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Partial and full inelasticity coefficients in ^{16}Op-collisions at 3.25 A GeV/c

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The partial inelasticity coefficients of baryon fragments of oxygen nuclei and pions were investigated and the full inelasticity coefficient was determined for the first time in ^{16}Op collisions at 3.25 A GeV/c. The fraction of kinetic energy of incident proton in ^{16}Op collisions at 3.25 A GeV/c spent on formation of all the baryon fragments and production of charged and neutral pions was found. The experimental results were compared with those obtained in other experiments at high energies. The experimental full inelasticity coefficient in ^{16}Op collisions at 3.25 A GeV/c was reproduced well by calculations within the framework of Glauber model of multiple scatterings in hadron–nucleus collisions.

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

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1. Introduction

One of the important tasks while studying hadron–nucleus collisions at high energies is to establish the fraction of incident energy going to the production of new particles and various fragments, and excitation of intermediate nuclei. This is quite a difficult task because one cannot detect all the products of a nuclear collision event. If all

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the incident particles in hadron–nucleus collisions were conserved among final reaction products, we could reconstruct the realistic distribution function of an energy lost by incident particle. However, for example, the charge exchange processes of incident particles (nucleons and pions) as well as production of other unobserved particles do not allow reconstructing reliably the value of the energy lost by incident particle. 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. Therefore, 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 $P_0 < 10\,A\,\mathrm{GeV}/c$, the partial inelasticity coefficient should be calculated as a ratio of 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 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. 1, it was established that the average values of partial inelasticity coefficients for π^{o} mesons in collisions of pions and nucleons with the light and heavy nuclei differed by almost a factor of two. For example, $\langle K(\pi^0)\rangle = 0.18 \pm 0.02$ and $\langle K(\pi^0)\rangle = 0.37 \pm 0.05$ were measured for collision of neutrons with aluminum nuclei and interactions of π^- mesons with aluminum nuclei at $200\,\mathrm{GeV}$, respectively. Such a difference was due to a charge exchange conversion of impinging charged pions into neutral pions.[2] Independence of $\langle K(\pi^0)\rangle$ 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 in Ref. 1. Analysis of experimental data on the average values of partial inelasticity coefficients of neutral pions, $\langle K(\pi^0)\rangle$, for interaction of protons with the nuclei of atmosphere in the interval of energies 1–100 TeV[3] revealed its practical independence on incident energy. The mean value of $\langle K(\pi^0)\rangle$ in these experiments proved to be 0.18 ± 0.01.

The experiment[4] showed that the average values of partial inelasticity coefficients for neutral pions proved to be considerably larger than that for negative pions at incident energies up to 10 GeV. This can be interpreted by the fact that the neutral pions can be produced both alone and in pair (if the energy transferred to a target or projectile is sufficient), whereas the negative pions can be produced alone only in target fragmentation region, and pair production of the negative and positive pion is suppressed due to energy–momentum conservation. 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 partial inelasticity coefficients were studied mostly for protons, pions and kaons. On the other hand, in accelerator experiments with a target at rest, the partial and full coefficients of inelasticity were not studied specifically. In particular, the data on partial inelasticity coefficients of fragments are practically absent in the physics literature due to nonobservance of such fragments in experiments with the target nuclei at rest. It is therefore of particular interest to study in detail the inelasticity coefficients.

It is worth mentioning that one can obtain practically full information on all the secondary particles and nuclei in hadron–nucleus collisions at incident energies larger than 2 GeV using the bubble chambers exposed to a magnetic field. Our experiment is a unique one,[5–8] since it allows registration and identification by charge and mass of all the charged particles and fragments of $^{16}\mathrm{O}p$ collision events, measured at 4π (full) solid angle. Emission angles and momenta of the charged fragments and particles were measured with a good enough precision.[5] In our case, the fragmenting oxygen nucleus is a projectile impinging on a hydrogen target, and, therefore, we could measure the momenta of all the charged fragments and produced particles (pions), starting from a zero momentum in oxygen nucleus rest frame.[5] Knowledge of kinematical characteristics of secondary particles and fragments allows us to measure with quite a good precision the full as well as partial inelasticity coefficients of light fragments: deuterons (^{2}H nuclei), tritium (^{3}H) nuclei, ^{3}He and ^{4}He nuclei using the experimental data obtained earlier from bubble chambers.

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 of the threshold energy for transition from nucleon into quark gluon degrees of freedom of a matter.

2. Partial Inelasticity Coefficients of Charged and Neutral Pions

Partial inelasticity coefficients of charged pions were calculated in oxygen nucleus rest frame using the expression in (2). The average values of partial inelasticity coefficients of negative and positive pions proved to be $\langle K(\pi^-)\rangle = 0.047 \pm 0.002$ and $\langle K(\pi^+)\rangle = 0.115 \pm 0.002$, respectively. It is seen that the average value of partial inelasticity coefficient of π^+ mesons is more than twice larger than that of the negative pions. This is, on the one hand, due to the larger mean multiplicity per event of π^+ mesons (0.46 ± 0.01) as compared to that for the negative pions (0.30 ± 0.01), and due to production of the relatively fast positive pions as a result of inelastic charge exchange of an impinging proton (in oxygen nucleus rest frame) on neutron and π^+ meson, on the other hand. No information was obtained about the neutral pions due to low efficiency of registration of these particles in experiment on 1 meter hydrogen bubble chamber. Therefore, we estimated the average partial inelasticity coefficient of neutral pions using the experimental data of Ref. 4, in which the relation $\langle K(\pi^0)\rangle/((\langle K(\pi^+)\rangle + \langle K(\pi^-)\rangle)) = 0.59 \pm 0.01$ was obtained for collisions of protons with light nuclei at energies $E_p \leq 10\,\mathrm{GeV}$. Hence, using this relation, we found $\langle K(\pi^0)\rangle = (\langle K(\pi^+)\rangle + \langle K(\pi^-)\rangle) \bullet (0.59 \pm 0.01) = 0.096 \pm 0.01$.

Hence, approximately 26% of kinetic energy of impinging proton in oxygen nucleus rest frame in $^{16}\mathrm{O}p$ collisions at $3.25A\,\mathrm{GeV}/c$ is used for production of all the three types of pions.

To establish the energy dependence of $\langle K(\pi^0)\rangle$ for collisions of protons with various nuclei, we complemented the analogous dependence, presented in Fig. 1 of Ref. 9, with the new data. Experimental point $\langle K(\pi^0)\rangle = 0.096 \pm 0.01$ at $E_0 = 3.4\,\mathrm{GeV}$ was obtained in the present work. For collisions of protons with carbon nuclei at $E_0 = 28\,\mathrm{GeV}$, the value 0.15 ± 0.02 was obtained in Ref. 10 for the average value of inelasticity coefficient of π^0 mesons. We also determined the average value of inelasticity coefficient for π^0 mesons using the experimental material available with us for collisions of protons with carbon nuclei at $E_0 = 9.94\,\mathrm{GeV}$, which

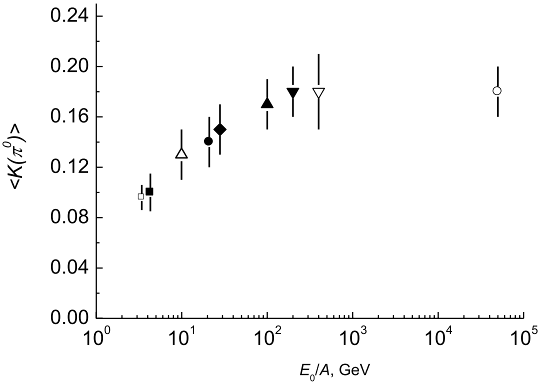

Fig. 1. The energy dependence of the average values of partial inelasticity coefficients of the neutral pions: (□, △) — obtained in the present work; (■) — obtained in Ref. 9 for nucleus–nucleus collisions at $4.3\,A\,\mathrm{GeV}$; (●) — obtained in Ref. 15 for collisions of high energy protons with heavy emulsion nuclei; (◆) — obtained in Ref. 10 for collisions of high energy protons with carbon nuclei; (◇) — obtained in Ref. 16 for collisions of high energy nucleons with copper and lead nuclei; (▼) – obtained in Ref. 11 for collisions of high energy cosmic protons and pions with nuclei of C_2H_4; (▽) — obtained in Ref. 1 for collisions of high energy neutrons with aluminum nuclei; and (◯) — obtained in Ref. 3 for collisions of high energy protons with the nuclei of atmosphere.

proved to be $\langle K(\pi^0)\rangle = 0.13 \pm 0.01$. The experimental point at $E_0 = 400\,\mathrm{GeV}$ equal to $\langle K(\pi^0)\rangle = 0.18 \pm 0.03$ was obtained in Ref. 11 for interactions of cosmic nuclear active particles (protons and pions) with polythene nuclei (C_2H_4). The results are presented in Fig. 1. Summarizing the data of Fig. 1, one can conclude that the average values of the partial inelasticity coefficients of pions in proton–nucleus collisions manifest transitive behavior: at low energies they had minimal values, and they increased further with increasing incident energy, reaching a plateau at $E_0 > 100\,A\,\mathrm{GeV}$. Hence, the value of $K(\pi^0) >$ practically does not depend on incident energy in region $E_0 > 100\,A\,\mathrm{GeV}$.

3. Partial Inelasticity Coefficients of Fragments of Oxygen Nuclei in ^{16}Op Collisions at 3.25 A GeV/c

Partial inelasticity coefficients of fragments of oxygen nuclei were calculated in oxygen nucleus rest frame using the expression

$$\langle K_F\rangle = \frac{\sigma(k)\langle T(F)\rangle}{\sigma_{\mathrm{in}}T_0}, \tag{3}$$

where $\sigma(k)$ is inclusive formation cross-section of the considered fragment, $\langle T(F)\rangle$ — average kinetic energy of this fragment, σ_{in} — inelastic cross-section of $^{16}\mathrm{O}p$ collisions, equal to $334 \pm 4\,\mathrm{mb}$,[5] T_0– kinetic energy of impinging proton in oxygen nucleus rest frame, equal to 2.469 GeV.

For identification of fragments by their masses, the following momentum intervals were selected in the laboratory frame: singly charged fragments with $1.75 < p \leq 4.75\,\mathrm{GeV}/c$ were considered as protons ($^1\mathrm{H}$). Those with $4.75 < p \leq 7.75\,\mathrm{GeV}/c$ were taken as $^2\mathrm{H}$ nuclei, and those with $p > 7.75\,\mathrm{GeV}/c$ were selected as $^3\mathrm{H}$ nuclei. Doubly charged fragments with $p \leq 10.75\,\mathrm{GeV}/c$ were referred to as $^3\mathrm{He}$ nuclei, and those with $p > 10.75\,\mathrm{GeV}/c$ were considered as $^4\mathrm{He}$ nuclei. Triply charged fragments with $p \leq 21.125\,\mathrm{GeV}/c$ were selected as $^6\mathrm{Li}$ nuclei, those with $21.125 < p \leq 24.375\,\mathrm{GeV}/c$ were referred to as $^7\mathrm{Li}$ nuclei, and those with $p > 24.375\,\mathrm{GeV}/c$ were selected as $^8\mathrm{Li}$ nuclei. Fragments having a charge of $Z = 4$ and falling in the momentum range $p \leq 24.375\,\mathrm{GeV}/c$ were referred to as $^7\mathrm{Be}$ nuclei, those with momenta $24.35 < p \leq 27.625\,\mathrm{GeV}/c$ were considered as $^9\mathrm{Be}$ nuclei, and those with momenta $p > 27.625\,\mathrm{GeV}/c$ were selected as $^{10}\mathrm{Be}$ nuclei. Fragments having a charge of $Z = 5$ and falling in the momentum range $p < 34.125\,\mathrm{GeV}/c$ were considered as $^{10}\mathrm{B}$ nuclei, those with momenta $34.125 < p \leq 37.375\,\mathrm{GeV}/c$ were taken as $^{11}\mathrm{B}$ nuclei, those with $p > 37.375\,\mathrm{GeV}/c$ were referred to as $^{12}\mathrm{B}$ nuclei. Fragments having a charge of $Z = 6$ and falling in the momentum range $p \leq 34.125\,\mathrm{GeV}/c$ were considered as $^{10}\mathrm{C}$ nuclei, those with $34.125 < p \leq 37.375\,\mathrm{GeV}/c$ were taken as $^{11}\mathrm{C}$ nuclei, and those with $p > 37.375\,\mathrm{GeV}/c$ were considered as $^{12}\mathrm{C}$ nuclei. Fragments having a charge of $Z = 7$ and falling in the momentum range $p \leq 43.875\,\mathrm{GeV}/c$ were referred to as $^{13}\mathrm{N}$ nuclei, those with momenta $43.875 < p \leq 47.125\,\mathrm{GeV}/c$ were considered as $^{14}\mathrm{N}$ nuclei, and those with momenta $p > 47.125\,\mathrm{GeV}/c$ were selected as $^{15}\mathrm{N}$ nuclei. Fragments having a charge of $Z = 8$ and falling in the momentum range $p \leq 47.125\,\mathrm{GeV}/c$ were

Table 1. The average values of partial inelasticity coefficients of fragments with $A \leq 4$ in $^{16}\mathrm{O}p$ collisions at $3.25\,A\,\mathrm{GeV}/c$.

Type of a fragment	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He
$\langle K \rangle$	0.0770 ± 0.0012	0.0145 ± 0.0003	0.0023 ± 0.0002	0.0022 ± 0.0002	0.0033 ± 0.0002

referred to as ^{14}O nuclei, those with momenta $47.125 < p \leq 50.375\,\mathrm{GeV}/c$ were taken as ^{15}O nuclei, and those with momenta $p > 50.375\,\mathrm{GeV}/c$ were considered as ^{16}O nuclei. At such a selection, the admixture of neighboring isotopes among selected fragments due to overlap of their momentum spectra does not exceed 3–4%.[5]

The partial inelasticity coefficients of fragments of oxygen nucleus with the mass numbers $A \leq 4$ in $^{16}\mathrm{O}p$ collisions at $3.25\,A\,\mathrm{GeV}/c$ are presented in Table 1.

As observed in Table 1, the average value of partial inelasticity coefficient is maximal for proton fragments among the light nuclei. This is likely due to a nature of formation of proton fragments. Proton fragments can be formed mainly due to three mechanisms[5]: mechanism of direct knocking out by incident particle, mechanism of Fermi breakup, and "Evaporation" process. Protons acquire quite a large momentum as a result of mechanism of their knocking out by incident particles.

As expected, the average values of partial inelasticity coefficients coincided for "mirror" ^{3}H and ^{3}He nuclei, like their mean multiplicities ($\langle n(^3\mathrm{He})\rangle = 0.145 \pm 0.04$, $\langle n(^3\mathrm{H})\rangle = 0.144 \pm 0.04$), being smaller than that for ^{4}He nuclei. The latter is due to more than three times larger mean multiplicity of ^{4}He nuclei (0.50 ± 0.02)[5] compared to that of "mirror" ^{3}H and ^{3}He nuclei. Though the mean multiplicity of deuterons (^{2}H) is 1.5 times smaller than that of ^{4}He nuclei, the average value of partial inelasticity coefficient of ^{2}H nuclei is larger than that of α particles. The latter fact is due to the fact that the mechanisms of quasi-elastic knocking out by incident particle, as well as that of "coalescence" of fast cascade nucleons of projectile nucleus contribute to the formation of deuterons, in addition to the processes of decay of excited nuclear fragments.[12] Whereas, α particles are formed mainly due to initial α cluster structure of oxygen nucleus in peripheral collisions at quite small excitations of fragmenting ^{16}O nucleus.

Assuming an equality of the mean kinetic energies of proton and neutron fragments and using the mean multiplicities of these nucleons ($\langle n_p\rangle = 1.78 \pm 0.02$, $\langle n_n\rangle = 1.73 \pm 0.05$), we found $\langle K_n\rangle = 0.075 \pm 0.002$ from relation $\langle K_p\rangle/\langle K_n\rangle = \langle n_p\rangle/\langle n_n\rangle$. Hence, the total value of partial inelasticity coefficient of nucleon fragments is $\langle K_N\rangle = 0.152 \pm 0.02$.

The average values of partial inelasticity coefficients (multiplied by 100, i.e., in %) of fragments of oxygen nucleus with the charges from 3 to 8, obtained by summing up the partial inelasticity coefficients of isotopes with a given charge, are presented in Table 2.

As seen from Table 2, the average values of partial inelasticity coefficients of fragments with the charges from 3 to 8 are more than 100 times smaller as compared

Table 2. The average values of partial inelasticity coefficients of fragments of oxygen nucleus with the charges from 3 to 8 in oxygen nucleus rest frame.

Charge of fragment	3	4	5	6	7	8
$\langle K\rangle, \%$	0.096 ± 0.008	0.051 ± 0.004	0.043 ± 0.004	0.130 ± 0.007	0.186 ± 0.007	0.164 ± 0.008

to that for proton fragments. This is likely due to the fact that the fragments with $Z \geq 3$ are products of breakup of oxygen or remnant nucleus, formed upon completion of a stage of multiple scattering of incident proton (or of a cascading of secondary nucleons of oxygen nucleus). Hence, kinetic energy of fragments with $Z \geq 3$ is determined by excitation energy of a fragmenting nucleus. The relatively low values of inelasticity coefficients of fragments with $Z = 3{-}4$ are obviously due to their small formation cross-sections. Among multi-charged fragments with $Z \geq 3$, the maximal value of the average partial inelasticity coefficient is observed for fragments with $Z = 7$, which is due to their maximal formation cross-section.

Using the data of Tables 1 and 2 and taking into account the value of $\langle K_N\rangle$, we found the average value of inelasticity coefficient of all fragments of oxygen nucleus, which proved to be $\langle K_F\rangle = 0.181 \pm 0.024$. Taking into account this value and the average value of partial inelasticity coefficient of charged and neutral pions ($\langle K_\pi\rangle = 0.258 \pm 0.004$), we calculated (accounting for the average value of kinetic energy ($49.2 \pm 2.1\,\mathrm{MeV}$) necessary for formation of multinucleon fragments observed in experiment) the average value of the full inelasticity coefficient in $^{16}\mathrm{O}p$ collisions, which proved to be $\langle K\rangle_{\mathrm{exp}} = 0.458 \pm 0.024$. The average kinetic energy (49.2 ± 2.1 MeV), necessary for formation of multinucleon fragments, gives additional contribution 0.019 ± 0.001 to $\langle K_F\rangle = 0.181 \pm 0.024$. Hence, the average value of inelasticity coefficient of all fragments of oxygen nucleus proved to be $\langle K_F\rangle = 0.20 \pm 0.02$.

The value $\langle K\rangle_{\mathrm{exp}} = 0.458 \pm 0.024$ of the full inelasticity coefficient in $^{16}\mathrm{O}p$ collisions is approximately 1.1 times smaller than that for nucleon–nucleon collisions at $E_0 > 100\,\mathrm{GeV}$. It is interesting to compare the average experimental value of the full inelasticity coefficient in $^{16}\mathrm{O}p$ collisions with the calculations within the framework of Glauber model of multiple scatterings.[13,14]

In nucleon–nucleus collisions at low and intermediate energies, the growth of the number of produced particles is explained as due to the increase in the number of intranuclear pair collisions. Glauber Model allows one to relate the geometrical characteristics of a collision with the different quantities measured in experiment (for example, fraction of energy, taken away by a hadron projectile after its scatterings on target nucleons). We used this approach to investigate the average inelasticity coefficient $K = E \cdot (1 - k_{NN})^\nu \cdot P(\nu)$, where, to calculate K, one has to enter the energy E of an impinging nucleon and inelasticity coefficient k_{NN} of nucleon–nucleon interaction, and then calculate the probability $P(\nu) = \sigma(\nu)/\sigma_{\mathrm{in}}^{\mathrm{h}A}$ where the hadron projectile experiences ν scatterings on nucleons of the target nucleus. In our case, we used the inelastic cross-section of $^{16}\mathrm{O}p$ collisions at $3.25\,A\,\mathrm{GeV}/c$ equal

$\sigma_{\text{in}}^{hA} = 334 \pm 4\,\text{mb}$.[5] The cross-section $\sigma(\nu)$ of ν times intranuclear scatterings of hadron projectile on target nucleons was calculated by using the equation

$$\sigma(\nu) = C_\nu^A \int_0^\infty \left(\frac{\sigma_N \cdot T(b)}{A}\right)^\nu \cdot \left(1 - \frac{\sigma_N \cdot T(b)}{A}\right)^{A-\nu} \mathrm{d}^2 b, \tag{4}$$

where σ_N is the cross-section of nucleon–nucleon interaction, b is the impact parameter of a collision, A is the mass number of a target nucleus, C_ν^A is the (binomial) coefficient accounting for the "homogeneity" of the nucleus nucleons (the number of combinations), $T(b)$ characterizes the transverse (with respect to collision axis) sizes of the nucleus, which can be defined through three-dimensional nucleon density $\rho(b, z)$ in the nucleus:

$$T(b) = \int_{-\infty}^{+\infty} \rho(b, z)\mathrm{d}z. \tag{5}$$

The distribution $\rho(b, z)$ was normalized to the total number A of the nucleons in the nucleus

$$\int \rho(\boldsymbol{r})\mathrm{d}^3\boldsymbol{r} = \int T(b, z) d^2 b\, dz = A, \quad r^2 = b^2 + z^2, \tag{6}$$

which was chosen realistically in the shape of Fermi distribution function

$$\rho(\mathrm{r}) = \rho_0 \left(1 + \exp\left(\frac{r - c_1}{c_2}\right)\right)^{-1}, \tag{7}$$

where the parameters $c_1 = 1.33 \cdot A^{1/3}$ fm and $c_2 = 0.6$ fm were used, where $A = 16$.

We varied the average value of the full inelasticity coefficient (k_{NN}) of proton-nucleon collision at 3.25 GeV/c as the parameter in the Glauber model and obtained the full inelasticity coefficient in $^{16}\mathrm{O}p$ collisions equal $\langle K \rangle_{\text{mod}} = 0.460$ at $k_{NN} = 0.40$, which practically coincided with our experimental $\langle K \rangle_{\text{exp}}$ value.

4. Summary and Conclusions

From the above results of investigation of the partial inelasticity coefficients of secondary particles and full inelasticity coefficient in $^{16}\mathrm{O}p$ collisions at 3.25 GeV/c, using also our findings from Ref. 9, we can conclude the following:

- The average values of the partial inelasticity coefficients of neutral pions in proton–nucleus collisions manifest transitive behavior: at low energies they had minimal values, and they increased further with increasing of incident energy (which is due to opening up of new channels of pion production through decay of resonances (mainly meson resonances)), reaching a plateau at $E_0 > 100\,A\,\text{GeV}$. Hence, the value of $K(\pi^0)$ practically does not depend on incident energy in the region of ultrahigh energies.
- Because the full inelasticity coefficient ($\langle K \rangle$) at high energies is determined mainly by the sum of partial inelasticity coefficients of charged and neutral pions, we can assume that the dependences of $\langle K \rangle$ and $\langle K_\pi \rangle$ on incident energy should be similar to each other.

- Among baryon fragments of oxygen nuclei, protons and neutrons have maximal values of partial inelasticity coefficient, which is mainly due to the mechanism of their direct knocking out by the incident particle.
- The average fraction of kinetic energy of incident proton in $^{16}\mathrm{O}p$ collisions, spent on the formation of all the baryon fragments, makes up 0.20 ± 0.02, and that used on production of charged and neutral pions is 0.26 ± 0.01.
- The experimental results are reproduced well in the framework of Glauber model of multiple scatterings in hadron–nucleus collisions at $k_{NN} = 0.40$.

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