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A COMPARATIVE ANALYSIS OF HADRON CREATION IN DEUTERON-DEUTERON INTERACTIONS AT ENERGIES OF 13.5 AND 27.0 GEV

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Abstract. This paper presents the results of nuclear modification factors for hadrons in deuteron-deuteron collisions at energies of $\sqrt{s_{NN}}$ = 13.5 GeV and $\sqrt{s_{NN}}$ = 27.0 GeV. We have applied the widely-used nuclear-modified parton distribution functions and parton distribution functions for free nucleons to determine nuclear modification factors (NMFs) of J/ψ, $D^{\pm}$ and π^0 mesons. The obtained results showed the NMFs values of J/ψ and π^0 ones to remain close to unity over the entire transverse momentum range from 0.5 to 4.5 GeV/c. The NMFs values of $D^{\pm}$ ones decreased sharply with increasing the transverse momentum at $\sqrt{s_{NN}}$ = 13.5 GeV, but they remained close to unity at $\sqrt{s_{NN}}$ = 27.0 GeV.

Keywords: nuclear modification factor, SPD, NICA, parton distribution function, hadron

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ ОСОБЕННОСТЕЙ РОЖДЕНИЯ АДРОНОВ В ДЕЙТРОН-ДЕЙТРОННЫХ ВЗАИМОДЕЙСТВИЯХ ПРИ ЭНЕРГИЯХ 13,5 И 27,0 ГЭВ

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Аннотация. В статье представлены результаты исследования факторов ядерной модификации адронов в столкновениях ядер дейтерия при значениях энергии $\sqrt{s_{NN}}$ = 13,5 ГэВ и $\sqrt{s_{NN}}$ = 27,0 ГэВ. Проведено сравнение полученных факторов ядерной модификации (J/ψ)-, $D^{\pm}$- и π^0-мезонов с использованием функций партонного распределения свободных нуклонов и ядерно-модифицированных функций партонного распределения. Полученные результаты показали, что факторы ядерной модификации (J/ψ)- и π^0-мезонов остаются близкими к единице на всем исследуемом диапазоне 0,5–4,5 ГэВ/c поперечного импульса. Значения факторов ядерной модификации $D^{\pm}$-мезонов резко снижаются при увеличении поперечного импульса при энергии $\sqrt{s_{NN}}$ = 13,5 ГэВ, тогда как при энергии $\sqrt{s_{NN}}$ = 27,0 ГэВ значения остаются близкими к единице.

Ключевые слова: фактор ядерной модификации, SPD, NICA, функция распределения партонов, адрон

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Introduction

Measurement of production of $D^{\pm}$, (J/ψ), π^0 mesons in proton-proton ($p+p$) interactions at $\sqrt{s_{pp}}$ = 27.0 GeV and deuteron-deuteron ($d+d$) interactions at energy $\sqrt{s_{NN}}$ = 13.5 GeV/nucleon [1] is one of the intended goals in the planned SPD experiment [2] at the NICA collider [3].

The main mechanism behind the production of $D^{\pm}$ and (J/ψ) mesons at the given energies is the fusion of a gluon pair (gg), leading to the production of a quark-antiquark pair ($c\bar{c}$) [4].

As follows from Fig. 1,*a*, a quark-antiquark pair ($c\bar{c}$) can produce a (J/ψ) meson during hadronization. The scheme for production of $D^{\pm}$ mesons is shown in Fig. 1,*b*: $c\bar{d} \to D^+$, $\bar{c}d \to D^-$.

The (J/ψ) mesons can be detected through weak muon decay modes within the framework of the SPD project [4]:

$$J/\psi \to \mu^+\mu^-.$$

$D^{\pm}$ mesons are to be detected in the following decay channels [4]:

$$D^+ \to \pi^+K^-\pi^+ \text{ (BF = 0.094)},$$

$$D^- \to \pi^-K^+\pi^- \text{ (BF = 0.094)}.$$

Thus, study of the processes associated with the production of $D^{\pm}$ and (J/ψ) mesons yields information about the properties and role of gluons in proton-proton and deuteron-deuteron interactions (as well as in the nucleon-nucleon interactions). In particular, information about gluon distribution functions in nucleons and nuclei can be extracted.

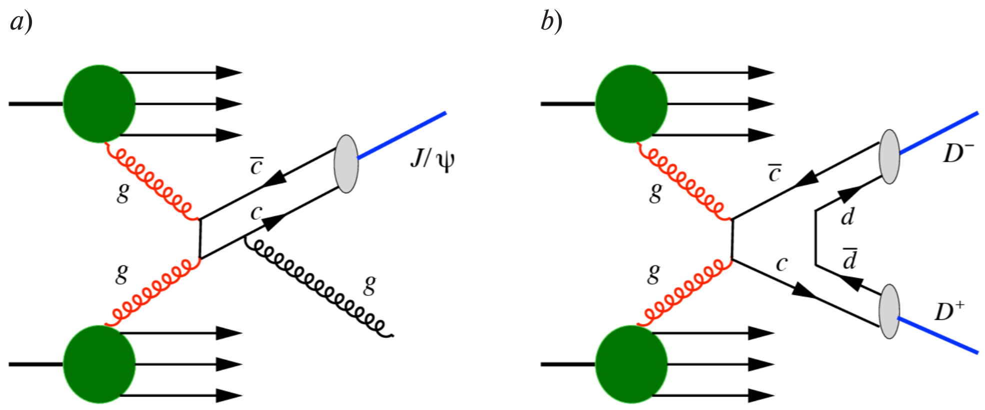

Fig. 1 [4]. Feynman diagrams for production of (J/ψ) meson (*a*) and $D^{\pm}$ mesons (*b*)
Production occurs through fusion of a gluon pair (gg),
leading to the production of a quark-antiquark pair ($c\bar{c}$)

Measurements of the yields of neutral pions consisting of $u\bar{u}$ and $d\bar{d}$ quarks can help verify and refine the existing models describing the production of these particles. Comparing the yields of neutral pions with heavier particles, such as $D^{\pm}$ and J/ψ mesons can provide insights into the role of heavy quarks in high-energy collisions of nucleons and nuclei.

Parton distribution functions (PDFs) are commonly used in studies of hadron production. The PDF $f_i(x,Q^2)$ is used to describe the probability of finding the ith parton in the hadron; x is the parton parameter determining the fraction of the nucleon momentum carried by the parton; Q^2 is a quantity following the expression

$$Q^2 = -q^2,$$

where q^2 is the four-momentum of the virtual particle [5].

The range of large x is of particular interest, as there is a significant discrepancy between the theoretical predictions for the gluon distribution function in the deuteron and the gluon distribution function in the nucleon [4].

Nuclear-modified parton distribution functions (nPDFs) were obtained to analyze the nucleon-nucleus and nucleus-nucleus collisions [6]. The fundamental difference between these functions and PDFs taken for free nucleons is that they take into account the nucleonic composition of nuclei and interactions between nucleons in the nucleus.

According to the factorization theorem [7], the differential cross section for the production of the hadron H can be represented as follows in the collinear approximation:

$$E_H \frac{d^3\sigma}{dp_H^3} = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}_{ab}^c \otimes D_c^H,$$

where f_a, f_b are the PDFs; $d\hat{\sigma}_{ab}^c$ is the cross section of the hard parton subprocess; a, b, c are the interacting partons; D^H_c is the fragmentation function.

Different PDFs influence the cross section for hadron production, provided that the same fragmentation functions are applied to each particle.

The goal of this study is to determine the characteristics of the production of hadrons in collisions of deuterium nuclei (d+d).

The nPDFs (with nuclear modifications) and PDFs (for free nucleons) were used to simulate (d+d) collisions.

Computational procedure

Hadron yields in (d+d) collisions at $\sqrt{s_{NN}}$ = 13.5 and 27.0 GeV were analyzed in this paper based on the simulation data we obtained using the Pythia8 software package [8].

The simulations were run using two types of functions:

parton distribution functions obtained for free nucleons (PDFs);

nuclear-modified (in this case in the deuteron) parton distribution functions (nPDFs).

Because the collision energy of deuteron beams is much higher than the binding energy of nucleons in the deuteron (2.23 MeV), a model of unbound (free) nucleons can be used for the deuteron, using PDFs for free nucleons within the parton model. Collisions of deuteron beams can be represented via PDFs as collision of each nucleon of one deuteron nucleus with each nucleon of another deuteron nucleus. There are four possible combinations of nucleon-nucleon collisions: pp, pn, np, nn. Since the total cross sections of these interactions are approximately similar [9], these interactions can be reasonable assumed to be equally probable without significant loss of accuracy.

It was found in our previous paper [10] that different combinations of interacting nucleons making up the deuterium nucleus produce different numbers of direct photons. However, this dependence should not be observed during the formation of (J/ψ) and $D^{\pm}$ mesons, since the probabilities of their formation do not depend on the electric charge of the quark. The cross section for the production of the quark-antiquark pair due to gluon-gluon interaction is proportional to the square of the strong interaction constant [4].

An alternative approach to the study of deuteron beam collisions are nPDFs obtained for deuterons [11–13]. A variety of functions is used because they originate from different experimental data, which may cause discrepancies in the results obtained. For this reason, we selected three different *n*PDFs to ensure the reliability and comparability of the data.

Since the Pythia8 program allows using only one PDF in the calculations, we used the weight *w* to speed up the calculation of all the *n*PDFs we selected (the formula for calculating it is given in [14]):

$$w = \frac{x_1 f_i^{p/d}(x_1;Q^2)}{x_1 f_i^{p}(x_1;Q^2)} \cdot \frac{x_2 f_i^{p/d}(x_2;Q^2)}{x_2 f_i^{p}(x_2;Q^2)}, \tag{1}$$

where $x_1 f_i^{p/d}(x_1,Q^2)$, $x_2 f_i^{p/d}(x_2,Q^2)$ are the *n*PDFs for deuterons in the first and second nuclei; $x_1 f_i^{d}(x_1,Q^2)$, $x_2 f_i^{p}(x_2,Q^2)$ are the PDFs obtained for free protons in the first and second nuclei.

This weight *w* characterizes the ratio of the probabilities of detecting the parton for two different PDFs with the same values of variables *x* and Q^2. Thus, using a weight in the calculations makes it possible to obtain hadron spectra for both PDFs and *n*PDFs within a single simulation run.

Due to the low probability that (J/ψ) and $D^{\pm}$ mesons are produced in $(d+d)$ collisions, we used custom settings in Pythia8 to increase the production statistics of (J/ψ) and $D^{\pm}$ mesons (see the Appendix). Importantly, the proposed modifications do not have any effect on the physical interpretation of the results obtained.

The PDFs are taken from the LHAPDF6 software package [14] connected directly to the Pythia8 collision generator. Computer analysis included application of the following PDFs (the numbers are highlighted in bold, see also the captions to the figures).

For PDFs: nNNPDF30_nlo_as_0118_p [11] **(FI),** TUJU21_nlo_1_1 [12] **(FII)**, nCTEQ15HIX_FullNuc_1_1 [13] **(FIII)**;

for *n*PDFs: nNNPDF30_nlo_as_0118_A2_Z1 [11] **(FIV),** TUJU21_nlo_2_1 [12] **(FV),** nCTEQ15HIX_FullNuc_2_1 [13] **(FVI).**

The nuclear modification factor (NMF) R_{dd} was used to quantify the differences in the hadron spectra obtained from $(d+d)$ collisions using *n*PDFs and PDFs.

The value of R_{dd} can be calculated by the following relation [15]:

$$R_{dd} = \frac{1}{N_{coll}} \cdot \frac{d^2 N_{dd} / dp_T dy}{d^2 N_{pp} / dp_T dy}, \tag{2}$$

The numerator of Eq. (2) contains the invariant spectrum of hadrons obtained in collisions of deuterium nuclei in the ranges of rapidity *dy* and transverse momentum dp_T. This spectrum is normalized by the number of binary nucleon-nucleon collisions N_{coll} (for $d+d$). The denominator in Eq. (2) contains the invariant spectrum of hadrons measured in $(p+p)$ interactions for the same ranges of rapidity and transverse momentum.

The rapidity range ($|y| < 3$) in this paper is taken from [16].

Results and discussion

Fig. 2 shows the values of R_{dd} for hadrons as a function of transverse momentum p_T at $\sqrt{s_{NN}}$ = 13.5 GeV and $\sqrt{s_{NN}}$ = 27.0 GeV in the rapidity range $|y| < 3$ using different PDFs (see functions FI–FIII).

Fig. 3 shows the values of R_{dd} for hadrons as a function of transverse momentum p_T at $\sqrt{s_{NN}}$ = 13.5 GeV and $\sqrt{s_{NN}}$ = 27.0 GeV in the rapidity range $|y| < 3$ using different *n*PDFs (see functions FIV–FVI).

It can be seen from Fig. *2* and Fig. 3 that the NMFs for $D^{\pm}$, (J/ψ) and π^0 mesons, calculated using *n*PDFs and PDFs, have similar values over the entire p_T range under consideration. Nevertheless, small differences in the values of R_{dd} obtained by the functions FII and FV may indicate the presence of nuclear phenomena influencing the particle production process.

The results for NMFs R_{dd} obtained using the remaining functions (FI, FIII, FIV, FVI) do not exceed unity, which predicts the absence of possible nuclear phenomena during the production of (J/ψ) and π^0 mesons in deuteron-deuteron collisions.

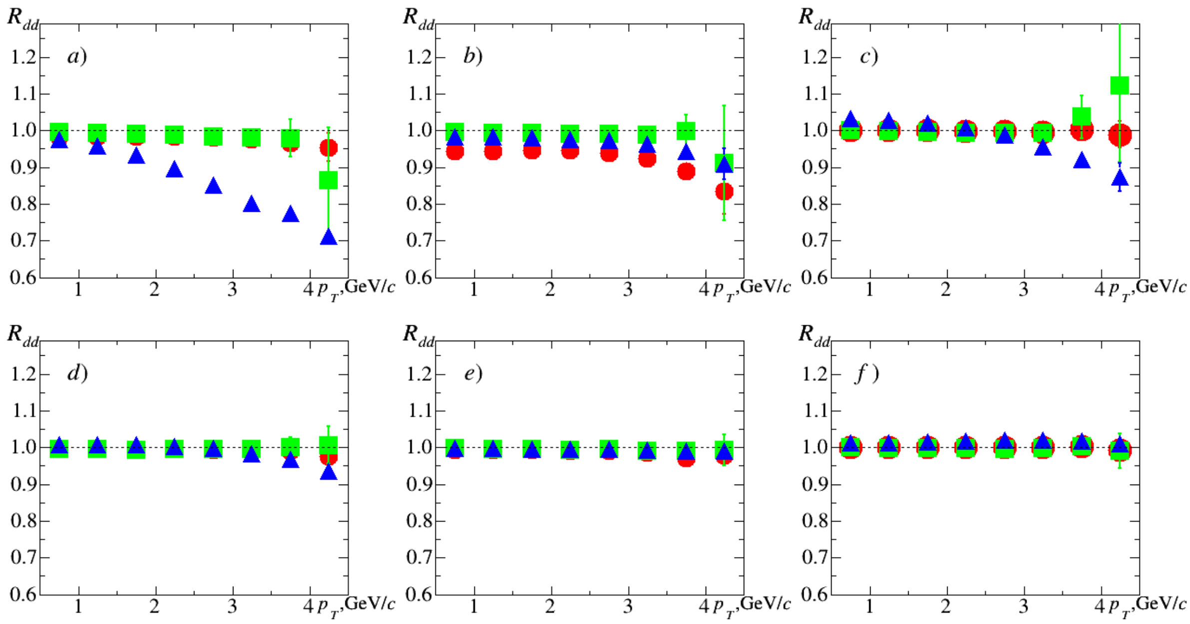

Fig. 2. Dependences of NMFs for mesons J/ψ (●), $D^{\pm}$ (▲), π^0 (■) on transverse momentum (see Eq. (2)) in (d+d) collisions at $\sqrt{s_{NN}}$ = 13.5 GeV (a–c) and $\sqrt{s_{NN}}$ = 27.0 GeV (d–f), in the rapidity range $|y| < 3$, using different PDFs: FI(a, d); FII(b, e); FIII(c, f); numbering of the functions is given in the text

The vertical bars correspond to statistical uncertainties

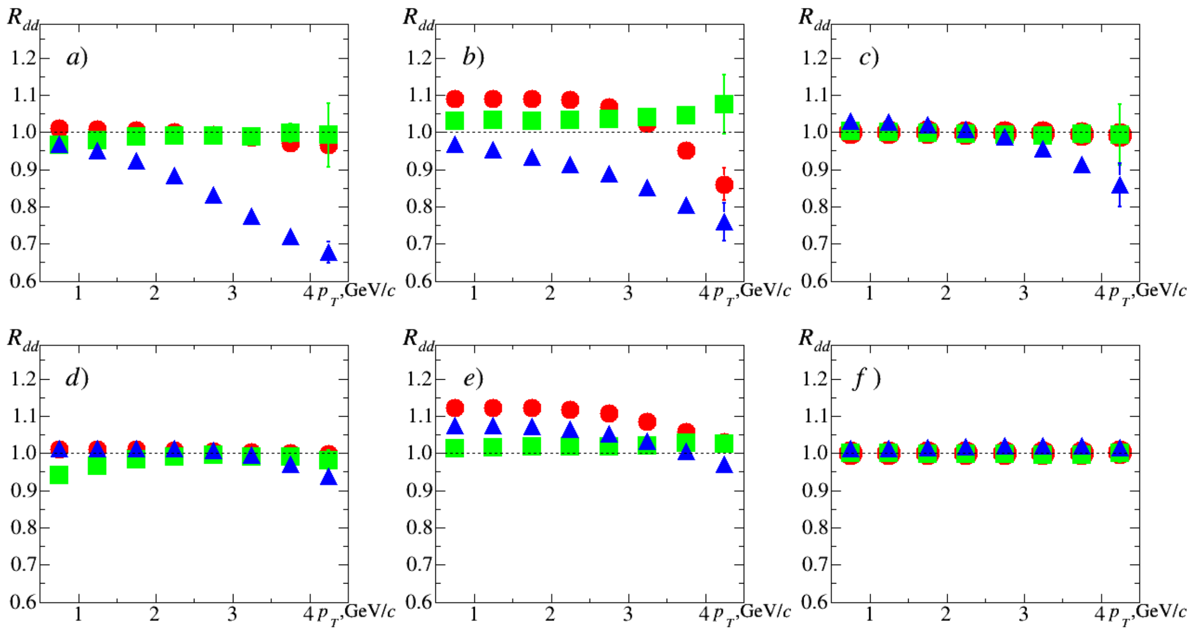

Fig. 3. Dependences similar to those in Fig. 2, at $\sqrt{s_{NN}}$ = 13.5 GeV (a–c) and $\sqrt{s_{NN}}$ = 27.0 GeV (d–f), for the remaining nPDFs: FIV (a, d); FV(b, e); FVI (c, f)

We should also note that the values of R_{dd} for $D^{\pm}$ mesons decrease with increasing p_T at $\sqrt{s_{NN}}$ = 13.5 GeV, in contrast to collisions at $\sqrt{s_{NN}}$ = 27.0 GeV, where the values of R_{dd} remain close to unity. The reason for this behavior of the dependences requires additional research.

Conclusion

We calculated the nuclear modification factors of $D^{\pm}$, (J/ψ) and π^0mesons in $(d+d)$ interactions at $\sqrt{s_{NN}}$ =13.5 and $\sqrt{s_{NN}}$ =27.0 GeV energies depending on the transverse momentum p_T in the rapidity range $|y| < 3$ s using PDFs (FI−FIII) and *n*PDFs (FIV−FVI).

Applying the weight (see Eq. (1)) for hadron spectra allowed to speed up the computations.

We established that using either PDFs or *n*PDFs yields very slight differences in the values of R_{dd} for hadrons.

We found that the ratios of the invariant spectra for (J/ψ) and π^0 mesons in $(d+d)$ and $(p+p)$ collisions differ insignificantly at the studied energies for all selected sets of PDFs and *n*PDFs. The invariant spectra of $D^{\pm}$ mesons in $(d+d)$ interactions at $\sqrt{s_{NN}}$ = 13.5 GeV are decreased compared to the invariant spectra in $(p+p)$ interactions with an increase in the transverse momentum p_T.

Appendix

Parameter settings of the Monte Carlo event generator in Pythia8 for increasing meson production

Parameter	Position
For (J/ψ) *mesons*	
Charmonium:all	on
PhaseSpace:pTHatMin	0.1
PhaseSpace:pTHatMax	10.0
PhaseSpace:pTHatMinDiverge	0.5
BeamRemnants:primordialKT	on
BeamRemnants:primordialKTsoft	0.9
BeamRemnants:primordialKThard	1.8
BeamRemnants:halfScaleForKT	2.0
BeamRemnants:halfMassForKT	4.0
BeamRemnants:reducedKTatHighY	0.5
BeamRemnants:primordialKTremnant	0.4
443:onMode	off
443:onIfAll	13–13

Parameter	Position
For $D^{\pm}$ *mesons*	
HardQCD:gg2ccbar	on
HardQCD:qqbar2ccbar	on
PhaseSpace:mHatMin	0.0
PhaseSpace:pTHatMinDiverge	0.5
BeamRemnants:primordialKT	on
BeamRemnants:primordialKTsoft	1.1
BeamRemnants:primordialKThard	1.8
BeamRemnants:halfScaleForKT	2.0
BeamRemnants:halfMassForKT	4.0
BeamRemnants:reducedKTatHighY	0.7
BeamRemnants:primordialKTremnant	0.4

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