Comparison of some characteristics of charged pions in p^{12}C and n^{12}C collisions at 4.2 GeV/c

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Abstract. The new experimental data on various characteristics of the secondary charged pions produced in n^{12}C collisions at 4.2 GeV/c are presented. A comparative analysis of the average multiplicities and various kinematic characteristics of the charged pions produced in n^{12}C and p^{12}C collisions at 4.2 GeV/c is made. The experimental data are compared systematically with the predictions of the modified FRITIOF model.

Key words. neutron-carbon collisions, proton-carbon collisions, intermediate energies, pion production, average multiplicities, total and transverse momentum distributions, rapidity distributions, emission angle distributions.

1. Introduction

In contrast to proton-nucleus collisions, there is very little data on the multiparticle production processes in high-energy neutron-nucleus interactions. At the same time, a comparative analysis of experimental data on proton-nucleus and neutron-nucleus interactions at the same energies and for the same target nucleus allows one to obtain information on different mechanisms of formation of final-state particles. In Ref. [1], a comparative analysis of the momentum characteristics of negative pions in p^{12}C and n^{12}C interactions at 4.2 GeV/c has been performed. The average values of the transverse momentum of the negative pions for both types of collisions were found to coincide within the uncertainties. As for the average values of the total momentum of π^- mesons, the observed difference in these two types of collisions was attributed to the processes of inelastic charge exchange conversion of the initial neutron into a proton and a negative pion, and/or to the decay of the Δ^0 resonance formed because of its (neutron) excitation. In Ref. [2], a comparative analysis of the average multiplicity of protons and charged pions as well as the momentum, angular, and rapidity distributions of protons in these collisions was performed.

This work is a continuation of a series of the papers [1−4] and is devoted to the comparative analysis of various characteristics of the charged pions produced in p^{12}C and n^{12}C collisions at 4.2 GeV/*c*. The experimental data are compared with the results of Monte Carlo calculations in the framework of the modified version of the FRITIOF model [5,6].

The experiment was performed using a 2-meter propane (C_3H_8) bubble chamber of the Laboratory of High Energies of Joint Institute for Nuclear Research (JINR, Dubna, Russia). The bubble chamber was irradiated by the beams of protons, deuteron and helium-4 nuclei accelerated to the momentum of 4.2 GeV/*c* per nucleon at the Dubna Synchrophasotron. The experimental data consist of 6736 p^{12}C, 7071 d^{12}C, 11974 ^{4}He^{12}C, and 2798 n^{12}C inelastic collision events. n^{12}C collisions were selected from d^{12}C and ^{4}He^{12}C interactions according to the procedures described in details in Ref. [1].

The procedure for determination of particle momenta with a track projection length in the working volume of the chamber $l < 4$ cm, as well as separation of protons and π^+ mesons in the momentum region p > 750 MeV/c are described in [2]. Other features of the experiment and detailed data on corrections for the loss of the secondary charged particles are given in Refs. [8−10].

2. Experimental results and their discussion

Table 1 shows the experimental data on the average multiplicities of charged pions (the mean number of the charged pions per one inelastic collision event) produced in p^{12}C and n^{12}C collisions at 4.2 GeV/*c*.

From Table 1 one can see that the average multiplicity of negative (positive) pions coincides with the average multiplicity of positive (negative) pions in p^{12}C and n^{12}C collisions, respectively. This resultis obvious from the isotopic invariance of the strong interactions considered by us. However, as seen from Table 1, the model overestimates the average multiplicities in comparison with the experimental data by approximately 10%, both for negative and positive pions.

Table 1.Average multiplicities of π^- and π^+ mesons, as well as their absolute differences ΔR in the experiment and in the modified FRITIOF model [5,6] in p^{12}C and n^{12}C collisions at 4.2 GeV/*c*

Quantity	**Type of collision**			
	p^{12}C		**n^{12}C**	
	Experiment	**Model**	**Experiment**	**Model**
$\langle n(\pi^-)\rangle$	0.36±0.02	0.40±0.01	0.64±0.02	0.70±0.01
$\langle n(\pi^+)\rangle$	0.63±0.02	0.71±0.01	0.37±0.02	0.39±0.01
ΔR	0.27 ± 0.03	0.31 ± 0.01	0.27 ± 0.03	0.31 ± 0.01

In order to determine the contribution of inelastic charge exchange reactionsof the initial neutron (proton) to the formation of negative (positive) pions, let us consider the difference in the average multiplicities of the negative (positive) and positive (negative) pions in n^{12}C (p^{12}C) collisions (see the last line of Table 1). The numbers of protons and neutrons in the ^{12}C- nucleus are the same, so the contribution of inelastic charge exchange reactions of the target nucleons to the formation of both the negative and positive pions of the final state should be the same due to the isotopic invariance of the strong interactions. Then the value of ΔR can be considered as an estimate of the contribution of inelastic charge exchange reactions of the initial neutron (proton) to the formation of the final state negative (positive) pions in n^{12}C (p^{12}C) collisions. One can see from the data of Table 1 that, both in the experiment and in the modified FRITIOF model [5,6], these contributions are equal for both types of collisions, respectively. If we consider that in the experiment the value of the inelastic charge exchange coefficient of the nucleon in nucleon-nucleus collisions (i.e. the average multiplicity of the initial nucleon lost during the collision process) is equal to 0.36 ± 0.01 [11,12], then, as can be seen from Table 1, three-fourths (¾) part of the inelastic charge exchange coefficient of the initial nucleon can be related with the formation of a single charged pion, and the remaining one-fourths (¼) part of this coefficient can be related with charge exchange reactions with nucleons of the target of the type $np \rightarrow pn$ or $pn \rightarrow np$. Hence, it can be concluded that more than 42% of the negative (positive) pions are produced due to inelastic charge exchange of the initial neutron (proton) in n^{12}C (p^{12}C) collisions at 4.2 GeV/*c*.

We have observed that our version of the modified FRITIOF model [5,6] overestimates the average multiplicities of the charged pions in the interactions considered. It is interesting to understand to what extent this discrepancy is reflected in the kinematic characteristics of the charged pions.

In Table 2 we present the experimental data on the mean values of the total, longitudinal and transverse momenta, emission angles, and the longitudinal rapidity in the laboratory frame, and the partial inelasticity coefficient for π^- and π^+ mesons produced in p^{12}C and n^{12}C collisions at 4.2 GeV/*c* in comparison with the results of model calculations.

It follows from Table 2 that the average values of the transverse momenta of the charged pions in the experiment coincide within statistical errors for p^{12}C and n^{12}C collisions. It can be noted also that the average values of the longitudinal momentum, as well as of the longitudinal rapidity for the negative (positive) pions are greater than those for positive (negative) pions in n^{12}C (p^{12}C) collisions, respectively. This difference can be explained, as noticed above, if we take into account both the contributions of inelastic charge exchange reaction (conversion)of incident neutron (proton) into the proton(neutron) and the negative (positive)pions, and of the decays of the Δ^0 (Δ^+) resonances into the nucleon and pion. The average values of the longitudinal rapidity of the charged pions, calculated according to the modified FRITIOF model, coincide within statistical errors with the results of the experiment.

Table 2 presents also the experimental and theoretical values of the partial inelasticity coefficients for π^- and π^+ mesons produced in p^{12}C and n^{12}C collisions, respectively. It should be noted that due to the comparability of the value of the incident momentum and the mass of the projectile-nucleon in the experiment, we have calculated the partial inelasticity coefficients of the charged pions as the ratio of the total energy of the secondary charged pions in a given individual collision event to the kinetic energy of the projectile nucleon. Table 2 shows that the average values of the partial inelasticity coefficients for the charged pions coincide within statistical errors in the experiment and the model. This indicates that distribution of the primary (incident) energy among the produced pions, or the ratios of the main mechanisms for pion production, is taken into account correctly in the model.

Table 2.The average values of the total, longitudinal and transverse momenta (in MeV/*c*), the emission angle (in degrees), the longitudinal rapidity and the partial inelasticity coefficient (*K*) for π^- and π^+ mesons in p^{12}C and n^{12}C collisions at 4.2 GeV/*c* in the experiment and in the modified FRITIOF model [5,6].

Quantity	**Type of collision**			
	p^{12}C		**n^{12}C**	
	Experiment	**Model**	**Experiment**	**Model**
$\langle P(\pi^-)\rangle$	501±8	495±3	575±10	526±2
$\langle P(\pi^+)\rangle$	571±7	527±2	511±7	492±3
$\langle P_l(\pi^-)\rangle$	395±9	381±3	464±11	414±3
$\langle P_l(\pi^+)\rangle$	454±7	414±2	386±12	376±3
$\langle P_t(\pi^-)\rangle$	243±3	233±1	245±3	243±1
$\langle P_t(\pi^+)\rangle$	263±3	242±1	262±5	234±1
$\langle \theta(\pi^-)\rangle$	48.0±0.7	45.8±0.2	43.6±0.7	43.9±0.2
$\langle \theta(\pi^+)\rangle$	46.2±0.5	44.0±0.2	47.7±0.9	46.3±0.2
$\langle Y(\pi^-)\rangle$	0.89±0.02	0.92±0.01	1.00±0.02	0.97±0.01

$<\boldsymbol{Y(\pi^+)}>$	0.95±0.02	0.97±0.01	0.88±0.02	0.91±0.01
$<\boldsymbol{K(\pi^-)}>$	0.06±0.01	0.06±0.001	0.12±0.01	0.12±0.01
$<\boldsymbol{K(\pi^+)}>$	0.11±0.01	0.12±0.01	0.06±0.01	0.06±0.01

It is important to understand which region of the momentum distributions is responsible for the discrepancy observed between the multiplicities of the charged pions in the experiment and the model. For this purpose, we consider, first of all, the total momentum distributions for the negative and positive pions in n^{12}C and p^{12}C collisions.

Figs. 1 and 2 show the total momentum distributions of π^- (a) and π^+ (b) mesons in n^{12}C (Fig. 1) and p^{12}C (Fig. 2) collisions at 4.2 GeV/*c*, normalized by the total number of inelastic events (N_{events}) and the width of the momentum interval (ΔP). The corresponding distributions calculated using the modified FRITIOF model are shown as histograms for comparison.

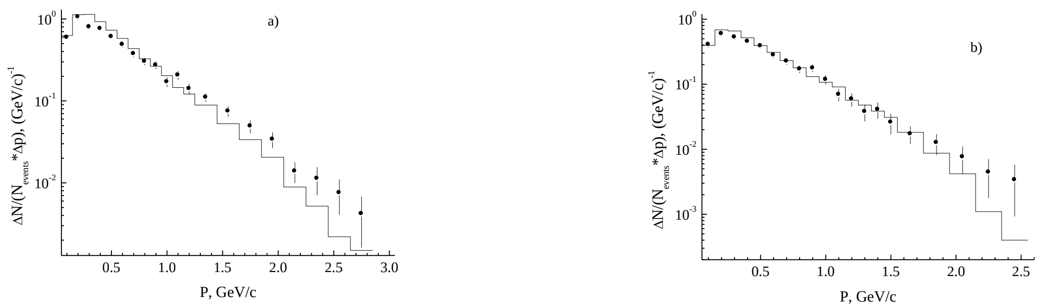

Fig. 1. The normalized total momentum distributions of the negative (a) and positive (b) pions in n^{12}C collisions at 4.2 GeV/*c*. Histograms–the calculations within the framework of the modified FRITIOF model [5,6].

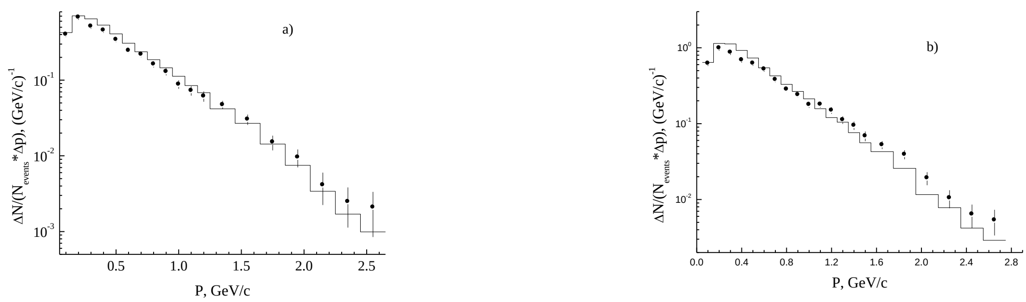

Fig. 2. The normalized total momentum distributions of the negative (a) and

positive (b) pions in p^{12}C collisions. Histograms – the calculations within the framework of the modified FRITIOF model [5,6].

We can see from Fig. 1 that the experimental momentum distribution of π^+ (b) mesons in n^{12}C collisions is a single-modal one, it demonstrates a smooth decrease with the pion momentum, and does not have any irregularities up to the largest values of the total momentum. Regarding the experimental spectrum of π^-(a) mesons in n^{12}C collisions, although in general it is similar to the spectrum of π^+ mesons, there is some deviation from the exponential dependence in the region of large momentum p> 1 GeV/c, where the spectrum decreases more slowly with increasing of the total momentum. This observed "shoulder" is probably related with the production of fast π^-mesons in n^{12}C collisions due to inelastic charge exchange reactions (conversions) of the incident neutron into the π^- meson and proton, and excitation of the incident neutron into intermediateΔ^0resonance, which decays swiftly into the same channel: π^- meson and proton. It is important to note that, based on the kinematical considerations, the contribution of the leading delta resonance to the pion spectrum will be particularly noticeable in the region of the total momenta $p \geq 1$ GeV/c.

The corresponding reverse pattern is observed for the momentum distributions of π^- (a) and π^+ (b) mesons in p^{12}C collisions in Fig. 2. Here, the irregularity in the momentum distribution of π^+ mesons can be caused by both the inelastic charge exchange reaction (conversion)of the incident proton into π^+ meson and neutron, and by the decay of the intermediate Δ^+ resonance formed due to excitation of the incident proton.

Figs. 1 and 2 show also that the calculated momentum spectra of the charged pions for both π^- (a) and π^+ (b) mesons are single-modal ones and there are no deviations from the general smooth behavior of the spectra with increasing the momentum. The theoretical data exceed the experimental ones for both π^- (a) and π^+ (b) mesons for both types of collisions in the momentum range of $p \leq 1$ GeV/c. The model describes well the shape of the experimental momentum distributions of the negative (positive) pions in n^{12}C (p^{12}C) collisions in the range $1 \leq p \leq 2$ GeV/c. Regarding the high momentum tail of the momentum distributions ($p \geq 1$ GeV/c), the model systematically underestimates the experimental data for the negative (positive) pions in n^{12}C (p^{12}C) collisions.

Hence, from comparison of the experimental data with model calculations we see that the modified FRITIOF model overestimates by about 10% the average multiplicity of the charged pionsinp^{12}C and n^{12}C collisions at 4.2 GeV/c. It is important to mention that the model overestimates the number of pions in the target fragmentation region ($p \leq 1$ GeV/c) and underestimates their number (π^- mesons for n^{12}C collisions and π^+ mesons for p^{12}C collisions) in the projectile fragmentation region ($p \geq 1$ GeV/c).

Thus, the 10% excess of the calculated values of the average multiplicity of the charged pions in the model in comparison with the experiment is due to the overestimation in the model of the contribution of intranuclear cascade processes to the production of pions in the target fragmentation region. This ultimately leads to lower average values of the momentum of the charged pions in the modified FRITIOF model [5,6] compared to the experiment. The average multiplicity of the protons with momenta $p > 140$ MeV/c (the lower detection threshold for the reliable registration of the protons in the experiment) inp^{12}C and n^{12}C collisions in the experiment and the model are as follows: $<n_p(n^{12}C)>_{exp} = 1.65 \pm 0.02$, $<n_p(n^{12}C)>_{mod} = 1.96 \pm 0.01$ and $<n_p(p^{12}C)>_{exp} = 1.92 \pm 0.02$, $<n_p(p^{12}C)>_{mod} = 2.32 \pm 0.01$. It can be seen that for both types of collisions the average multiplicity of protons is approximately 1.2 times greater in the model than that in the experiment.

On the other hand, the fact that the model underestimates the number of pions in the region of projectile fragmentation, as well as the absence of a "shoulder" in the considered pion spectra (π^- mesons for n^{12}C collisions and π^+ mesons for p^{12}C collisions) indicates that the model underestimates contribution of Δresonances to pion production in the projectile fragmentation region ($p \geq 1$ GeV/c).

Figures 3 and 4 show the normalized experimental data on the transverse momentum distributions of π^- (a) and π^+ (b) mesons in the analyzed collisions compared with the calculated theoretical distributions (shown as histograms).

Figures 3 and 4 show that both the experimental and theoretical transverse momentum distributions of the charged pions are smooth and flat for both types of collisions with their tails extending up to p_t = 1 GeV/*c* values. The model overestimates the experimental spectra in the region $p_t < 0.5$ GeV/*c* and underestimates them at $p_t > 0.5$ GeV/*c*. In fact, the behavior of the theoretical transverse momentum distributions reflects the behavior of the total momentum distributions discussed by us previously, because the emission angle distributions of the charged pions in both the model and the experiment are very close to each other. On the whole, the model describes qualitatively the data on the transverse momentum distributions of the charged pions.

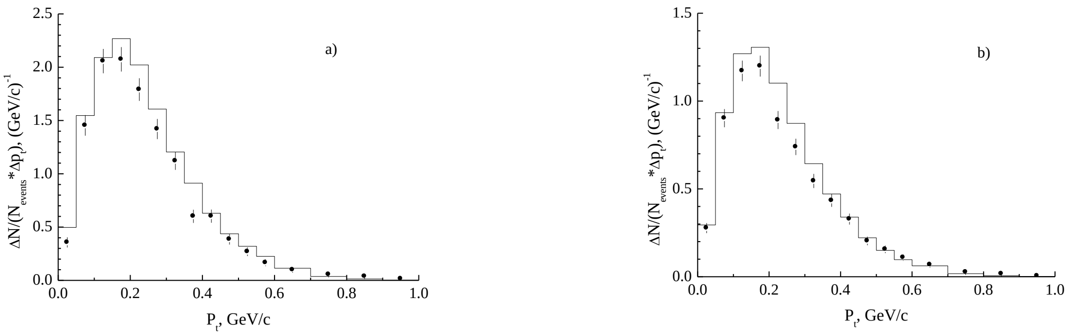

Fig. 3. The normalized transverse momentum distributions of the negative (a) and positive (b) pions in n^{12}C collisions. Histograms – the calculations within the framework of the modified FRITIOF model [5,6].

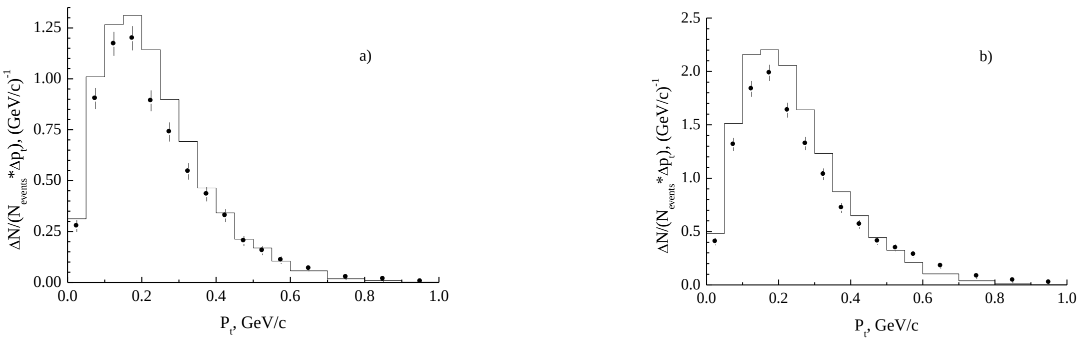

Fig. 4. The normalized transverse momentum distributions of the negative (a) and positive (b) pions in p^{12}C collisions. Histograms – the calculations within the framework of the modified FRITIOF model [5,6].

Figures 5 and 6 show the longitudinal rapidity distributions of π^- (a) and π^+ (b) mesons in n^{12}C and p^{12}C collisions at 4.2 GeV/*c* normalized by the total number of inelastic events (N_{events}) and the width of the interval (ΔY). The longitudinal rapidity is defined as Y=0.5*ln ((E+P_L)/(E-P_L)), where E and P_L are the total energy and longitudinal momentum of the charged pion, respectively. The model calculations for π^- (a) and π^+ (b) mesons are presented as histograms in Figs. 5 and 6.

It can be seen from Figs. 5 and 6 that both the experimental and calculated rapidity distributions of the charged pions for both types of collisions are the smooth curves and have quite wide maxima in the region $0.6 \leq Y \leq 1.4$. As seen from Figs. 5 and 6, the model overestimates the experimental longitudinal rapidity distributions of the negative pions at midrapidity (central rapidity) region around the maxima in both analyzed collision type. On the whole, the model describes qualitatively the shapes of the longitudinal rapidity distributions of the charged pions in n^{12}C and p^{12}C collisions at 4.2 GeV/*c*.

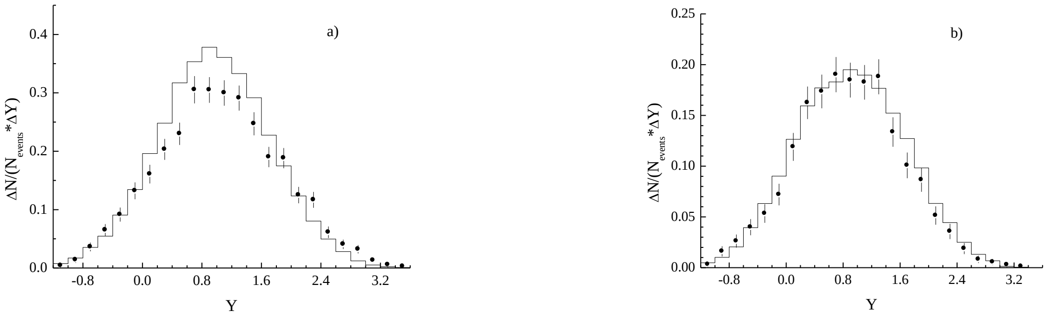

Fig. 5. The normalized longitudinal rapidity distributions of the negative (a) and positive (b) pions in n^{12}C collisions Histograms – the calculations within the framework of the modified FRITIOF model [5,6].

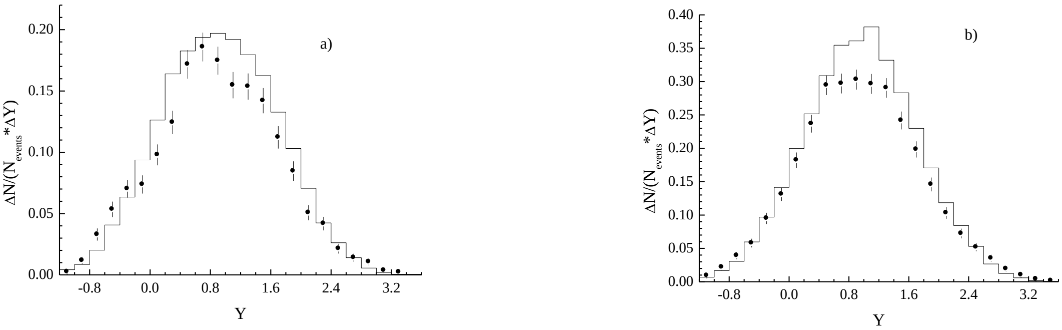

Fig. 6. The normalized longitudinal rapidity distributions of the negative (a) and positive (b) pions in p^{12}C collisions. Histograms – the calculations within the framework of the modified FRITIOF model [5,6].

3. Conclusions

We have presented the new experimental data on various characteristics of the secondary charged pions produced in n^{12}C collisions at 4.2 GeV/*c*. We have also performed a comparative analysis of the average multiplicities and various kinematic characteristics of the charged pions produced in n^{12}C and p^{12}C collisions at 4.2 GeV/*c*. Experimental data were compared systematically with the calculations using the modified FRITIOF model.

It is shown that in n^{12}C (p^{12}C) collisions at 4.2 GeV/*c* around half of the negative (positive) pions are produced due to inelastic charge exchange reaction (conversion)of the initial neutron (proton) into proton (neutron) and the negative (positive) pion.

The momentum distributions of the negative (positive) pions proved to be more rigid than those of the positive (negative) pions produced in n^{12}C (p^{12}C) collisions. This fact can be related with production of the fast negative (positive) pions due to the inelastic charge exchange reaction (conversion)when the incident neutron transforms intoπ^- meson and proton, and the decay of the intermediate Δ^0resonance formed due to excitation of the incident neutron (or when the incident proton transforms intoπ^+ meson and neutron, and the decay of the intermediate Δ^+resonance formed due to excitation of the incident proton) in n^{12}C (p^{12}C) collisions, respectively.

It is found that the modified FRITIOF model overestimates the average multiplicities of the charged pions in n^{12}C (p^{12}C) collisions at 4.2 GeV/*c* compared to the experiment. It is shown that this is due to the fact that the model overestimates the contribution of the intranuclear cascade processes in production of pions in the target fragmentation region compared to the experiment.

It is also found that the model underestimates the multiplicity of the charged pions in the projectile fragmentation region. It is shown that this is due to the fact that the model underestimates the contribution of decays of Δ resonances to the generation of the fast charged pions in the analyzed collisions.

It is shown that the modified version of the FRITIOF model [5,6]used in the present work describes well the experimental values of the partial inelasticity coefficients for the charged pions, indicating that this model takes correctly into account the processes of redistribution of an incident (primary) energy among the charged particles produced in the final state in the analyzed collisions.

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