INTRANUCLEAR CASCADES EFFECTS ON THE COMPOSITION AND ENERGY OF Si(*p*,*x*) AND Fe(*p*,*x*) NUCLEAR REACTION PRODUCTS

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INTRODUCTION

The composition and energy spectrum of the products of a nuclear reaction carry information not only about the mechanism of the nuclear reaction, but also about the dynamics of the formation and decay of a compound excited nucleus. The mechanisms of nuclear reactions can be divided into direct processes (DP) and reactions with the formation and subsequent decay of an excited compound nucleus (CN). SPs proceed during the flight of a particle through the nucleus (~ 10^{-24}–10^{-22} s). CNs are formed in a time (t ~ 10^{-22}–10^{-21} s) and release their excitation by the emission of secondary particles for a relatively long time (up to t ~ 10^{-16} s, see Fig. 1).

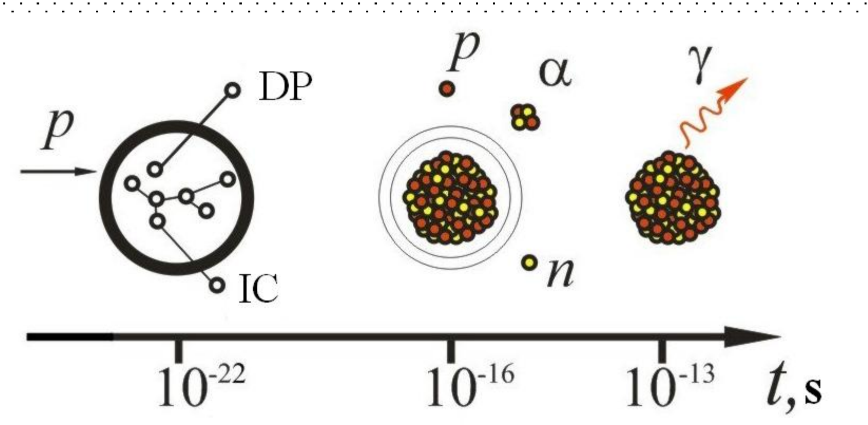

Fig: 1. The main stages of a nuclear reaction and their characteristic time: formation of a compound nucleus taking into account the mechanisms of direct processes (DP) and intranuclear cascades (IC); decay of a compound nucleus with emission or evaporation of light fragments and then with the formation of a residual nucleus and its relaxation with emission of γ-quanta.

In this work, we calculate the differential cross sections for elastic and inelastic interaction of a proton with an energy $E_0 \leq 10$ GeV with silicon and iron nuclei using several software packages: EMPIRE [1] and TALYS [2], in which intranuclear cascades (IC) are not considered, but also program codes GEANT4 [3], FLUKA [4], in which cascades are taken into account. This comparison makes it possible to study the effect of intranuclear cascades on the composition and average energy of reaction products as a result of inelastic collisions of fast protons with the nuclei of silicon Si(*p*,*x*) and iron Fe(*p*,*x*).

CALCULATION RESULTS

Table 1 - Results of calculations of the cross section of inelastic interaction in mb for the Fe(p, x) reaction. The error in theoretical sections is associated with the use of several calculation models.

Model	Program	E_0=0.3 GeV	E_0=0.5 GeV	E_0=0.75 GeV	E_0=1 GeV	E_0=1.5 GeV
DP	TALYS	728	735	687	632	
DP, IC	GEANT4	691 ± 3	729 ± 1	767 ± 1	797 ± 2	807 ± 3
Experiment [5]		701 ± 56	660 ± 53	767 ± 66	811 ± 76	822 ± 73

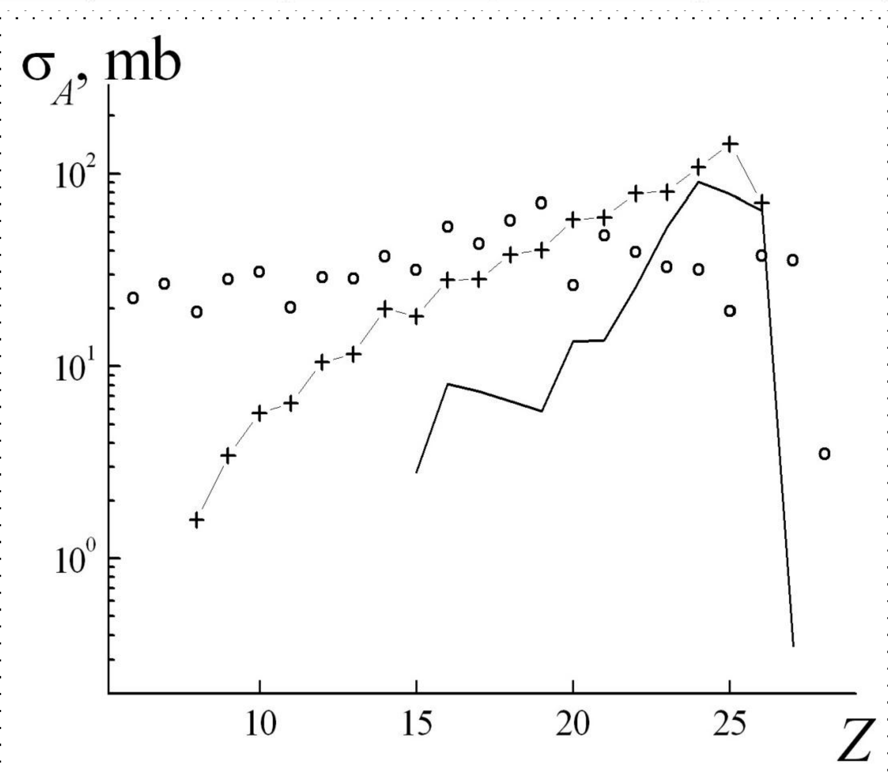

Fig: 2. The cross section for the production of residual nuclei in collisions of protons with E_0 = 1 GeV with an iron nucleus Fe(p,x). Calculation results: solid line - TALYS; circles - GEANT4. The experimental data [5] are shown with crosses.

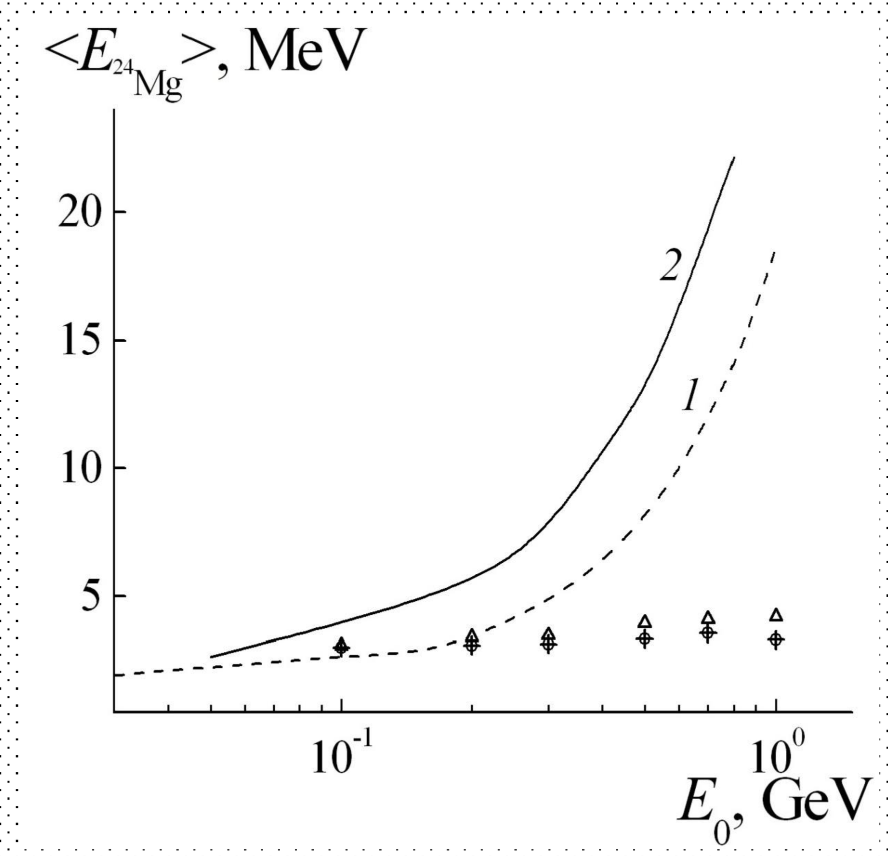

Fig. 3. Dependence of the average kinetic energy of the secondary ^{24}Mg nucleus on the energy E_0 proton in the reaction Si(p,x), calculated using the programs: *1* - TALYS, *2* - EMPIRE-2.18.
The symbols show the results of calculations using the GEANT4 program with various models:
(Δ) – QBBC, (o) – FTFP_BERT, (+) – QGSP_BERT.

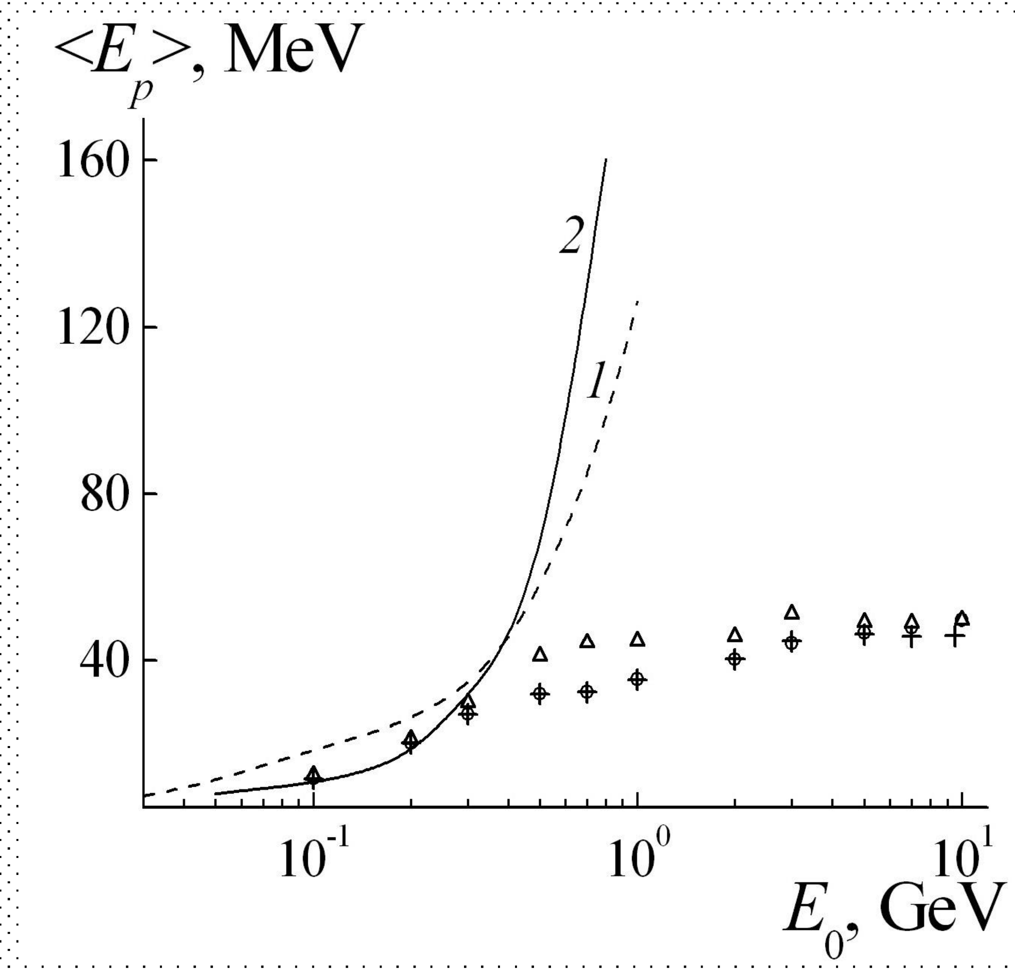

Fig. 4. Dependence of the average energy of secondary protons on the energy E_0 of the primary proton in the reaction Si(*p*,*x*), calculated by the programs: *1* – TALYS, *2* – EMPIRE-2.18.
Symbols show the results of calculations using the GEANT4 program with various models:
(Δ) – QBBC, (o) – FTFP_BERT, (+) – QGSP_BERT.

CONCLUSIONS

Quantum mechanical models and the Monte Carlo method are used to study the composition and energy of the products of nuclear reactions occurring in collisions of fast protons with silicon and iron nuclei.

The results of calculating the cross sections using the GEANT4 and FLUKA programs agree with the experimental data over the entire range of primary ion energies.

For fast protons E_0 > 0.5 GeV, the results of calculations using the EMPIRE and TALYS programs give an underestimated value of the inelastic cross section in relation to the experimental data.

At proton energies above 500 MeV, intranuclear cascades at the stage of formation of a compound nucleus in a pre-equilibrium state lead to an increase in the number of secondary ions and a decrease in their average energy, which is explained by the redistribution of the momentum transferred to nucleons in the nucleus in cascade collisions.

REFERENCES

[1] M. Herman, R. Capote, M. Sin, *et al.*, EMPIRE-3.2 Malta. http://www-nds.iaea.org/empire.

[2] A. Koning, S. Hilaire, S. Goriely, TALYS-1.9 (2017). http://www.talys.eu

[3] J. Allison,, *et al.*, NIM A., **835**, 186 (2016). https://geant4.web.cern.ch

[4] T.T. Böhlen *et al.*, Nuclear Data Sheets, **120**, 211 (2014). www.fluka.org/fluka.php

[5] C. Villagrasa, A. Boudard, J.-E. Ducret, *et all*, Phys. Rev. C **75**, 044603 (2007).