ISSN 0021-3640, JETP Letters, 2024, Vol. 120, No. 11, pp. 800–803. © The Author(s), 2024. This article is an open access publication.
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FIELDS, PARTICLES, AND NUCLEI

On the Theoretical Interpretation of the Data on Collisions of Argon Nuclei with Various Nuclei at High Energies

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Received October 3, 2024; revised October 19, 2024; accepted October 20, 2024

Recently (2024), the NA61/SHINE collaboration has presented new experimental data on $\pi^{\pm}$, $K^{\pm}$, proton, and antiproton productions in central ^{40}Ar + ^{45}Sc collisions at the laboratory momenta $P_{\rm lab}$ = 13–150 A GeV/c and has compared these data with predictions of popular theoretical models. It turned out that the models poorly describe the data in the entire energy range. In this work, it has been suggested for the first time that nucleons participating in non-diffractive collisions cannot diffractively dissociate in subsequent nucleon–nucleon collisions. This idea has been implemented in the Geant4 FTF model. Good description of the data, including the first NICA BM@N data on π^+ meson production in the collisions of ^{40}Ar nuclei with various nuclei at an energy of 3.2 A GeV, has been achieved.

DOI: 10.1134/S0021364024603944

In last decades, nucleus–nucleus collisions at relativistic energies have been actively studied in high energy physics. In experimental studies, the main attention was paid to collisions of heavy nuclei. Along this path, a new state of matter called the quark–gluon plasma and some new phenomena such as jet quenching and strong collective flows were discovered. However, in recent years, increasing attention has been paid to collisions of light and intermediate nuclei in order to determine the conditions for the quark–gluon plasma formation and the equation of state of quark–gluon plasma. From this point of view, the direction of researches of the NA61/SHINE collaboration seems to be very relevant.

Recently, the NA61/SHINE collaboration has published [1] new experimental data on various particle productions in ^{40}Ar + ^{45}Sc collisions at $P_{\rm lab}$ = 13, 19, 30, 40, 75, and 150 A GeV/c. The collaboration has compared the data, in particular, rapidity distributions with predictions of theoretical Monte Carlo models including EPOS 1.99 [2], parton–hadron-string dynamics (PHSD 4.1) [3, 4], and simulating many accelerated strongly-interacting hadrons (SMASH 2.1.4) [5, 6]. It turned out that EPOS, on average, overestimates the data on the distributions of π^+ mesons on rapidities, while the SMASH and PHSD models underestimate the data (see Fig. 1). Predictions of the EPOS and SMASH models approach the experimental data (see Fig. 1) only at momenta higher than 40 A GeV/c. Calculations by the PHSD models are not shown in Fig. 1 since they are close to the predictions of the SMASH model. Predictions of the standard Geant4 FTF model [7] are mainly close to the results of the SMASH model.

The EPOS model involves the Glauber–Regge approximation at simulation of multiparticle production processes. Pomeron exchanges, hard parton collisions, and splitting of parton chains are only taken into account. Non-vacuum reggeon exchanges, which are very important at low energies, are disregarded. This explains why the model calculations approach the experimental data from above with increasing collision energy. The contributions of pomeron and non-vacuum exchanges to proton–proton collisions decrease and increase with decreasing collision energy, respectively. The corresponding cross sections behave in the same way.[1] This is the first factor. The second factor is that the multiplicity in processes induced by the non-vacuum exchanges is less than in those induced by the pomeron ones.

The UrQMD [8, 9], PHSD, and SMASH models are extensions of the classical intranuclear cascade model and include the production of meson and baryon resonances, particle formation time, etc. It is assumed that at sufficiently high energies, the produc-

[1] Vacuum and non-vacuum exchanges enter into the elastic scattering amplitude with different signs. Therefore, one has to speak about cross sections with a certain caution. This is especially true for inelastic cross sections, which contain interference terms.

tion of particles in hadron–hadron collisions is due to the formation of two quark–gluon strings in non-diffractive processes, or one string and a surviving hadron in diffractive processes, as in the FRITIOF model [10, 11]. According to the FRITIOF model, the mass distribution of strings has the form $\sim 1/M_{\text{str}}$. This ansatz of the model is criticized in the literature: hadron–hadron collisions in the FRITIOF model are treated as double diffractive dissociation processes.[2] To simulate string decays/fragmentations that result in the production of hadrons, the LUND algorithm [12] is used. Each of the produced particles is assigned a momentum and a time of the particle formation in the rest frame of the original string, under the assumption that the birth of the string occurred at one space-time point. Having the four-momentum of the string, the point of formation of the particle in the laboratory frame can be found. However, the nucleon that transformed into the string had a size of about 1 fm. Thus, the created string initially had a size of about 1 fm. This can be taken into account by reducing the formation time of each particle in the rest frame of the string by ~1 fm/c. This will reduce the particle formation times in the laboratory system, which in the case of hadron–nucleus and nucleus–nucleus collisions can lead to an increase in the total multiplicity of produced particles. The disregard of this circumstance can apparently explain the underestimated multiplicity of π^+-mesons in Fig. 1 predicted by the SMASH model.

It should be noted that the UrQMD, PHSD, and SMASH models violate the basic principle of the FRITIOF model. The FRITIOF model suggests that in hadron–nucleus collisions, strings arising in the first intranuclear collision can collide with other nuclear nucleons and increase their mass. The string lifetime is disregarded. It is assumed that strings decay/fragment outside the nuclei. In nucleus–nucleus collisions, in the presence of many strings, they can collide with each other and increase their masses. A possible fusion of strings can simulate the formation of quark–gluon plasma (see, e.g., [13]).

Interactions of strings with nuclear nucleons and with other strings are forbidden in the UrQMD, PHSD, and SMASH models based on the FRITIOF model. Strings being born decay before possible subsequent collisions. As a result, nucleus–nucleus collisions are considered as a set of hadron–hadron collisions. In each hadron–hadron collision there are low-multiplicity diffractive processes and high-multiplicity non-diffractive processes. Therefore, the simplest way to increase the meson yield is to increase the probability of non-diffractive collisions.

In the FRITIOF model, nucleons/strings can be in four states: nucleons in the ground state (GS); strings formed in the processes of diffractive dissociation of

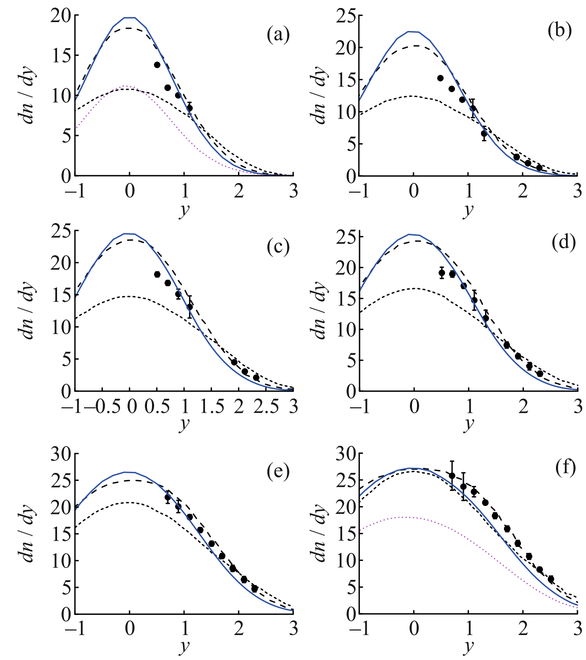

Fig. 1. (Color online) Rapidity distributions of π^+ mesons in ^{40}Ar + ^{45}Sc collisions at centralities of 0–10% and P_{lab} = (a) 13, (b) 19, (c) 30, (d) 40, (e) 75, and (f) 150 A GeV/c. Circles are the NA61/SHINE experimental data without systematic errors. Solid lines are calculations using the new Geant4 FTF model. Long- and short-dashed lines are calculations performed by the collaboration using the EPOS and SMASH models, respectively. Dotted lines shown only in (a, f) are calculations using the old version of the Geant4 FTF model.

nucleons of the projectile nucleus (PrD), or the target nucleus (TrD); strings formed in non-diffractive processes (Str). The possible interactions between them are presented in Table 1.

It is obvious that all processes are possible in GS–GS collisions. In PrD–GS collisions there must be TrD and ND. By analogy with the interactions of atoms, there may be transitions of diffraction states to other diffractive states. However, the excitation spectra of strings with small masses are poorly known. Therefore, in the process PrD → PrD, we redefine (resample) the mass of the original system. In the Str–GS process, it is difficult to imagine that a string or a nucleon in the ground state can transform to a diffractive state. The probability of diffraction of the target

Table 1. Possible processes in hadron/string interactions

	GS	PrD	Str
GR	PrD, TrD, ND	PrD, TrD, ND	ND
TrD	PrD, TrD, ND	PrD, TrD, ND	ND
Str	ND	ND	ND

[2] In the Geant4 FTF model, the string mass distribution has the form $a/M_{\text{str}} + b$.

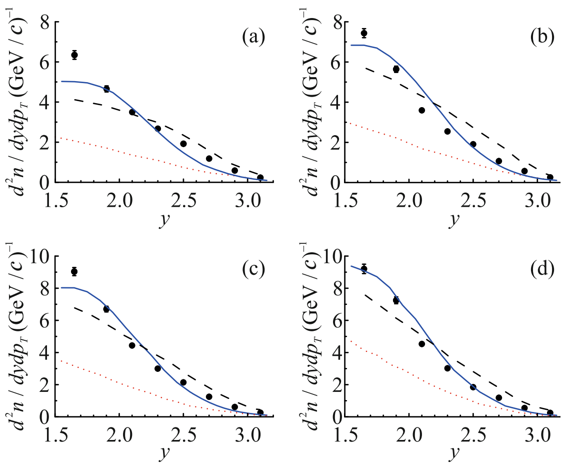

Fig. 2. (Color online) Rapidity distributions of π^+ mesons with 0.1 GeV/c ≤ p_T ≤ 0.2 GeV/c in collisions of ^{40}Ar nuclei with (a) Al, (b) Cu, (c) Sn, and (d) Pb nuclei at E_{lab} = 3.2 A GeV. Circles are the BM@N experimental data [14] without systematic errors. Solid and dotted lines are calculations using the new and old Geant4 FTF models, respectively. Dashed lines are calculations using the DCM model [15] performed by the collaboration.

nucleon is unlikely. Therefore, we have forbidden such transitions.

We assume that the relations between the probabilities of the processes listed in each cell of Table 1 are the same as in free collisions. If any process is missing, the probabilities of the remaining processes are renormalized so that their sum is equal to one.

Table 1 is implemented in the Geant4 FTF program. The results of calculations for this (new) version of the program are presented in Fig. 1 by solid lines. As seen, our results are close to the predictions of the EPOS model. Calculations using the old version of the program are shown only in Figs. 1a and 1f for the momenta of incident nuclei of 13 and 150 A GeV/c. As seen, calculations using the old version of the program significantly underestimate the yields of π^+ and π^- mesons. Note that the Geant4 FTF model includes processes of quark exchange between colliding partners (non-vacuum exchanges), which disappear with increasing energy.

In our calculations, we sampled the impact parameter of central collisions of argon and scandium nuclei with a quadratic measure in the range of 0–2.87 fm.

The most significant hypothesis of the proposed approach is that only non-diffractive processes are possible in string interactions. As a result, most nucleons in the final state of central nuclear collisions will be strings and the multiplicity of produced mesons observed in central nuclear collisions will be larger than that predicted by conventional models. The calculations shown in Fig. 1 by solid lines confirm this conclusion.

It was completely unexpected for us that the proposed approach gives good results when applied to the NICA BM@N data on the yields of π^+ mesons in collisions of argon nuclei with nuclei at an energy of 3.2 A GeV (see Fig. 2). Difficulties arose only with the description of the spectra of π^+ mesons in the collisions of argon nuclei with carbon nuclei (not shown in Fig. 2). As shown in experimental work [14], the PHSD, DCM, and UrQMD models also do not give satisfactory results for these collisions.

Some problems certainly remain in the proposed approach. In particular, it underestimates the yield of K^+ and K^- mesons in Ar + Sc collisions. Perhaps, this is the most difficult issue for all theoretical models. Another problem in our approach is the unsatisfactory description of the particle distributions on p_T in the collisions of argon nuclei with nuclei at low energies.

CONCLUSIONS

The assumption of different interactions of nucleons participating in diffractive and non-diffractive collisions with nuclear nucleons and with each other has allowed us to satisfactorily reproduce the rapidity distributions of π^+ mesons in the collisions of argon nuclei with various nuclei measured by the NA61/SHINE and NICA BM@N collaborations. Thus, the problem of taking into account diffraction, which remained open in the Geant4 package for more than 15 years, has been solved.

ACKNOWLEDGMENTS

We are grateful to the JINR staff members V.V. Voronyuk, A.B. Larionov, and V.A. Plotnikov for fruitful discussions and to the staff of the JINR HybriLIT computing complex for assistance in performing the calculations.

FUNDING

This work was supported by ongoing institutional funding of the Joint Institute for Nuclear Research and in part by the Ministry of Science and Higher Education of the Russian Federation (agreement no. 075-15-2024-667 dated August 23, 2024).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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