Three steps in intranuclear cascading

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Abstract
Between the initial excitation of nucleons by the passing throughout each other and the final cascading of newly created hadrons there should be considered one more step. We call it the second step cascading process. It acts as an interaction of wounded nucleon from one nucleus with another nucleon from the same nucleus. This mechanism leads to the significant increase on the inelasticity for nuclei collisions without changing the hadron–hadron interaction characteristics.

The nucleus–nucleus interaction can be described quite successfully within the framework of wounded nucleon model. It can be expressed in the statement that once one of projectile nucleons interacts inelastically with the one from a target nucleus intermediate states called "wounded nucleons" are created. The spatial extension of the wounded nucleon is the same as original nucleon before the collision. The subsequent collisions inside the target nucleus take place before this "excited state" hadronize.

The detailed insight into the intranuclear collisions process gave a surprising result which lead to the revision of, e.g., the conventional interpretation of connections between inelasticity in nuclei and hadronic collisions and respective cross section ratios [1]. In the wounded nucleons picture of the high-energy nucleus–nucleus interaction the non-zero time interval between excitation and hadronization leads to the possibility which we will call hereafter second step cascading: the interaction of wounded nucleon from one (target or projectile) nucleus with another nucleon from the same nucleus before the hadronization occurs.

The great influence of second step cascading process is straightforward. On the projectile side (high laboratory energy) the excitation of one initially untouched nucleons by a excited state going backward in anti-laboratory frame of reference leads to transfer a part of nucleon energy to the secondary produced particles. Their energy in the nucleus center of mass system are rather small but after transformation to the laboratory system the effect is expected to be quite considerable.

Results presented in the present paper are obtained using the geometrical chain model. Recently [2] the geometrical multichain (GMC) extension to very high energies of the geometrical two-chain model [3] has been presented. Obtained proton–proton multiparticle production characteristics show that up to at least SPS energies the underlying physics can be treated as competitive to that used by Dual Parton-like models or relativistic jet (LUND-like) idea.

The GMC model of the nucleon–nucleon (hadron–hadron) collision differs from the others (DPM- or LUND-type models) in a details of the treatment of the creation of "wounded nucleons" (excited states, chains, strings). In the GMC model a phenomenological description of the chain creation is used with a very few parameters to be adjusted directly to the soft hadronic interaction data, instead of using structure functions approach. The geometrization of the interaction picture is in the parametrization of the multiparticle production process as a function of the impact parameter of colliding hadrons.

The wounded nucleon picture is adopted for GMC nucleus–nucleus interactions. The detailed four-dimensional space-time history of each nucleon in both colliding nuclei is traced. Each wounded nucleon in moving for the constant time measured in its c.m.s. equal in the present calculation to 1 fm/c. Calculation shows that this is enough for the wounded nucleon (in the most of cases) to get out from its own nucleus before the hadronization occurs, if the interaction energy in the laboratory frame of about 1 TeV/nucleon or more. This means that for high energies sometimes wounded nucleons excited to the high masses collide with ordinary nucleons from its own nucleus. The GMC procedure described in [3], without any changes, is used in such cases.

The number of nucleons participating in the inelastic nuclei collision is related closely to the respective cross-section ratios and studied extensively in nucleus–nucleus interaction examinations. The commonly used approximation based on the point–nucleon optical approximation gives

$$n_A = \frac{A\sigma_{pB}}{\sigma_{AB}} \quad , \qquad n_B = \frac{B\sigma_{pA}}{\sigma_{AB}} \quad , \tag{1}$$

where n_A in the average number of participants from A nucleus. The second step cascading process obviously has to increase of the number of excited nucleons in both colliding nuclei what is clearly seen. The effect is stronger on the projectile (heavier) nucleus side. In Fig. 1 mean numbers of nucleons participating in Fe–N collision for different interaction energies are given. Dashed lines represent the approximation used in evaluation of Eq.(1). This approach does not take into account the second step cascading mechanism, thus these lines depict only the "primarily wounded" nucleons in each colliding nucleus (interacting inelastically during the passage of one nucleus through the other – the first step cascading). After this the second step cascading takes place. The primarily wounded nucleons inside each nucleus moves back and, when they traverse its own nucleus, they can excite nucleons which survives the "primary" collision.

The increase of the number of wounded nucleons has to lead to increase of the inelasticity. The inelasticity is defined as a fraction of interaction energy transferred to the secondary particles created in the interaction. The remaining energy is carried by the "leading particle" and transported downward to next subsequent interaction in the hadronic cascade. In the present paper we use the following definition:

$$K_{\mathcal{NN}} = \frac{\langle \text{Energy carried by produced secondaries} \rangle}{\text{Initial energy of the projectile nucleus}} = \frac{E_{\text{in}} - E_{\text{nuclei}} - (E_{\text{proton}} + E_{\text{neutron}} - E_{\text{antiproton}} - E_{\text{antineutron}})}{E_{\text{lab}}}, \tag{2}$$

where E_{nuclei} is the energy of all nuclei remaining from colliding nuclei (if there are any). All energies are given in laboratory system of reference. The GMC model inelasticity for p–air is presented in Fig. 2 by a thick solid curve. (For the comparison inelasticities of the other models discussed in Ref.[4] are also presented.) As one can seen, it is almost constant over a wide range of interaction energies.

In this paper we want to exhibit the role of the second step cascading process in the nuclei interactions. The quantitative evidence for the change in inelasticities between the model with and without this process is given in Fig. 3, where the inelasticities for iron–air interactions are presented.

The depth of the position of the shower longitudinal development curve $x_{\rm max}$ is one of the indisputable observable related directly to the energy degradation rate in EAS. The GMC model with the nucleus–nucleus interaction mechanism described above was introduced to the CORSIKA code [5] developed by the KASCADE group. The respective calculations were performed for primary protons and iron nuclei. For the second case, the model with and without second step cascading mechanism was used. Results together with Fly's Eye and Yakutsk data [6] are given in Fig. 4.

The role of the second step cascading process in clearly seen. It is increasing slowly with energy giving the positions of the shower maxima higher in the atmosphere of about 10 g cm^{-2} at 10^{16} eV and 30 g cm^{-2} at 10^{19} eV. Thus, if without this process the experimental data show the "heavier than iron" mass of primary cosmic rays, then with the second step cascading taken into account data points lay between the proton and iron mass predictions. The elongation rate changes from 76 g cm^{-2} to 70 g cm^{-2} when the second step cascading is switched on for pure iron (for protons is equal to 63 g cm^{-2}). All these values are in good agreement with the measured rates as can be seen in Fig. 4.

It is important to note that this conclusion is obtained using the interaction model which does not introduce any "extraordinary" effects which starts to dominate the interaction picture at ultra high energies. Our model for proton–proton inelastic collision is, at this point, a very "conservative" one (see, e.g., Fig. 2). The agreement with data is mainly a consequence of the second step cascading process which has to be present in high energy nucleus–nucleus interactions. This mechanism leads to the significant increase on the inelasticity for nuclei collisions without changing the hadron–hadron interaction characteristics.

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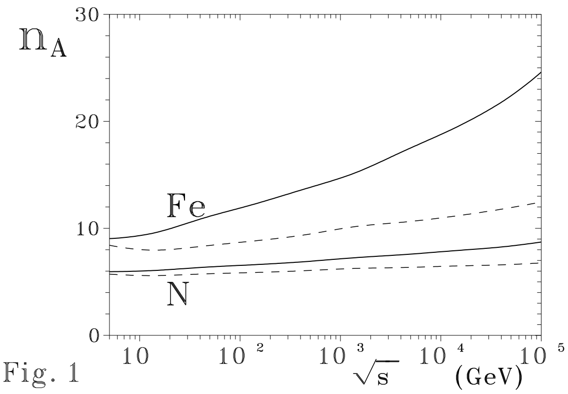

Fig. 1

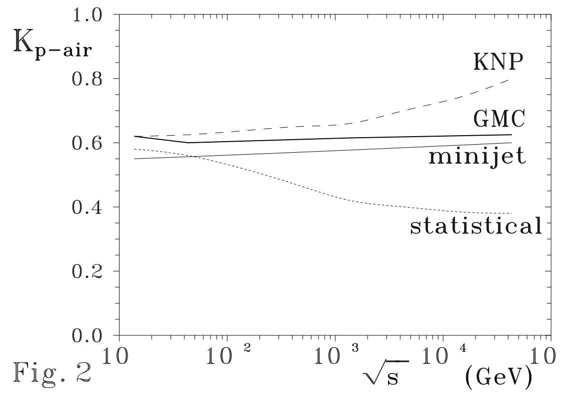

Fig. 2

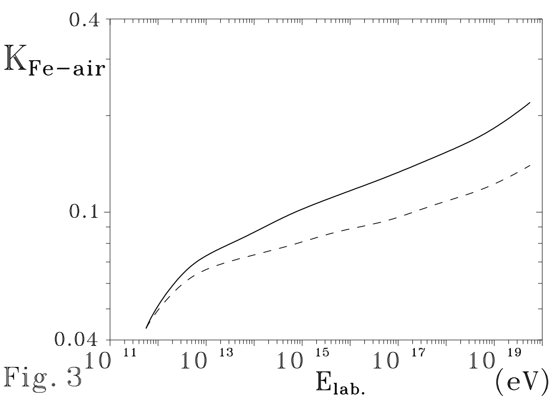

Fig. 3

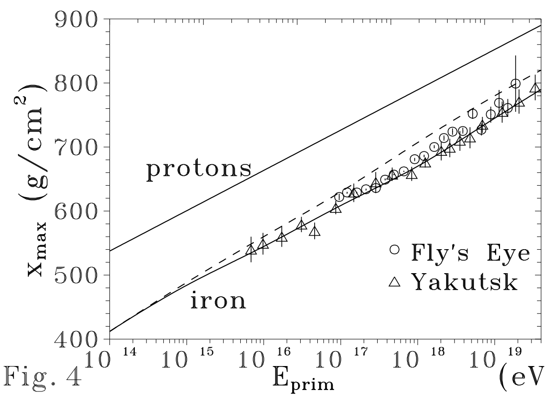

Fig. 4

Fig.1. Average wounded nucleon number for Fe–N interaction. Two upper curves are for iron, lower – for nitrogen nucleus respectively. Dashed lines shows number of primary wounded nucleons (before second step cascading), solid lines represent final wounded nucleon numbers (after second step cascading process).

Fig.2. Inelasticity coefficient of *p–air* collisions. Three models of *p–air* used in Ref. [4] analysis are presented (thin lines) in comparison with the GMC model predictions (thick line).

Fig.3. Inelasticity for *Fe–air* collisions. The solid and dashed lines in were obtained with and without second step cascading process taken into account. for different laboratory energies.

Fig.4. Depth of the sower maxima calculated with the GMC model compared with the Fly's Eye and Yakutsk data. For the iron primaries the dashed line represents the model without second step cascading process while the solid one is obtained with this process taken into account.