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Partial inelasticity coefficients of negative pions in p, d, α, ^{12}C+^{12}C and p, ^{12}C+^{181}Ta collisions at 4.2 GeV/c per nucleon

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The partial inelasticity coefficients of the negative pions were determined in minimum bias p, d, α, ^{12}C+^{12}C and p, ^{12}C+^{18}Ta collisions at $4.2A$ GeV/c taking into account the average number of participant nucleons of a projectile nucleus. In nucleus–nucleus collisions, the average values of partial inelasticity coefficients ($\langle K(\pi^-)\rangle$) of the negative pions did not depend on the mass numbers of projectile and target nuclei. Increase of $\langle K(\pi^-)\rangle$ in going from p+^{12}C to $d, \alpha,^{12}$C+^{12}C collisions was due to an additional source of production of fast negative pions in nucleus–nucleus collisions — a charge exchange conversion of one or more neutrons of a projectile nucleus into a proton and π^-. Linking the experimental results of the present analysis at intermediate energy with those obtained at high and ultra-high energies, it was concluded that the average values of partial inelasticity coefficients of pions in nucleon–nucleus and nucleus–nucleus collisions manifest a transitive behavior. At intermediate energies, the values of $\langle K(\pi^-)\rangle$ were smaller by a factor of two and more as compared to those at high energies, and they increased further with increasing incident energy, reaching a plateau at $E_0 > 100A$ GeV.

Keywords: Inelasticity coefficient; pions; relativistic nuclear collisions; hadron–nucleus collisions; nucleus–nucleus collisions.

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Due to their low production threshold energies, pions are the most abundant particles produced in relativistic nuclear collisions. Pions, being produced either directly in nucleon–nucleon collisions or through decay of various resonances, or being emitted from a "hot" core of collision zone at initial stage of central heavy ion collisions, carry information about practically all the stages of such a complex phenomenon as nucleus–nucleus collisions at high energies. Hence investigation of the various properties of pions, produced in relativistic nuclear collisions, is important for understanding the dynamics of a nuclear collision and to unravel the state of a highly compressed nuclear matter created in central collisions.[1–8]

Inelasticity coefficients, being the averaged characteristics of nuclear collisions, contain useful information about an energy transferred from an impinging hadron or projectile nucleus to the produced particles. In practice, one deals with a partial inelasticity coefficient measured for a given type of particles, produced in nuclear collisions. The partial inelasticity coefficient is defined as a ratio of a total energy of c-type particles, produced in an individual collision event, to a total energy of impinging hadron or projectile nucleus

$$K_c = \sum_i \frac{E_i}{E_0}, \tag{1}$$

where E_i is the total energy of an ith c-type particle and E_0 is the total energy of an impinging hadron or projectile nucleus. This method of determination of partial inelasticity coefficient is valid provided that a mass of an impinging particle is much smaller compared to its total energy. At relatively low incident momenta $P_0 < 10A\,\mathrm{GeV}/c$, the partial inelasticity coefficient should be calculated as a ratio of a total energy of c-type particles, produced in an individual collision event, to a kinetic energy of an impinging hadron or projectile nucleus:

$$K_c = \sum_i \frac{E_i}{T_0}, \tag{2}$$

where E_i is the total energy of an ith c-type particle and T_0 is the kinetic energy of an impinging hadron or projectile nucleus.

The partial inelasticity coefficients of particles were measured mostly at high and super high energies.[9–14] The main part of experimental data on partial inelasticity coefficients was obtained for γ quanta in cosmic ray experiments at energies $E_0 \geq 200\,\mathrm{GeV}$. In particular, in Ref. 12 it was established that the average values of partial inelasticity coefficients for π^{o} mesons in collisions of pions and nucleons with the nuclei differed by almost a factor of two. For example, $\langle K(\pi^{\mathrm{o}})\rangle = 0.18 \pm 0.02$ and $\langle K(\pi^{\mathrm{o}})\rangle = 0.37 \pm 0.05$ were measured for collisions of neutrons with aluminum nuclei and interactions of π^- mesons with aluminum nuclei at 200 GeV, respectively. Such a difference was due to a charge exchange conversion of impinging charged pions into neutral pions.[13] Independence of $\langle K(\pi^{\mathrm{o}})\rangle$ on incident energy E_0 in the interval $E_0 = 200$–$2000\,\mathrm{GeV}$ and its very weak dependence on the mass number of a target nucleus was observed.[12] Analysis of experimental data on the average values of partial inelasticity coefficients of neutral pions, $\langle K(\pi^{\mathrm{o}})\rangle$, for interactions of protons with the nuclei of atmosphere in the interval of energies 1–100 TeV[14] revealed its practical independence on incident energy. The mean value of $\langle K(\pi^{\rm o})\rangle$ in these experiments proved to be 0.18 ± 0.01.[14]

For proton–nucleus collisions, one can expect that the partial inelasticity coefficients of the neutral and negative pions coincide, because in this case, both of them are the newly produced particles. For positive pions in proton–nucleus collisions, one expects $\langle K(\pi^+)\rangle$ to be somewhat larger than that for the negative and neutral pions due to a charge exchange conversion of an impinging proton into a neutron and positive pion.

It is necessary to mention that the data on partial inelasticity coefficients of charged pions in collisions of hadrons and nuclei with the nuclei at incident energies on the order of a few GeV/nucleon are practically absent in the physics literature. It is therefore of particular interest to study the partial inelasticity coefficients of pions in hadron–nucleus and nucleus–nucleus collisions at intermediate energies. Hence, the present work complements the existing data on partial inelasticity coefficients measured at high and super high energies by presenting the corresponding data absent at a few GeV/nucleon energy range, which is just below the threshold energy for transition from nucleon into quark gluon degrees of freedom of a matter. It is expected that the average values of partial inelasticity coefficients in nucleus–nucleus collisions should be larger as compared to those in hadron–nucleus collisions. This is because not all nucleons of the colliding nuclei (especially in the case of light nuclei) participate in a collision, i.e., a part of nucleons remains as spectators.

The present work is devoted to analysis of partial inelasticity coefficients of the negative pions in minimum bias p, d, α, ^{12}C+^{12}C and p, ^{12}C+^{181}Ta collisions at $4.2A\,{\rm GeV}/c$ ($\sqrt{s_{nn}} = 3.14\,{\rm GeV}$, $E_{\rm kin} \approx 3.4A\,{\rm GeV}$).

The experimental data on p, d, α and ^{12}C+^{12}C collisions were obtained using 2 m propane bubble chamber of the Laboratory of High Energies of Joint Institute for Nuclear Research (JINR, Dubna) exposed to protons, deuterons, α particles and carbon-12 nuclei accelerated to a momentum of $4.2\,{\rm GeV}/c$ per nucleon at Dubna synchrophasotron. Experimental material on p and ^{12}C+^{181}Ta collisions was also obtained using 2 m propane bubble chamber, in which three tantalum plates of 1 mm thickness were placed perpendicularly to a beam direction at a distance of 93 mm from each other. The chamber was also irradiated by beams of protons and carbon-12 nuclei accelerated to a momentum of $4.2\,{\rm GeV}/c$ at Dubna synchrophasotron. The methodological procedures of the experiment were given in detail in Refs. 15–18. In these experiments, the negative pions were identified with more than 95% probability and the average relative uncertainty of their momentum measurement was about 6%. Statistics of the analyzed experimental data is presented in Table 1.

We determined the partial inelasticity coefficients of the negative pions in the studied collision systems using the expression in (2). The mean values of the partial inelasticity coefficients of π^- mesons in p, d, α, ^{12}C+^{12}C and p, ^{12}C+^{181}Ta collisions at $4.2A\,{\rm GeV}/c$ are given in Table 2. For a comparison with the experimental data, we also calculated the partial inelasticity coefficients of negative pions

Table 1. Statistics of the experimental data on p, d, α, ^{12}C+^{12}C and p, ^{12}C+^{181}Ta collisions at 4.2 GeV/c per nucleon.

Type of collision and statistics					
pC	dC	αC	CC	pTa	CTa
6,736	7,071	11,974	20,527	1,517	2,420

Table 2. The average values of partial inelasticity coefficients of π^-mesons in p, d, α, ^{12}C+^{12}C and p, ^{12}C+^{181}Ta collisions at 4.2 GeV/c per nucleon.

	Type of collision					
Quantity	pC	dC	αC	CC	pTa	CTa
$\langle K(\pi^-)\rangle$ Experiment	0.057 ± 0.006	0.059 ± 0.006	0.047 ± 0.005	0.021 ± 0.002	0.059 ± 0.006	0.039 ± 0.004
$\langle K(\pi^-)\rangle$ MFM	0.067 ± 0.001	0.058 ± 0.001	0.044 ± 0.001	0.021 ± 0.001	—	—

in the analyzed collision systems using modified FRITIOF model (MFM),[19,20] also presented in Table 2. The experimental values of partial inelasticity coefficients are shown with a ≈10% average uncertainty resulting from the mean experimental error of measurement of a pion momentum in the considered collisions.

The FRITIOF model assumes the two particle kinematics of inelastic hh interactions, $a + b \to a' + b'$, where a' and b' are excited states of initial hadrons a and b, respectively. The excited states are characterized by their masses. In case of hA and AA interactions, it is assumed that nucleons excited in primary collisions can interact with each other and with other nucleons, and so their masses increase steadily with successive interactions. The probability of multiple scatterings was calculated using Glauber approach. Excited hadrons were considered as QCD strings and fragmentation of these strings resulted in production of hadrons. The multiplicity of secondary particles increased with increasing string mass. To determine the time sequence of nucleon–nucleon collisions in case of hA and AA interactions, the Glauber approximation was used. Since cascade processes involving secondary particles were disregarded, the characteristics of slow particles produced in the breakup of a nucleus could not be described in the FRITIOF model. To overcome this drawback, it was suggested to modify FRITIOF model by supplementing it with the Reggeon model of a nucleus breakup. Modifications of the characteristics of NN interactions in a nuclear medium were not considered in the Modified FRITIOF model. The details about the model can be found in Refs. 19 and 20.

It is seen from Table 2 that the mean values of the partial inelasticity coefficients of π^- mesons in all the considered collision systems at $4.2A$ GeV/c are several times smaller than those at $E_0 \geq 200$ GeV. The obtained data also show that the values of $\langle K(\pi^-)\rangle$ coincide within the uncertainties for p+^{12}C, d+^{12}C and p+^{181}Ta collisions. Equality of $\langle K(\pi^-)\rangle$ values for p+^{12}C and d+^{12}C collisions can be explained by that there is an additional source of fast pion production through inelastic charge exchange conversion of a neutron of a projectile deuteron ($n \to p+\pi^-$) in the latter case. Coincidence of $\langle K(\pi^-)\rangle$ values for p+^{12}C and p+^{181}Ta collisions indicates an absence of dependence of partial inelasticity coefficient on the mass number of a target nucleus in hadron–nucleus collisions at intermediate energies. For α+^{12}C, ^{12}C+^{12}C and ^{12}C+^{181}Ta collisions, $\langle K(\pi^-)\rangle$ proved to be smaller than those for p+^{12}C, d+^{12}C and p+^{181}Ta collisions, which is probably due to a decrease in the fraction of participant nucleons with an increase in the mass number of a projectile nucleus. The larger value of $\langle K(\pi^-)\rangle$ in ^{12}C+^{181}Ta collisions as compared to that in ^{12}C+^{12}C collisions is likely due to the greater number of participant nucleons from a projectile nucleus in ^{12}C+^{181}Ta collisions compared to that in ^{12}C+^{12}C collisions.

Table 2 shows that the experimental values of $\langle K(\pi^-)\rangle$ in d+^{12}C, α+^{12}C and ^{12}C+^{12}C collisions at $4.2A$ GeV/c agree within the uncertainties with the corresponding values calculated using MFM. Some small difference between the values of $\langle K(\pi^-)\rangle$ in the experiment and MFM in p+^{12}C collisions is due to some overestimation of the experimental mean multiplicities of the negative pions in the model.

It was shown in Ref. 21 that the nucleons of a projectile nucleus interact independently from each other with the nucleons of a target nucleus. It was demonstrated that the dependence of a mean multiplicity of the negative pions on the average number of projectile participant nucleons, $\langle\nu\rangle$, could be described successfully taking into account a decrease in contribution of successive collisions with the target nucleons into a pion production with increasing ν.[21] If independence of interactions of nucleons of the colliding nuclei holds true and one accounts for a decrease in contribution of successive collisions into multiplicity of produced pions, the average values of their partial inelasticity coefficients should not depend on the mass number of a projectile nucleus. At first approximation, the average number of participant nucleons from a projectile nucleus was defined by an expression given in Refs. 22–25

$$\langle\nu_p^{\text{calc}}\rangle = \frac{A_p\sigma_{NA_t}}{\sigma_{A_pA_t}}, \tag{3}$$

where A_p — mass number of a projectile nucleus, σ_{NA_t} — inelastic cross-section of a nucleon interaction with a target nucleus, defined as an average of inelastic cross-sections of interactions of proton and neutron with the target nucleus, $\sigma_{A_pA_t}$ — inelastic cross-section of interaction of a projectile nucleus with the target nucleus. At incident momenta on the order of a few GeV/nucleon, inelastic cross-sections of protons and neutrons with the nuclei can be considered as approximately equal, and, instead of σ_{NA_t}, one can use an inelastic cross-section of a proton–nucleus interaction. The results on inelastic cross-sections of $p, d, \alpha,^{12}$C+^{12}C and $p, d, \alpha,^{12}$C+^{181}Ta collisions at $4.2A$ GeV/c from Ref. 22, presented in Table 3, were used to estimate the average number of participant projectile nucleons. The results of calculation of the average number of participant projectile nucleons in $d, \alpha,^{12}$C+^{12}C and ^{12}C+^{181}Ta collisions at $4.2A$ GeV/c are presented in Table 4, and the corresponding average partial inelasticity coefficients of the negative pions,

Table 3. Inelastic cross-sections of nuclear interactions (in mb).

	A_p			
A_t	p	d	^{4}He	C
C	265 ± 15	400 ± 20	450 ± 20	830 ± 50
Ta	1695 ± 70	1975 ± 80	2390 ± 95	3445 ± 140

Table 4. The average numbers of participant projectile nucleons in d, α, ^{12}C+^{12}C and ^{12}C+^{181}Ta collisions at 4.2 GeV/c per nucleon.

Type of collision and the average number of participant projectile nucleons			
dC	αC	CC	CTa
1.33 ± 0.10	2.36 ± 0.17	3.83 ± 0.32	5.90 ± 0.34

Table 5. The average values of partial inelasticity coefficients of π^- mesons, calculated taking into account the average number of participant projectile nucleons in d, α, ^{12}C+^{12}C and ^{12}C+^{181}Ta collisions at 4.2 GeV/c per nucleon.

	Type of collision			
Quantity	dC	αC	CC	CTa
$\langle K(\pi^-)\rangle$	0.076 ± 0.008	0.073 ± 0.008	0.069 ± 0.008	0.072 ± 0.011

defined as a ratio of the total kinetic energy of these pions to the total kinetic energy of $\langle\nu\rangle$ nucleons of a projectile nucleus are given in Table 5. For calculation of $\langle K(\pi^-)\rangle$ in d+^{12}C and α+^{12}C collisions, the experimentally determined values of $\langle\nu\rangle$, 1.53 ± 0.02 and 2.50 ± 0.05, respectively, from Ref. 21 were used. While calculating the errors of $\langle K(\pi^-)\rangle$, the experimental uncertainties of determination of $\langle\nu\rangle$ and an average relative error of measurement of a pion momentum were taken into account.

As seen from Table 5, the average values of partial inelasticity coefficients of the negative pions became significantly larger as compared to those in Table 2, where $\langle K(\pi^-)\rangle$ was defined as a ratio of a total kinetic energy of produced pions to the total kinetic energy of a projectile nucleus. $\langle K(\pi^-)\rangle$ for all the considered nucleus–nucleus collisions proved to be a factor of more than 1.4 times greater than $\langle K(\pi^-)\rangle$ in p+^{12}C and p+^{181}Ta collisions. It was due to an additional source of creation of fast π^- mesons in nucleus–nucleus collisions — a charge exchange conversion of one or more neutrons of a projectile nucleus into a proton and π^-. Table 5 shows that $\langle K(\pi^-)\rangle$ values coincide within the uncertainties in $d, \alpha,^{12}$C+^{12}C and ^{12}C+^{181}Ta collisions at 4.2 GeV/c per nucleon. This results suggests that, at correct accounting for the average number of participant nucleons, the value of $\langle K(\pi^-)\rangle$ depends neither on the mass number of a projectile nucleus nor on that of a target nucleus. The values of $\langle K(\pi^-)\rangle$, determined in the considered collisions taking into

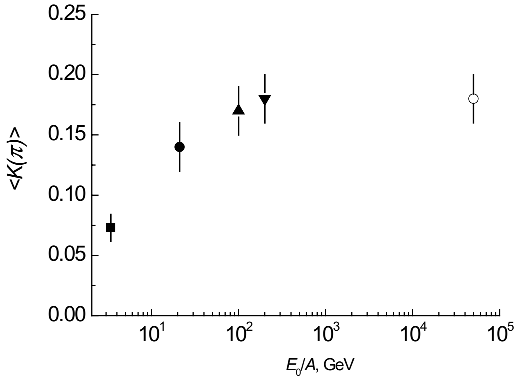

Fig. 1. The energy dependence of the average values of partial inelasticity coefficients of pions: Obtained in the present work (■) for nucleus–nucleus collisions at $3.4A$ GeV, obtained (●) in Ref. 37 for collisions of high energy protons with heavy emulsion nuclei, obtained (▲) in Ref. 38 for collisions of high energy nucleons with copper and lead nuclei, obtained (▼) in Ref. 12 for collisions of high energy neutrons with aluminum nuclei and obtained (○) in Ref. 14 for collisions of high energy protons with the nuclei of atmosphere.

account the average number of interacting (participant) nucleons of a projectile nucleus, proved to be more than two times smaller than those measured at high and ultra-high energies (0.18 ± 0.01).[14] This is due to the experimentally established fact that, at incident energies on the order of a few GeV/nucleon, Δ resonances represent a main source of a pion production.[4,27–36] With increasing incident energy, the fraction of pions, generated from decay of meson resonances, increases, and these pions will have a considerably larger kinetic energies as compared to those of pions coming from Δ decays.

The energy dependence of the average values of partial inelasticity coefficients of pions obtained for nucleus–nucleus collisions at $3.4A$ GeV (the average value from Table 5) in the present work and in other high energy experiments are presented in Fig. 1. Summarizing the experimental results of the present analysis with those obtained at high and ultra-high energies in the past, one can conclude that the average values of the partial inelasticity coefficients of pions in nucleon–nucleus and nucleus–nucleus collisions manifest transitive behavior: At intermediate energies, they were smaller by a factor of two and more as compared to those at high energies, and they increased further with increasing incident energy, reaching a plateau at $E_0 > 100A$ GeV. When the average number of participant nucleons of a projectile nucleus was taken correctly into account, the average values of partial inelasticity coefficients of the negative pions did not depend on the mass numbers of projectile and target nuclei. Growth of $\langle K(\pi^-)\rangle$ in going from $p+{}^{12}\mathrm{C}$ to $d, \alpha, {}^{12}\mathrm{C}+{}^{12}\mathrm{C}$ collisions was due to an appearance of an additional source of production of fast negative pions in nucleus–nucleus collisions — a charge exchange conversion of one or more neutrons of a projectile nucleus into a proton and π^-.

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