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EVOLUTION OF INTRANUCLEAR COLLISIONS AT INTERMEDIATE ENERGIES

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The experimental data on energy and multiplicity distributions of protons and momentum spectra of deuterons emitted in the reactions of pions and protons of energy ranging from 2.5 to 200 GeV with several nuclei are compared to the calculations based upon two different model approaches: DCM Monte Carlo [3] code and the tube-fireball (TF) model [4]. The results of this confrontation are discussed within the framework of the intranuclear interaction mechanism assumed. A detailed study of the intranuclear scenario presented by the DCM Monte Carlo program gives grounds to build simplified analytic models like the TF which may turn out very useful in many practical problems as being of predictive nature.

Проведено сравнение экспериментальных данных по множественности и энергетическим спектрам протонов, а также импульсным спектрам дейтронов, испускаемых во взаимодействиях с несколькими ядрами пионов и протонов с энергией от 2,5 до 200 ГэВ, с расчетами, основанными на двух различных модельных подходах: программе DCM [3] и ТФ [4]. Результаты выполненного сравнения обсуждаются в рамках заложенного в этих подходах механизма внутриядерного взаимодействия. Подробное изучение внутриядерного сценария, на котором базируется программа DCM, дает основание для построения упрощенных аналитических моделей наподобие упомянутой выше ТФ-модели, которая может оказаться очень полезной во многих практических задачах в силу предсказуемости.

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INTRODUCTION

The problem of modeling of intranuclear processes initiated by high enough energy hadrons has a long, more than a half-century history (for example, [1]). Similar is the situation concerning analytic attempts of simple model description of this complex phenomenon (for example, [2]). Nowadays, there exist several different computer codes simulating intranuclear interactions, which are based on various theoretical approaches. But it is evident that all codes of this kind should lead to similar results consistent with the experiment. Nevertheless, at present, the situation is far from being satisfactory in this regard. It concerns in particular such important properties of nuclear reactions as nuclear fragmentation, cumulative particle production and correlation even between the basic features of the interaction. So, the main current problem of hadron–nucleus and nucleus–nucleus collisions is a deep understanding of the evolution of multiparticle interactions inside nuclei. To analyze this problem, we have chosen two diverse models of intranuclear process initiated by a relativistic hadron, which are built upon completely different scenarios of interaction: the MCAS code [3] and the so-called tube-fireball (TF) model [4]. The MCAS code [3] is based on a traditional scenario of intranuclear cascading [1], whereas TF model [4] is founded on a simplified assumption of the thermalized statistical source formed in the interaction occurring mainly along the trajectory of an impinging particle.

In this work, we compare the results obtained by using the MCAS code [3] and the TF model [4] with various experimental data [5–7], and trace the space-time evolution of multiparticle production in hadron–nucleus collisions at intermediate and high energies applying the above-mentioned scenarios.

1. SPACE TOPOGRAPHY OF INTRANUCLEAR COLLISIONS

The simplest way to gain a more penetrating insight into the phenomenon of hadron/nucleus–nucleus interaction in the intermediate energy range (i.e. within several GeV), which is also of particular interest from the practical standpoint, for example, in connection with the transmutation of radioactive waist by means of spallation reactions in extended heavy targets, is to use a typical cascade model based on the conventional concept of space-time sequence of intranuclear collisions and target-nucleus structure, as well as sufficiently exhaustive experimental information on the hadron–nucleon interaction channels involved. At the same time, the such a model should be previously confronted with the experiment and proved to give acceptable results in respect of, at least, the main characteristics of interaction: multiplicity, energy and angular distributions of secondary particles. The MCAS code [3] satisfactorily fits these requirements.

The space evolution of the intranuclear cascade initiated by a relativistic hadron may be illustrated, following the MCAS code [3], by the dependence of the probability P of inelastic intranuclear collisions of this hadron with target-nucleus nucleons on the impact parameter b, when all these collisions (both primary and secondary) may take place within a disk of the radius R and thickness $\Delta z = 0.5$ fm along the trajectory of the impinging particle.

As a specific example Fig. 1 displays the probability P of inelastic intranuclear collisions initiated by a 3.5 GeV/c π^- meson in its straight-line trajectory through the ^{131}Xe target-nucleus stricken at two different impact parameters, $b = 2$ fm and $b = 4$ fm, as a function of the radius R of the disk perpendicular to the π^--meson trajectory, calculated according the MCAS code. One can make the inference that in the beginning the interactions are concentrated predominately inside an $R \approx 1$ fm thin tube around the straight-line path of a primary relativistic particle (latter on called the z-axis) hitting the target nucleus. Next, the radius R increases with increasing of the length of the trajectory through the target-nucleus.

To follow the space development of direct intranulear interactions along the z-axis one can use a disk of the radius R_m and thickness $\Delta z = 0.5$ fm of a tube around the hadron trajectory in which a share m (%) of inelastic collisions takes place (i.e. the so-called cascade radius). Figure 2 demonstrates the z-dependence of R_m for 3.5 GeV π^- meson striking a target-nucleus ^{131}Xe at two values of impact parameter, $b = 2$ fm and $b = 4$ fm, all calculated according to MCAS.

One can conclude that in the case of standard intranuclear cascading approach (i.e., after the MCAS code) the cascade radius R_m initially increases up to the center of the target

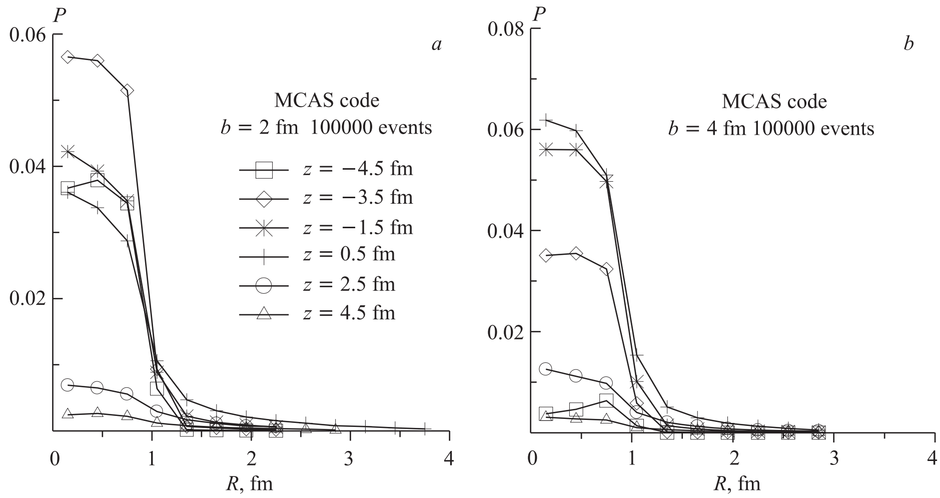

Fig. 1. Probability P of inelastic $\pi^- + {}^{131}\text{Xe}$ intranuclear collisions at 3.5 GeV: *a*) $b = 2$ fm; *b*) $b = 4$ fm. Calculations performed according to the MCAS code [3]. R is the distance from a primary hadron trajectory; z denotes the trajectory axis (see also Fig. 5)

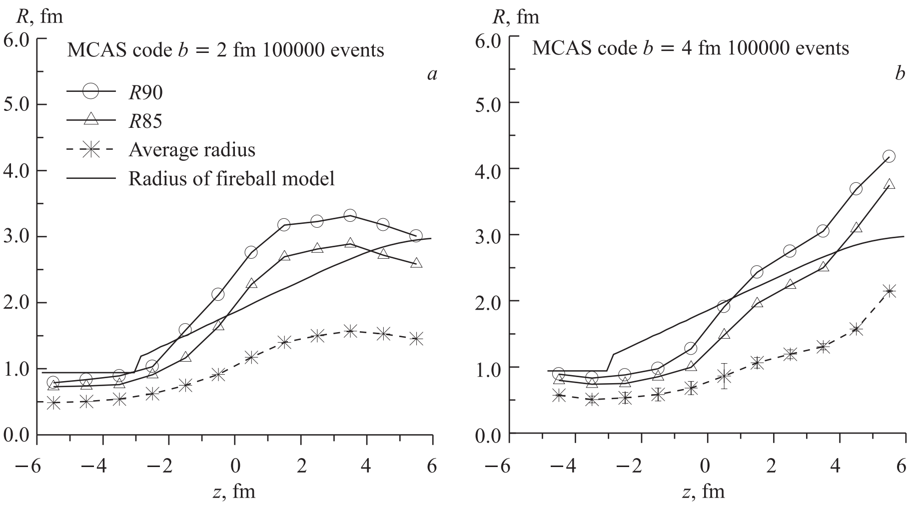

Fig. 2. z-dependence of the cascade radius R_m of the tube-like trajectory of a primary 3.5 GeV π^- meson inside a target-nucleus ^{131}Xe at two values of impact parameter: $b = 2\,\text{fm}$ (*a*) and $b = 4\,\text{fm}$ (*b*), according to MCAS [3] and TF [4]. z-dependence is also drawn for the averaged collision radius (1)

nucleus where the nucleon density is maximal and then it slightly diminishes behind it at $b = 2$ fm (Fig. 2, *a*). For much more peripheral collisions (i.e., when $b = 4$ fm) the radius R_m increases steadily with increasing z as is displayed in Fig. 2, *b*.

The average collision radius presented in Figs. 2 and 4 (i.e., the average distance of collisions from the hadron path) is defined as usual:

$$\bar{R} = \int_0^\infty RP(z,R)dR, \tag{1}$$

where $P(z,R)$ mean the probability of collisions within a unit volume up to the distance R from the hadron trajectory.

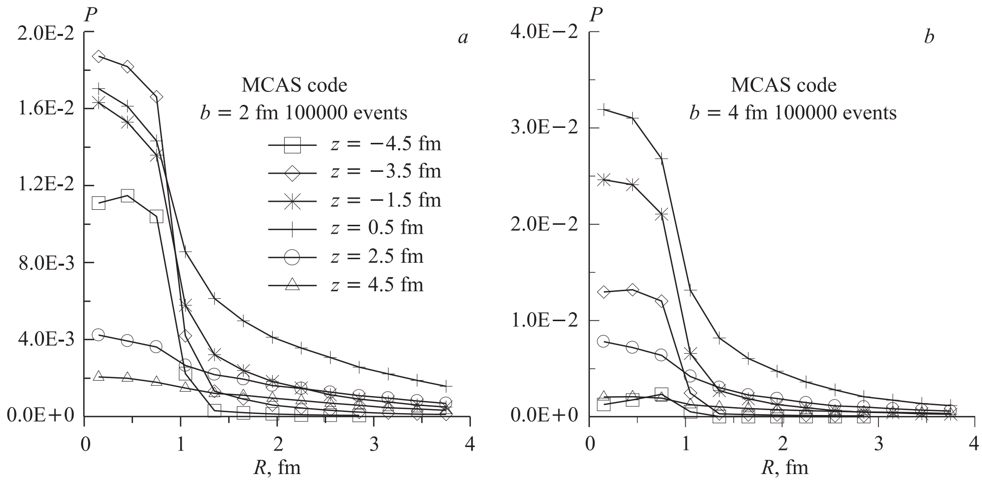

Fig. 3. The same as in Fig. 1 but for all intranuclear collisions: both elastic and inelastic

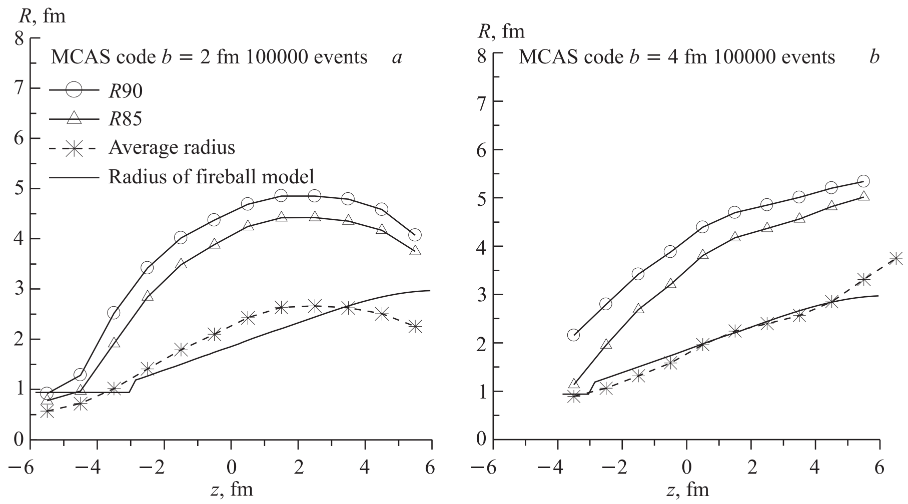

Fig. 4. The same as in Fig. 2 but for all intranuclear collisions: both elastic and inelastic

If all interactions of the primary hadron with intranuclear nucleons are included, i.e. both inelastic and elastic, and not only inelastic ones as those above (Figs. 1 and 2), the general picture of R- and z-dependences do not change, as shown in Figs. 3 and 4, correspondingly.

The foregoing outline provides the basis for the construction of a simplified model of the interaction like the TF [4].

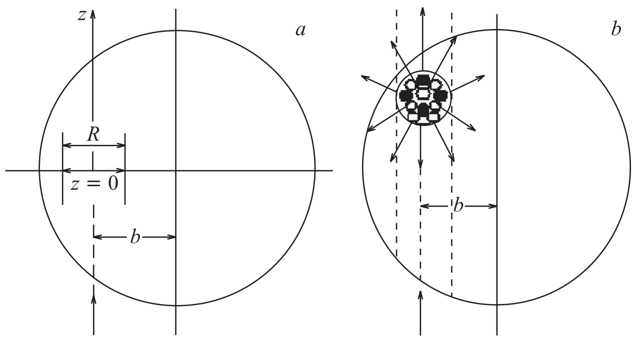

Fig. 5. Schematic picture of the space structure of intranuclear interaction according to the TF model [4]: *a*) system of reference (also valid for the MCAS model investigated in this work); *b*) passage and decay of a formed fireball: b is the impact parameter, R is the local value of the radius of the tube inside which a primary particle, moving along z-axis, initiates a fireball at temperature T depending on b

The space structure of intranuclear interactions according to the TF scenario is sketched in Fig. 5. In short, it comes down to the following picture: a primary particle striking a target nucleus at an impact parameter b moves inside it along the straight-line trajectory and during this passage it adiabatically amasses nucleons in the form of a localized and thermalized fermionic system at temperature T depending on b. Next, this system, often called a fireball, decays emitting mesons and nucleons isotropically in its center-of-mass system [4].

2. ENERGY AND MOMENTUM CONSERVATION

The most important problem determining the reliability of a Monte Carlo based program modeling intranuclear process of the cascade type is the accuracy of energy and momentum conservation. To check to what extent this condition is fulfilled in the case of the MCAS code, we have performed the relevant calculations. The corresponding results graphically demonstrates Fig. 6.

So, in Fig. 6, *a* depicts the distributions of the difference between the kinetic energy of 3.5 GeV/c π^- meson $E_{\rm ki}$ and the summary kinetic energy $E_{\rm kf}$ of all secondary particles emitted in the interactions of this π^- meson with ^{131}Xe nuclei. Here $E_{\rm kf}$ is defined as follows:

$$E_{\rm kf} = \sum_n E_{\rm kn}^{\rm nucl} + \sum_n E_{\rm kn}^{\rm frag} + \sum_n E_{\rm Tn}^{\rm mes}, \tag{2}$$

whilst $E_{\mathrm{kn}}^{\mathrm{nucl}}$, $E_{\mathrm{kn}}^{\mathrm{frag}}$ and $E_{\mathrm{Tn}}^{\mathrm{mes}}$ are the kinetic energy of nucleons, nuclear fragments and total mesons energy, respectively. These distributions have been obtained by using the MCAS code for four values of impact parameter b: 0 (i.e. head-on collisions), 2, 4 and 5 fm (mostly peripheral collisions).

Figure 6, *a* shows similar distributions obtained according the MCAS code for the same π^- Xe reaction at 3.5 GeV/c but for particles momenta, when p_i is the momentum of the primary pion and p_f is the total momentum of all secondary particles emitted in this interaction. By definition we have

$$\mathbf{p}_f = \sum_n \mathbf{p}_n^{\mathrm{nucl}} + \sum_n \mathbf{p}_n^{\mathrm{frag}} + \sum_n \mathbf{p}_n^{\mathrm{mes}}. \tag{3}$$

Here $\mathbf{p}_n^{\mathrm{nucl}}$, $\mathbf{p}_n^{\mathrm{frag}}$ and $\mathbf{p}_n^{\mathrm{mes}}$ are the momentum of nucleons, complex fragments and mesons in the laboratory system of reference (LAB), respectively.

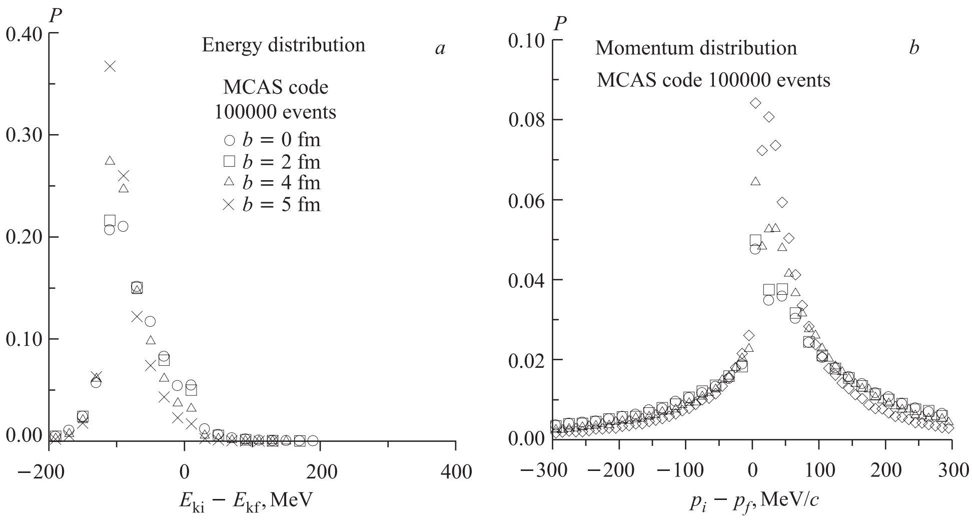

Fig. 6. *a*) Distributions of the difference between the kinetic energy E_{ki} of a primary hadron and the summary kinetic energy E_{kf} of all secondary particles produced in the $\pi^- + {}^{131}\mathrm{Xe}$ reaction at 3.5 GeV/*c*. Calculations are performed using the MCAS code at various values of impact parameter: $b = 0$, 2, 4, 5 fm. Secondary particles are both from fast and evaporation stages. *b*) The same as in *a*) but for momenta of particles

One can notice that the shape of both energy and momenta distributions do not depend on impact parameter. Moreover, the energy spectra are shifted left with respect to zero by a value of about the pionic rest energy, $m_\pi c^2$, because just such an energy of a primary π^- meson has been transformed into the kinetic energy of particles involved in the interaction. The widths of these spectra, $\sim m_\pi c^2/2$ and $\sim m_\pi c$, respectively, determine the accuracy of calculation by using the MCAS code and may be considered as typical for such an approach.

3. COMPARISON WITH THE EXPERIMENT

Figure 7 shows the multiplicity distributions of hydrogen isotopes emitted in $p + {}^{197}\mathrm{Au}$ interactions at 2.5 GeV (*a*) [5] and $p + {}^{131}\mathrm{Xe}$ interactions at 200 GeV (*b*) [6]. The results of corresponding calculation performed using both the MCAS code and the TF model are also depicted.

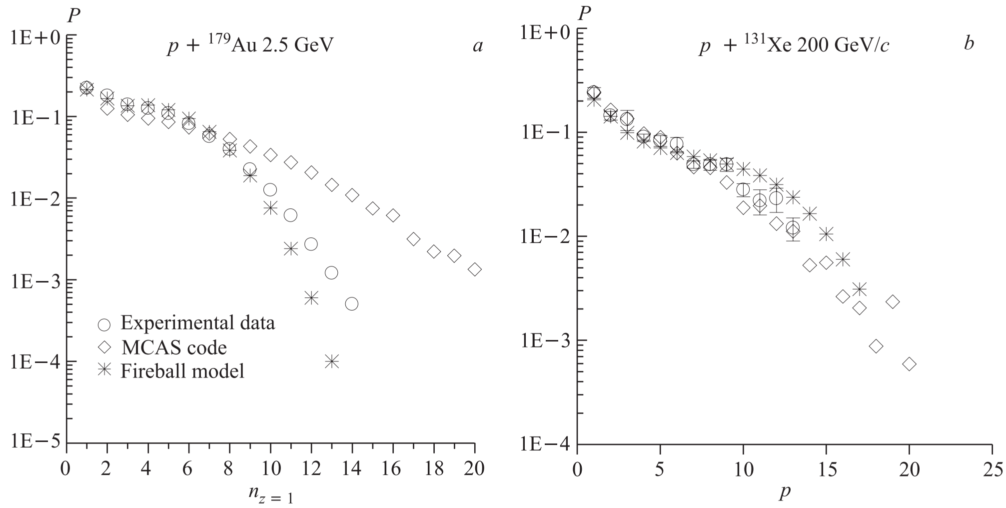

Fig. 7. Multiplicity distributions of hydrogen isotopes ($n_{z=1}$) of energy 2.8–200 MeV registered at an angular acceptance 4π emitted in $p + {}^{197}\mathrm{Au}$ interactions at 2.5 GeV [4] (*a*), and protons (n_p) of momentum 100–600 MeV/*c* at an angular acceptance 4π emitted in $p + {}^{131}\mathrm{Xe}$ interactions at 200 GeV [5] (*b*). Experimental data are compared with calculations performed using the MCAS code and the TF model

One can see a significant discrepancy between the results calculated using the mentioned code and the experimental data for the reaction $p + {}^{197}\mathrm{Au}$ at 2.5 GeV, whereas the TF model slightly underestimates the multiplicity at $n_{z=1} \gtrsim 10$. It happens so because TF does not take into account particle evaporation whereas the MCAS code overestimates the data as early as at $n_{z=1} \gtrsim 8$.

In the case of the reaction $p + {}^{131}\mathrm{Xe}$ at 200 GeV (Fig. 7, *a*) the MCAS code and TF model reproduce satisfactorily the experimental data.

Experimental data presented in Figs. 8–10 are taken from the experiment [7] in which a proton beam from accelerator SATURNE (Saclay) and three types of detectors were used: DENSE (the energy range of neutrons 2–14 MeV) and DEMON (the energy range 4–400 MeV) and the spectrometer (the energy range above 200 MeV).

Figures 8–11 show a considerably better agreement of calculations of energy distributions done according to TF model with experimental data for neutrons emitted into backward hemisphere, i.e. at angles in the range $0 > \cos(\theta) > -1$ than for forward emitted neutrons ($1 > \cos(\theta) > 0$). In this case the disagreement is caused by the fact that elastic collisions

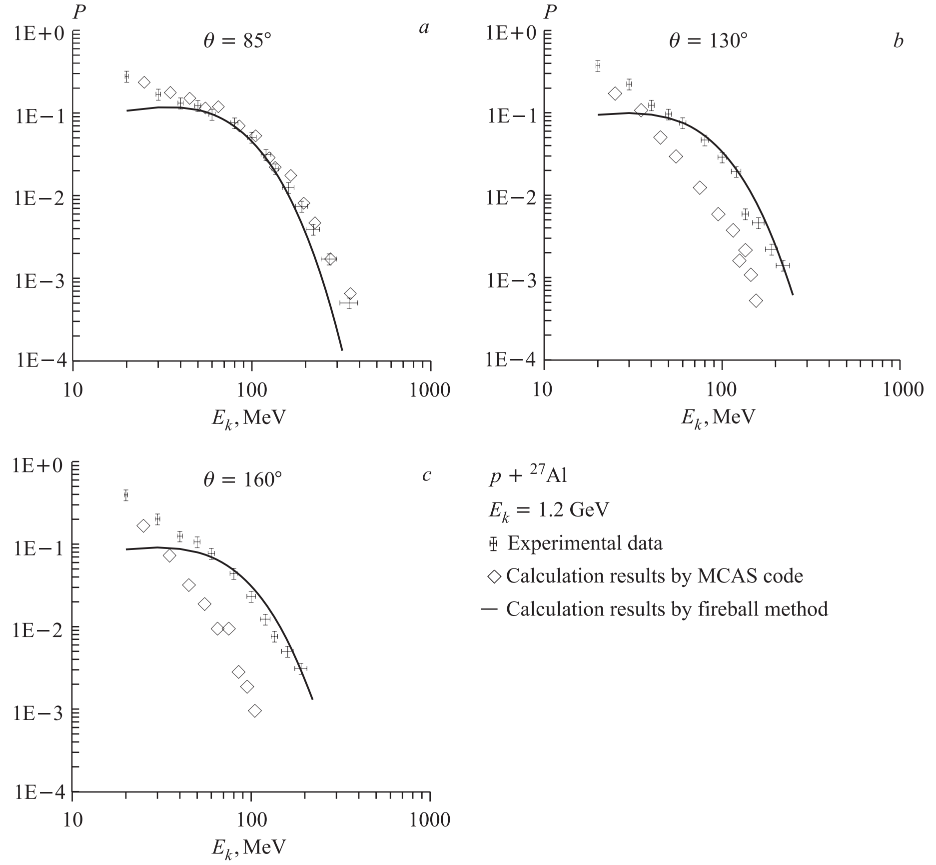

Fig. 8. Energy distributions of neutrons emitted in the reaction $p + {}^{27}$Al (1.2 GeV) at the angles 85 (*a*), 130 (*b*) and 160° (*c*). Experimental data are taken from work [7]. P, E_k are the probability and the kinetic energy, respectively. The number of calculated events by the MCAS code [3] is equal to 100000

were neglected in calculations whereas the products of elastic collisions move predominantly at angles $1 > \cos(\theta) > 0$ in LAB.

Figures 8–10 also display a disagreement of energy-angular distributions of neutrons calculated using the fireball approach with experimental data in the low energy range (below 30 MeV) as the TF model does not take into account the excitation of the target nucleus whilst such neutrons mostly originate as a result of evaporation of excited target-nuclei.

One can notice as well a disagreement of energy-angular distributions of neutrons calculated by MCAS code with the quoted experiment in the range of higher energies, i.e., above 30 MeV at angles equal to 130 and 160°.

CONCLUSION

We have performed the investigation of the space structure and evolution of intranuclear process initiated by high enough energy hadrons in different atomic nuclei. For this reason a

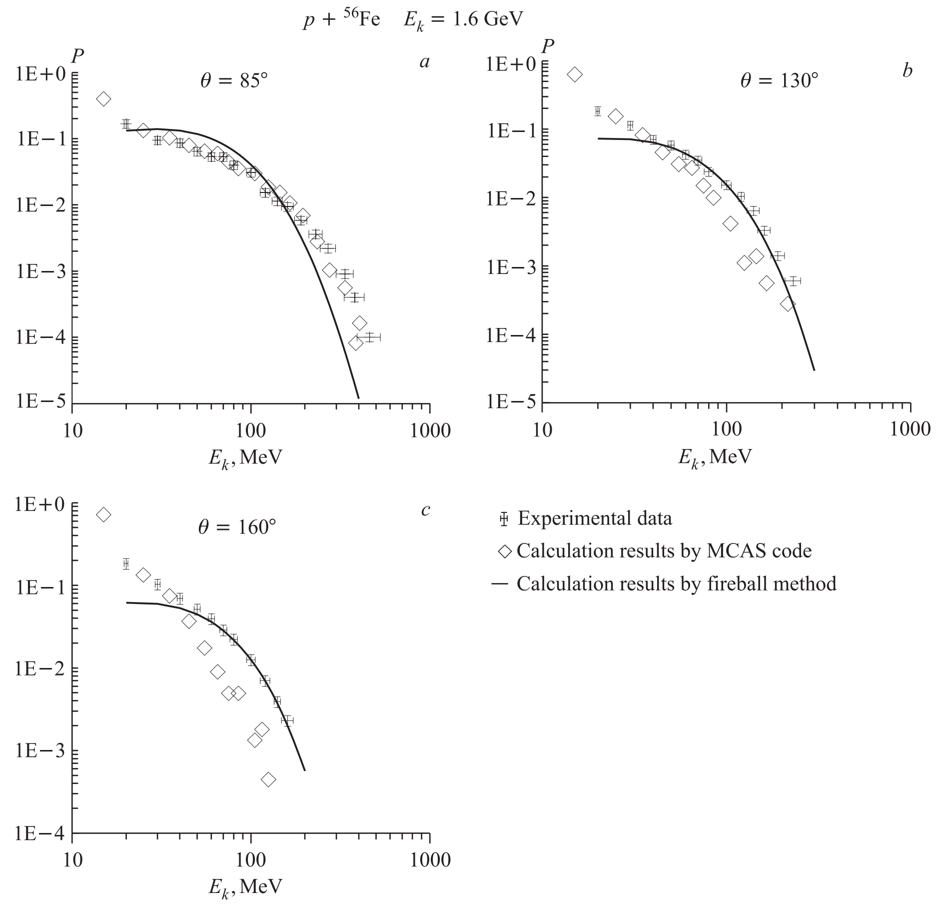

Fig. 9. The same as in Fig. 8 for the reaction $p + {}^{27}\mathrm{Al}$ (1.2 GeV)

typical Monte Carlo based model – the MCAS code [3] has been used. The analysis of the dependence of the probability of intranuclear reactions on impact parameter strongly suggests the idea that a dominant part of fast intranuclear collisions is concentrated in a tube-like region around the trajectory of a primary hadron broadening as the path of the hadron increases, thus supporting the well-known conception which forms the basis of the TF model [4]. Moreover, a comparison of both these models — MCAS and TF — with the experimental data seems to justify satisfactorily as well the second important assumption of the TF model that the hadronic system adiabatically amassed during the passage of the primary particle through the target-nucleus is thermalized at the temperature depending on impact parameter, and next, it decays isotropically in its center-of-mass system emitting pions owing to extra (i.e. above thermal in its center-of-mass system) and nucleons.

It should be emphasized that the TF model can be considerably improved by taking into account both elastic scatterings and excitation of target nuclei.

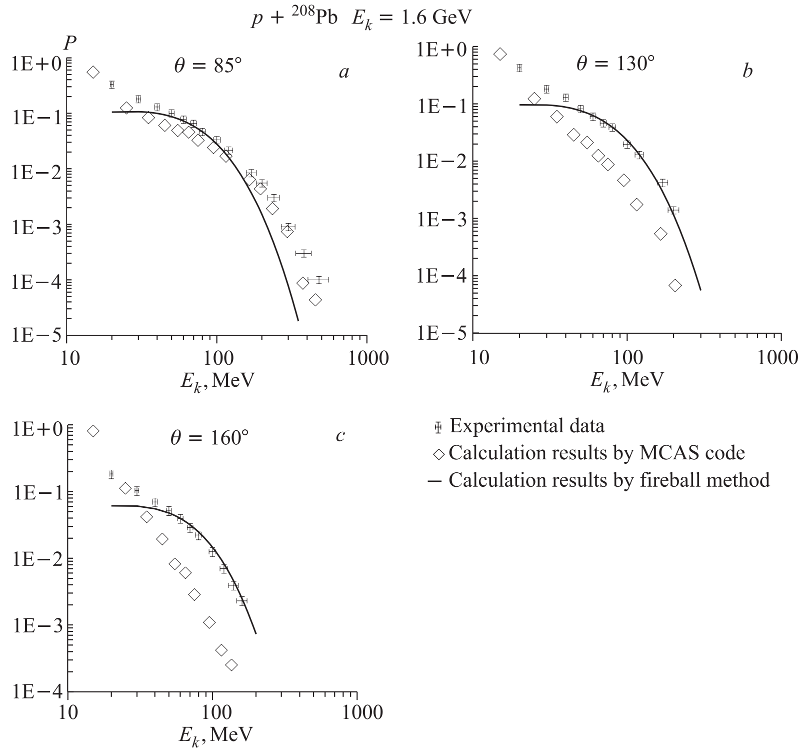

Fig. 10. The same as in Fig. 8 for the reaction $p + {}^{208}\mathrm{Pb}$ (1.2 GeV)

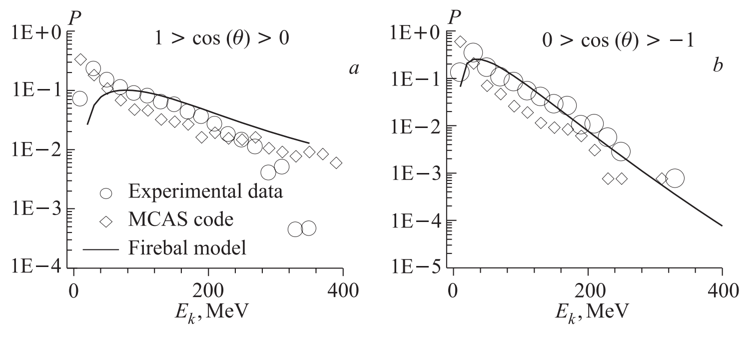

Fig. 11. The energy distribution of protons in the reaction ${}^{131}\mathrm{Xe}(\pi^-, p)$ emitted into the intervals of angles $1 > \cos(\theta) > 0$ (*a*) and $0 > \cos(\theta) > -1$ (*b*). The range of the energy of protons 10–350 MeV, the width of the energy channel 20 MeV. The solid line, ○, ◇ mean the results obtained by using the FM [4], experimental data [7] and the results calculated after the MCAS code [3]. P, E_k mean the probability and kinetic energy, respectively. The number of calculated events by MCAS code is equal to 6000

Finally, we can also conclude that even a simple formulation, as in the case of the TF model, of such a complex phenomenon as the intranuclear reaction initiated by relativistic hadrons, proved to be sufficiently adequate and practically useful having an advantage over numerical simulation codes for its predictability and permits the direct insight into the spatial structure and evolution of the process.

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