production at the late stages in the evolution of the system formed in heavy ion collisions; furthermore, φ meson daughter particles are not rescattered in the hadron phase.

Thus, the properties of φ mesons mainly depend on the conditions in the early parton phase, and measuring φ meson yields can be regarded as a clean test for the behavior of the matter produced in collisions of relativistic nuclei.

Measuring φ meson yields can be used to study the so-called cold nuclear matter (CNM) effects in small collision systems [5]. Cold nuclear matter effects are understood as modifications of parton distributions in the nucleus [6], the Cronin effect [7] associated with multiple rescattering of incoming partons inside the target nucleus, and other effects.

Analysis of CNM effects by measuring φ meson production in small systems can explain whether the effects observed in heavy ion collisions are connected with the effects of cold or hot nuclear matter. In particular, results of such studies can help understand the difference between nuclear modification factors of π^0 mesons, φ mesons, and protons obtained in collisions of gold (Au+Au), copper (Cu+Cu), copper-gold (Cu+Au) nuclei at $\sqrt{s_{NN}}$ = 200 GeV, as well as uranium nuclei (U+U) collisions at $\sqrt{s_{NN}}$ = 192 GeV [8, 9].

Measurement procedure

We used the measurement results obtained with the PHENIX detector at RHIC. Our goal consisted in reconstructing the production of φ mesons decaying into charged kaons ($\varphi \to K^+K^-$) in collisions of proton and aluminum nuclei (*p*+Al) at $\sqrt{s_{NN}}$ = 200 GeV.

We primarily focused on obtaining invariant transverse momentum spectra and nuclear modification factors R_{AB} for φ mesons in *p*+Al collisions.

As kaons produced in φ meson decay are indistinguishable from other kaons, so all kaon tracks from each event are combined into unlike-sign pairs. The components of the three-momentum vector **p** for each track were measured using the drift chamber. Invariant mass and transverse momentum are calculated for kaon pairs based on two-body decay kinematics.

The invariant mass spectrum for unlike-sign kaon pairs contains both the signal of φ mesons and the combinatorial background. The latter includes two components: correlated and uncorrelated background. The event-mixing technique is used to estimate combinatorial background [12]. After subtracting the uncorrelated background from the total spectrum, the correlated background is estimated by fitting the invariant mass distributions to a Breit–Wigner distribution convoluted with a Gaussian (where the dispersion equals the experimental mass resolution of the detector) to describe the signal, plus a polynomial to describe the background.

The experimental mass resolution of the detector is estimated by Monte Carlo simulation of the spectrometer with zero width for $\varphi \to K^+K^-$, where φ mesons have infinite lifetimes. We obtained φ meson yields by integrating the invariant mass distribution within ±9 MeV/c[2] of the φ meson mass (1.019 GeV/c[2] [13]) after subtracting the combinatorial background.

The invariant spectrum of φ meson production is calculated as follows in each transverse momentum bin:

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = \\ = \frac{1}{2\pi p_T}\frac{1}{N_{event}\mathrm{Br}}\frac{1}{\varepsilon_{eff}(p_T)}\frac{N(\Delta p_T)}{\Delta p_T \Delta y}, \quad (1)$$

where p_T and Δp_T, GeV/*c*, are the meson transverse momentum and its bin width respectively; *y* and Δy are the rapidity and its bin width; $N(\Delta p_T)$ is the number of mesons reconstructed with the experimental detector (meson yields); N_{event} is the total number of events reconstructed in the given centrality bin; $\varepsilon_{eff}(p_T)$ is the φ meson reconstruction efficiency obtained using Monte Carlo models of decay, passage and regeneration of mesons in the PHENIX experiment; Br is the probability of meson decay via the given channel.

Suppression of particle yields in relativistic heavy ion collisions is studied by finding the nuclear modification factors R_{AB}, calcue lated as a ratio of invariant particle yields measured in relativistic heavy ion collisions to the yields of the same particles measured in elementary collisions of protons (*p*+*p*). The yield for *A*+*B* collision is normalized to the number of inelastic nucleon-nucleon collisions.

Nuclear modification factors of particles in collisions of different nuclei are used to account for the collective effects governing the transverse momentum spectra of particle production, and are calculated by the formula:

$$R_{AB}(p_T) = \frac{f_{bias}\sigma_{pp}^{inel}}{N_{coll}}\frac{dN_{AB}(p_T)}{d\sigma_{pp}(p_T)}, \quad (2)$$

where

$$dN_{AB}(p_T) = \frac{1}{2\pi p_T}\frac{d^2N_{AB}(p_T)}{dp_T dy}$$

is the invariant spectrum of meson production in heavy ion collisions;

$$d\sigma_{pp}(p_T) = \frac{1}{2\pi p_T}\frac{d^2\sigma_{pp}}{dp_T dy}$$

is the invariant differential cross-section for production of these particles in *p*+*p* collisions at the same center-of-mass energy; f_{bias} is the Bayes factor correcting for the bias in centrality measurements; σ_{pp}^{inel} = 42.2 mb is the cross section for inelastic proton-proton scattering; N_{coll} is the number of binary collisions in the given centrality bin.

If $R_{AB}(pT) \approx 1$, collective effects are probably absent in heavy ion interactions, and the interactions may be represented by superposition of individual nucleon interactions.

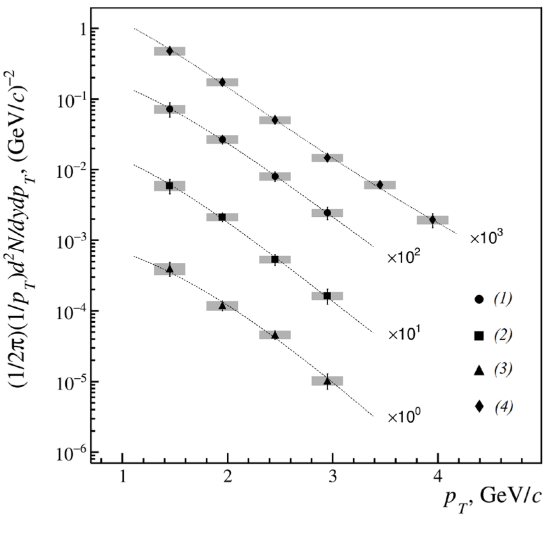

Fig. 1. Invariant transverse momentum spectra of φ meson production in *p*+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV in four centrality bins, %: 0–20 (*1*), 20–40 (*2*), 40–72 (*3*), 0–72 (*4*).
The dotted curves were fitted with the Lévy function.
Bars and boxes correspond to statistic and systematic uncertainty, respectively

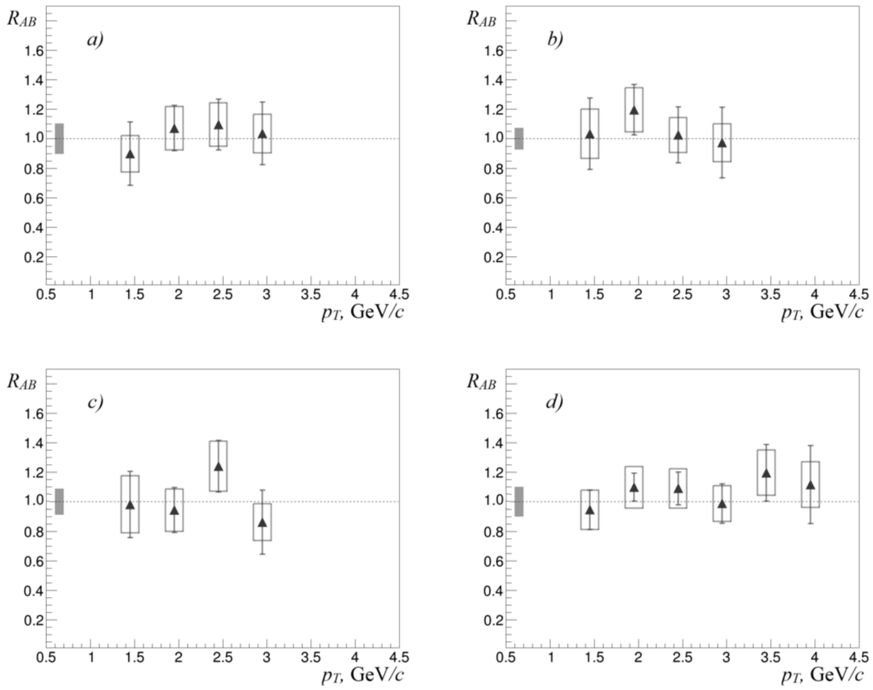

Fig. 2. Distributions of nuclear modification factors as function of transverse momentum for φ meson production in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV in four centrality bins, %: 0–20 (a), 20–40(b), 40–72(c), 0–72(d); $|y| < 0.35$

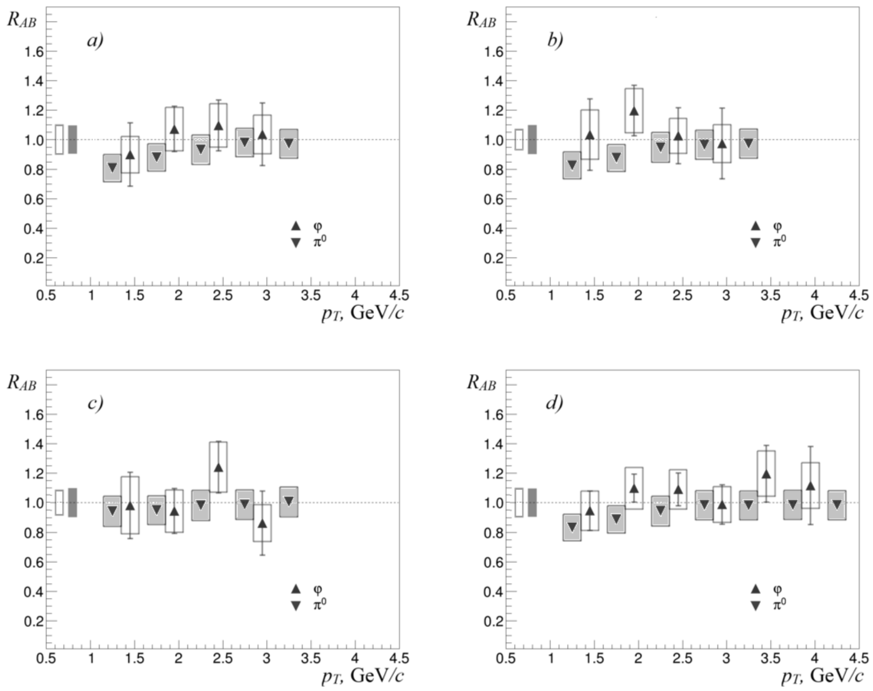

Fig. 3. Distributions of nuclear modification factors as function of transverse momentum for φ and π^0 meson production in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV in four centrality bins, %: 0–20 (a), 20–40 (b), 40–72 (c), 0–72 (d); $|y| < 0.35$

If $R_{AB}(pT)$ < 1 (> 1), particle yields are supressed (or, respectively, excessive), which may confirm the presence of collective effects in heavy ion interactions.

Experimental results and discussion

Fig. 1 shows invariant transverse momentum spectra of φ meson production in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV. These spectra were measured in four centrality bins, %: 0–72, 0–20, 20–40 и 40–72, with transverse momenta ranging from 1.0 to 4.0 GeV/c, and fitted with the Lévy distribution:

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}=\frac{m}{2\pi}\times$$
$$\times\frac{(n-1)(n-2)}{\left(k+m_\varphi(n-1)\right)\left(k+m_\varphi\right)}\left(\frac{k+\sqrt{p_T^2+m_\varphi^2}}{k+m_\varphi}\right), \quad (3)$$

where m_φ, GeV/c^2, is the invariant mass of the φ meson, k, m, n are free parameters.

The transverse momentum spectra obtained were used to calculate nuclear modification factors of φ mesons in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV.

Fig. 2 shows the distributions of nuclear modification factors R_{AB} depending on transverse momentum, measured for φ mesons in p+Al interactions at $\sqrt{s_{NN}}$ = 200 GeV in different centrality bins. Evidently, the nuclear modification factors R_{AB} for φ mesons equal unity in all centrality bins over the entire range of transverse momenta within uncertainties.

Fig. 3 shows a comparison of nuclear modification factors for φ and π^0 mesons in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV. Apparently, the nuclear modification factors for φ and π^0 mesons take the same values in all centrality bins over the entire range of transverse momenta within uncertainties. This may indicate that CNM effects have no impact on the difference between the nuclear modification factors for φ and π^0 mesons in collisions of gold, copper and uranium nuclei (Au+Au, Cu+Cu, Cu+Au, U+U) [8, 9].

Conclusion

We have measured the invariant transverse momentum spectra and nuclear modification factors for φ mesons in p+Al collisions at $\sqrt{s_{NN}}$ = 200 GeV.

The nuclear modification factors for φ mesons equal unity in all available centrality bins and over the entire range of transverse momenta within the uncertainties. The results obtained confirm that the collisions under consideration produce no quark-gluon plasma.

REFERENCES

1. **Adcox K., Adler S.S., Afanasiev S., et al.,** Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX Collaboration, Nuclear Physics. A. 757 (1–2) (2005) 184–283.

2. **Adcox K., Adler S. S., Aizama M., et al.** (PHENIX Collaboration), PHENIX detector overview, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 499 (2–3) (2003) 469–479.

3. **Harrison M., Ludlam T., Ozaki S.,** RHIC project overview, Nuclear Instruments and Methods in Physics Research, A., 499 (2–3) (2003) 235–244.

4. **Koch P., Müller B., Rafelski J.,** Strangeness in relativistic heavy ion collisions, Physics Reports. 142 (4) (1986) 167–262.

5. **Armesto N.**, Small collision systems: theory overview on cold nuclear matter effects, EPJ Web of Conferences. 171 (2018) 11001.

6. **Arneodo M.,** Nuclear effects in structure functions, Physics Reports. 240 (5–6) (1994) 301–393.

7. **Kopeliovich B.Z., Nemchik J., Schдfer A., Tarasov A.V.,** Cronin effect in hadron production of nuclei // Physical Review Letters. 88 (23) (2002) 232303.

8. **Adare A., Afanasiev S., Aidala C., et al.** Nuclear modification factors of φ mesons in d + Au, Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV// Physical Review. C. 2011. Vol. 83 (2) (2011) 024909.

9. **Berdnikov A., Berdnikov Ya., Kotov D., et al.,** Phi meson measurements in Cu + Au collisions at 200 GeV and in U + U collisions at 192 GeV, J. Phys.: Conf. Ser. 1135 (1) (2018) 012044.

10. **Adcox K., Ajitanand N.N., Alexander J., et al.** (PHENIX Collaboration). PHENIX central arm tracking detectors, Nuclear Instruments and Methods in Physics Research, A. 499 (2–3) (2003) 489–507.

11. **Ikematsu K., Iwata Y., Kaimi K., et al.,** A start-timing detector for the collider experiment

PHENIX at RHIC-BNL, Nuclear Instruments and Methods in Physics Research. Section, A. 411 (2–3) (1998) 238–248.

12. **L'Hôte D.,** About resonance signal extraction from multiparticle data: combinatorics and event mixing methods, Nuclear Instruments and Methods in Physics Research. Section, A. 337 (2–3) (1994) 544–556.

13. **Beringer J., et al.** (Particle Data Group), Review of particle physics, Physical Review, D. 86 (1) (2012) 010001.

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СПИСОК ЛИТЕРАТУРЫ

1. **Adcox K., Adler S.S., Afanasiev S., et al.** Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX Collaboration // Nuclear Physics A. 2005. Vol. 757. No. 1–2. Pp. 184–283.

2. **Adcox K., Adler S. S., Aizama M., et al.** (PHENIX Collaboration), PHENIX detector overview // Nuclear Instruments and Methods in Physics Research. Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2003. Vol. 499. No. 2–3. Pp. 469–479.

3. **Harrison M., Ludlam T., Ozaki S.** RHIC project overview // Nuclear Instruments and Methods in Physics Research. A. 2003. Vol. 499. No. 2–3. Pp. 235–244.

4. **Koch P., Müller B., Rafelski J.** Strangeness in relativistic heavy ion collisions // Physics Reports. 1986. Vol. 142. No. 4. Pp. 167–262.

5. **Armesto N.** Small collision systems: theory overview on cold nuclear matter effects // EPJ Web of Conferences. 2018. Vol. 171. P. 11001.

6. **Arneodo M.** Nuclear effects in structure functions // Physics Reports. 1994. Vol. 240. No. 5–6. Pp. 301–393.

7. **Kopeliovich B.Z., Nemchik J., Schдfer A., Tarasov A.V.** Cronin effect in hadron production of nuclei // Physical Review Letters. 2002. Vol. 88. No. 23. P. 232303.

8. **Adare A., Afanasiev S., Aidala C., et al.** Nuclear modification factors of φ mesons in d + Au, Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV// Physical Review. C. 2011. Vol. 83. No. 2. P. 024909.

9. **Berdnikov A., Berdnikov Ya., Kotov D., et al.** Phi meson measurements in Cu+Au collisions at

200 GeV and in U+U collisions at 192 GeV // J. Phys.: Conf. Ser. 2018. Vol. 1135. No. 1. P. 012044.

10. **Adcox K., Ajitanand N.N., Alexander J., et al.** (PHENIX Collaboration). PHENIX central arm tracking detectors // Nuclear Instruments and Methods in Physics Research. A. 2003. Vol. 499. No. 2–3. Pp. 489–507.

11. **Ikematsu K., Iwata Y., Kaimi K., et al.** A start-timing detector for the collider experiment PHENIX at RHIC-BNL // Nuclear Instruments and Methods in Physics Research. Section A. 1998. Vol. 411. No. 2–3. Pp. 238–248.

12. **L'Hôte D.** About resonance signal extraction from multiparticle data: combinatorics and event mixing methods // Nuclear Instruments and Methods in Physics Research. Section A. 1994. Vol. 337. No. 2–3. Pp. 544–556.

13. **Beringer J., et al.** (Particle Data Group). Review of particle physics // Physical Review. D. 2012. Vol. 86. No. 1. P. 010001.

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