# Development of dynamic model for simulation of nuclear spallation.

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# Motivation

- The UrQMD is one of actively used model to simulate nucleon-nucleus and nucleus-nucleus collisions at high energies.
- The model’s shortcoming is absence of a residual nucleus and the products of its fragmentation.
- Intranuclear Cascade Model (INC) can describe nuclear spallation and in modified version – multifragmentation.
- Idea: using INC as a guide to try to modify UrQMD for description of spallation and multifragmentation channels.

# Intra nuclear Cascade

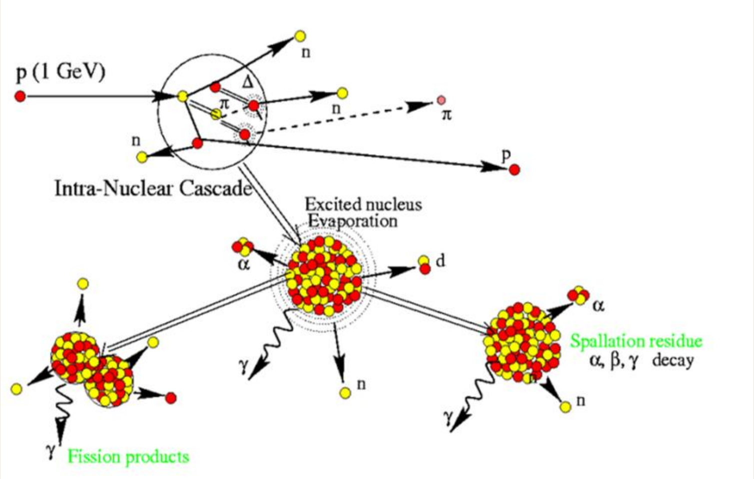
**Fast Direct Process**

• In the first, fast, stage, an intranuclear cascade occurs inside the target and (or) the projectile nuclei and some nucleons from the target and projectile nuclei are knocked out, together with mesons production.

**Excited state**

In the second stage, residual nuclei divide into two remnants in the fission channel or evaporate protons, neutrons, and (or) light nuclei, including helium isotopes.

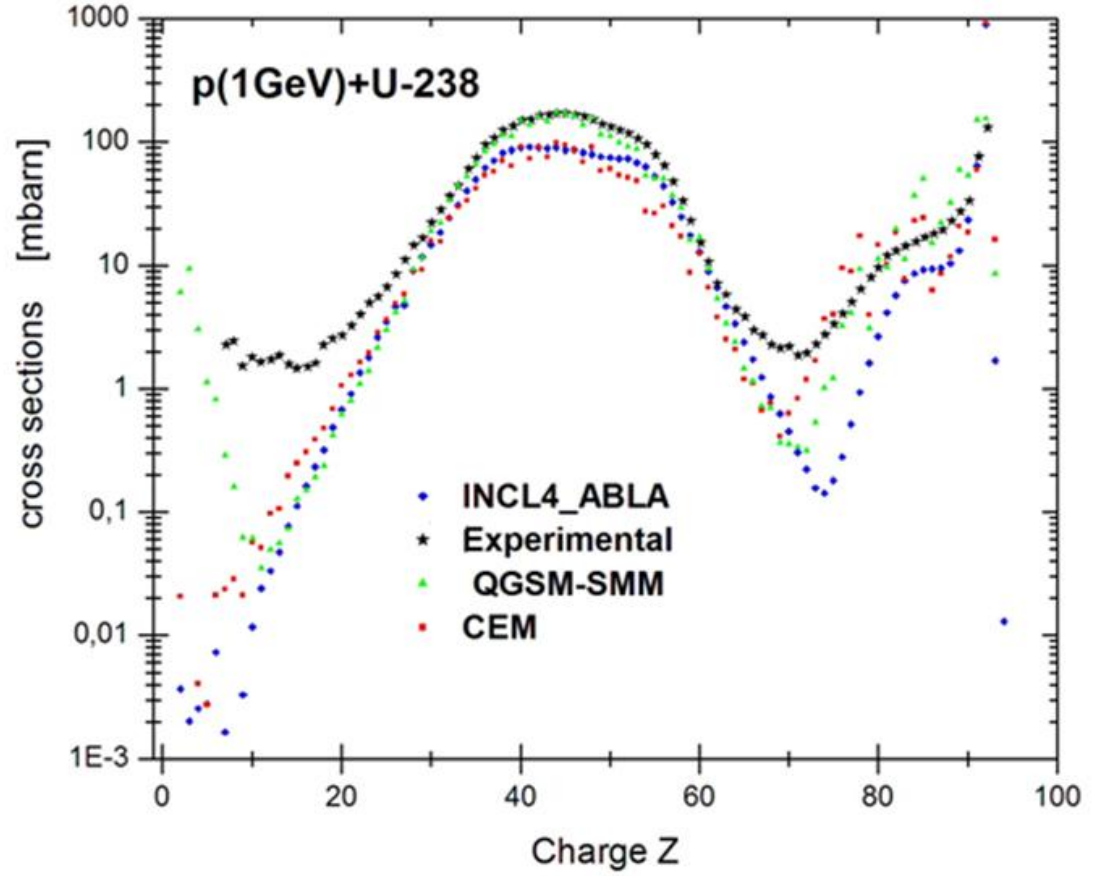
**Preequilibrium**




Codes for direct process:
(Dubna Intranuclear Cascade Model,Bertini Model,INCL, Cascade-Exciton Model,Isabel

Codes for statistical decay: EVAPOR, GEM2, ABLA, Dresner,Gemini,SMM

# Distribution of fragments
# Cascade-evaporation model



# Multifragmentation of Nuclei

However, experimental data indicate that,
at high energies, a third competing process,
multifragmentation, comes into play, in which
excited remnants break up into intermediate
mass fragments (IMFs).
There are two approaches to theoretical
description of multifragmentation:

- dynamical
- statistical.

# Describing of the process of multifragmentation by percolation models.

- Percolation models treat the nucleus as a lattice with nucleons located at nodes of the lattice.
- The face-centered-cubic (FCC) lattice reproduces the experimental distributions of fragment masses and their energy spectra.
- Modified Dubna Cascade Model -The process of nuclear multifragmentation has been implemented, together with evaporation and fission channels of the disintegration of excited remnants using percolation theory.

# QMD and UrQMD

In the QMD model each nucleon (or quasi-particle) is assumed to be a constant width minimal wave packet (coherent state):

$$\psi_i(\vec{r},t) = \frac{1}{(2\pi L)^{3/4}} e^{-\frac{(\vec{r}-\vec{r}_{\circ i}(t))^2}{4L}} e^{-\frac{i}{\hbar}\vec{p}_{\circ i}(t)\vec{r}}$$

where $\vec{r}_0 i$ and $\vec{p}_0 i$ are the mean position and momentum of the nucleon $i$ and the width of the wave packet is characterized by parameter $L$. The $N$-body "wave function", $\psi_N$, describing the entire nucleus is taken to be a direct product of single particle states $\psi_i$.

The one-body densities in coordinate and momentum space look like:

$$\rho(\vec{r}) = \int f(\vec{r},\vec{p})d^3p = \frac{1}{(2\pi L)^{3/2}} \sum_{i=1}^{N} e^{-\frac{1}{2L}(\vec{r}-\vec{r}_{\circ i})^2}$$

$$g(\vec{p}) = \int f(\vec{r},\vec{p})d^3r = \left(\frac{2L}{\pi\hbar^2}\right)^{3/2} \sum_{i=1}^{N} e^{-\frac{2L}{\hbar^2}(\vec{p}-\vec{p}_{\circ i})^2}$$

The total *N*-body Hamiltonian has the form:

$$H = \sum_{i=1}^{N} \frac{p_{\circ i}^2}{2m} + U_N + U_P + U_C$$

where $U_N$ is the nuclear potential energy, $U_P$ is the total energy arising from the "Pauli interaction", and $U_C$ -- the Coulomb energy of the system.

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The Skyrme parametrization of the nuclear potential energy density takes the form:

$$U^{loc}(\rho) = \alpha(\frac{\rho}{\rho_0}) + \beta(\frac{\rho}{\rho_0})^{\gamma}$$

The time evolution of the centroids of the Gaussian wave packets is described by two processes: the propagation due to classical equation of motion and the stochastic short range two body scattering.The equations of motion

$$\begin{cases} \dot{\vec{r}}_{0i} = \frac{\vec{p}_{0i}}{m} + \vec{\nabla}_{p_{0i}} U \\ \dot{\vec{p}}_{0i} = -\vec{\nabla}_{r_{0i}} U \end{cases} \qquad i = 1, \ldots, A_P + A_T$$

are solved numerically. During the evolution any two nucleons become candidates for scattering if their spatial distance is less than the distance etermined by the N-N cross section

$$r_{ij} < \sqrt{\sigma_{NN}/\pi}$$

# High Energies - UrQMD

- The UrQMD approach includes:
- consideration of cross-section of various meson-meson, meson-baryon,
- and baryon baryon interactions.
- It considers QQ string creation a la FRITTOF model at P > *3 GeV/c*.
- It also considers string fragmentation and formation time of particles.
- At lower energies, P < 3 GeV/c there are reaction channels:

$$N + N \to \Delta N, \Delta\Delta, N^* N, etc., \quad M + N \to \Delta^0, \Lambda, \ldots$$

- The potential interactions are supposed between the particles, especially, Yukawa, Coulumb, Pauli potentials.

# UrQMD
# The total baryon-baryon cross-section

- The total baryon-baryon cross-section of the reaction A + *C* = *D* + E has the following general form:

$$\sigma_{tot}^{BB} \propto (2S_d + 1)(2S_E + 1)\frac{\langle p_{D,E}\rangle}{\langle p_{A,C}\rangle}\frac{1}{s}|M|^2,$$

- with the spins of the particles, S, momenta of the pairs of particles, p in the two particle rest frame, and the matrix element M.

- At high energies, two quark strings are produced in the hadron interaction with target nucleon.
- The first fast string can collide with other target nucleon or emit a meson(s), before the collision with the second nucleon of the target.
- The second string, slow in the Lab. system, decays in the nucleus and its products interact with the nuclear nucleons.

# The total meson-meson reaction cross-sections

To describe the total meson-meson reaction cross-sections, the additive quark model (AQM) and the principle of detailed balance are used. That assumes the reversibility of the particles interactions.

To model meson-meson interactions above the resonance region, one applies the rescaled total proton-meson cross section:

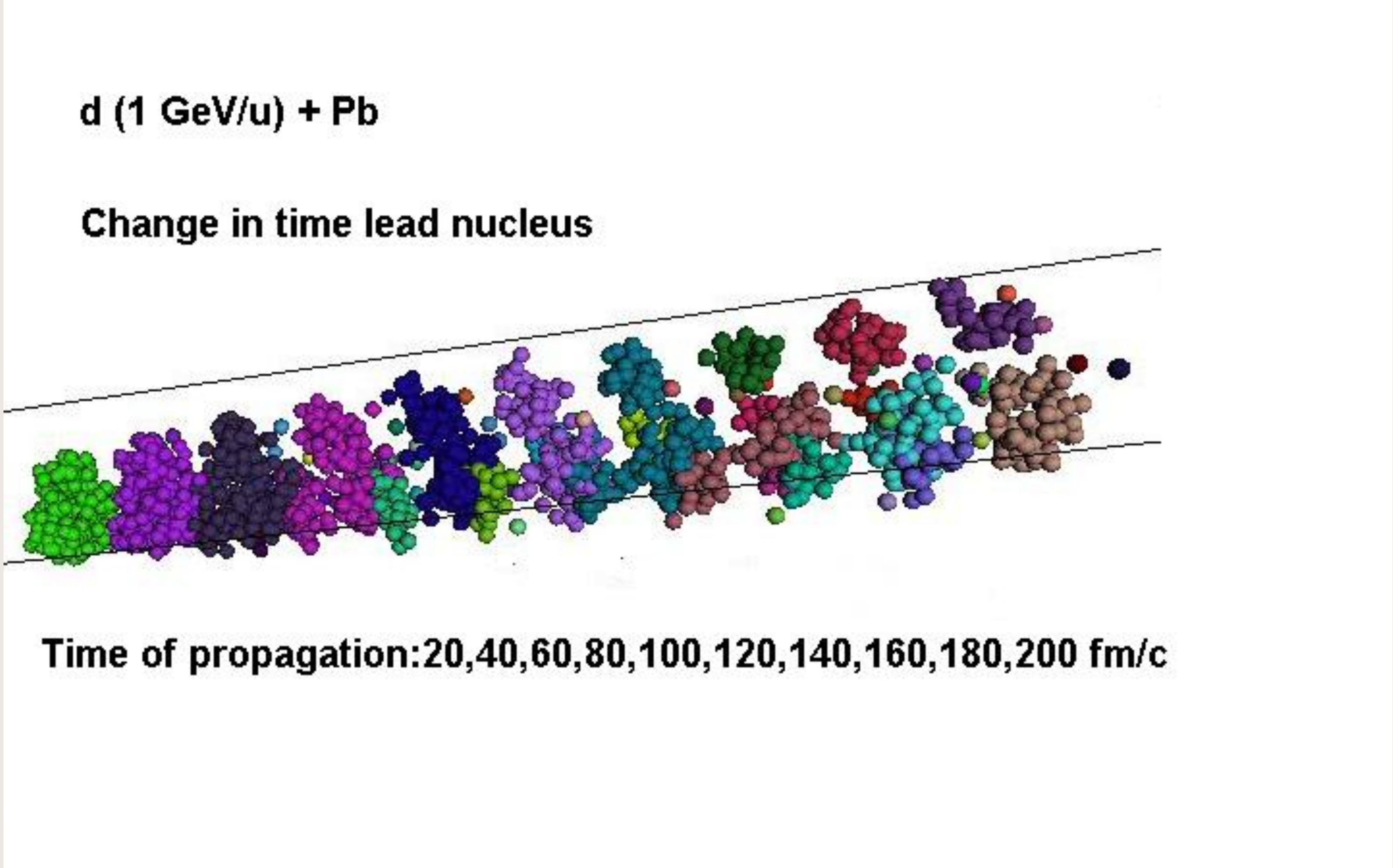
$$\sigma_{tot}^{MM}(\sqrt{s} > 1.7GeV) = \sigma_{tot}^{\pi p}(\sqrt{s})\frac{\sigma_{AQM}^{MM}}{\sigma_{AQM}^{\pi p}}.$$

If we look at the cascade model it only considered the reactions

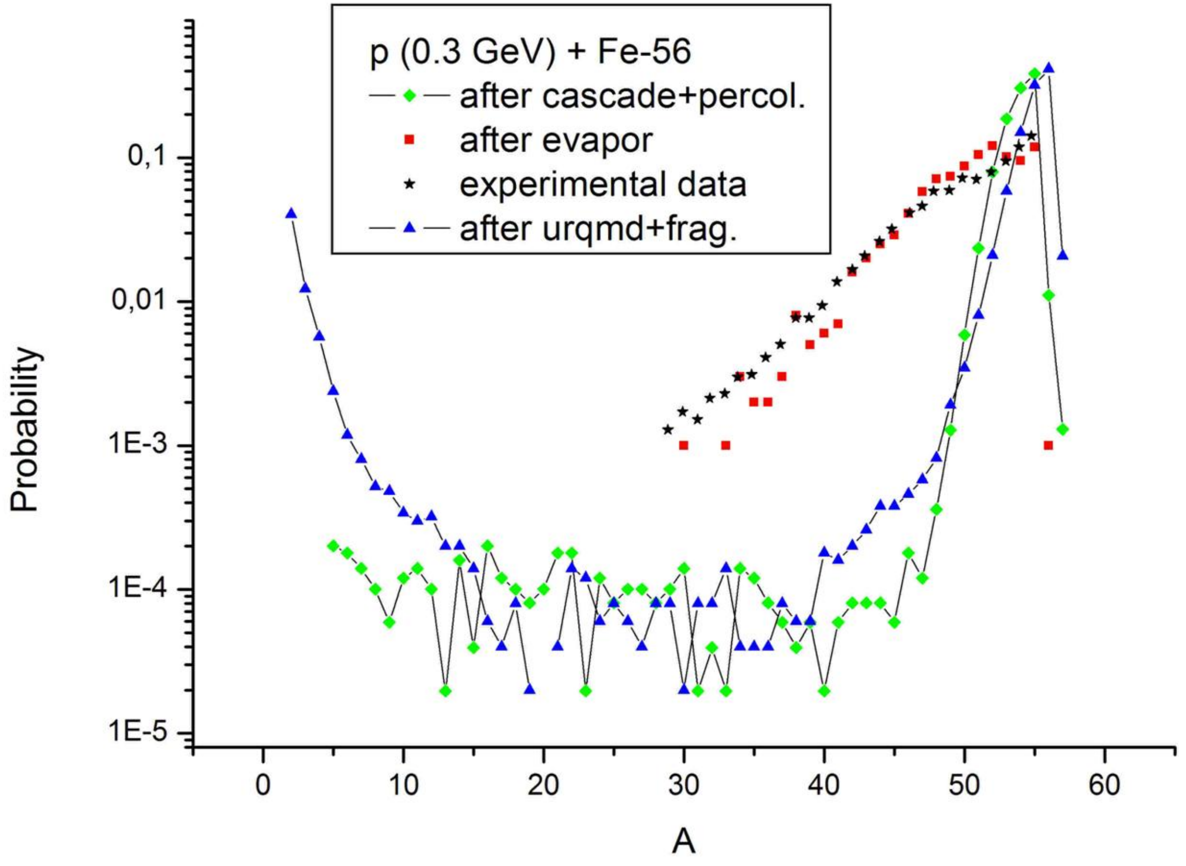
$$NN \to NN + m\pi, \pi N \to \pi N, \pi N \to N + m\pi, \pi + (NN) \to NN.$$

# Dynamical model.

Fragments are formed at the fast stage of nuclear collision via dynamical forces between nucleons during the evolution of the total system.



# Mass distribution of residues



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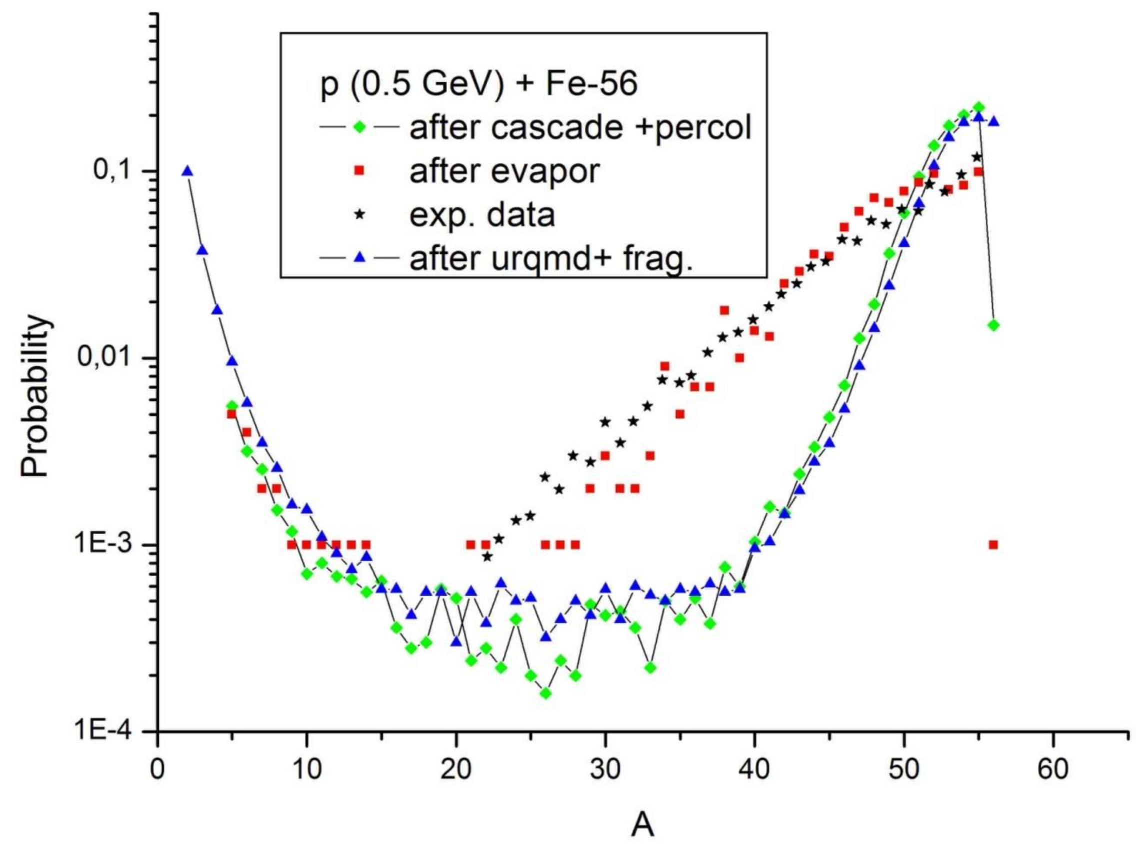

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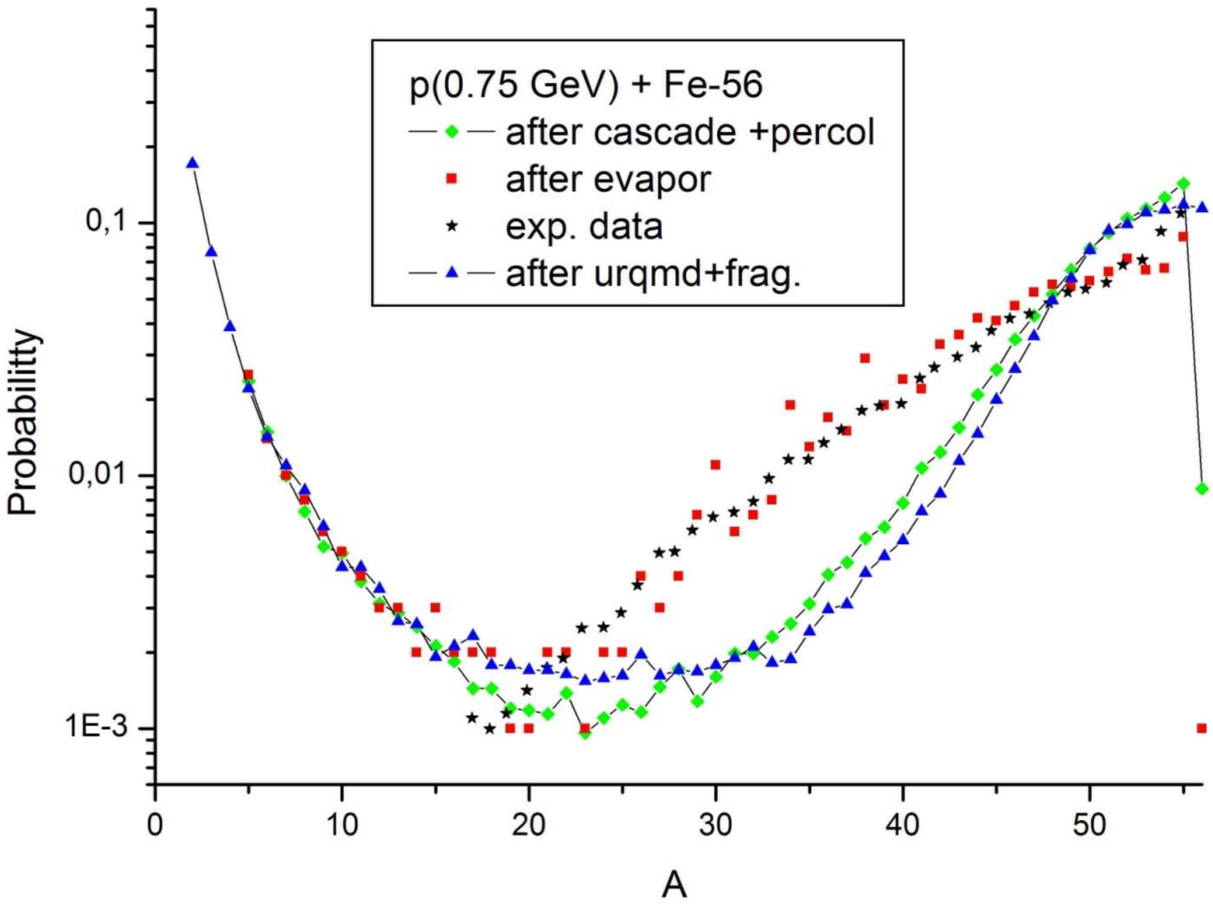
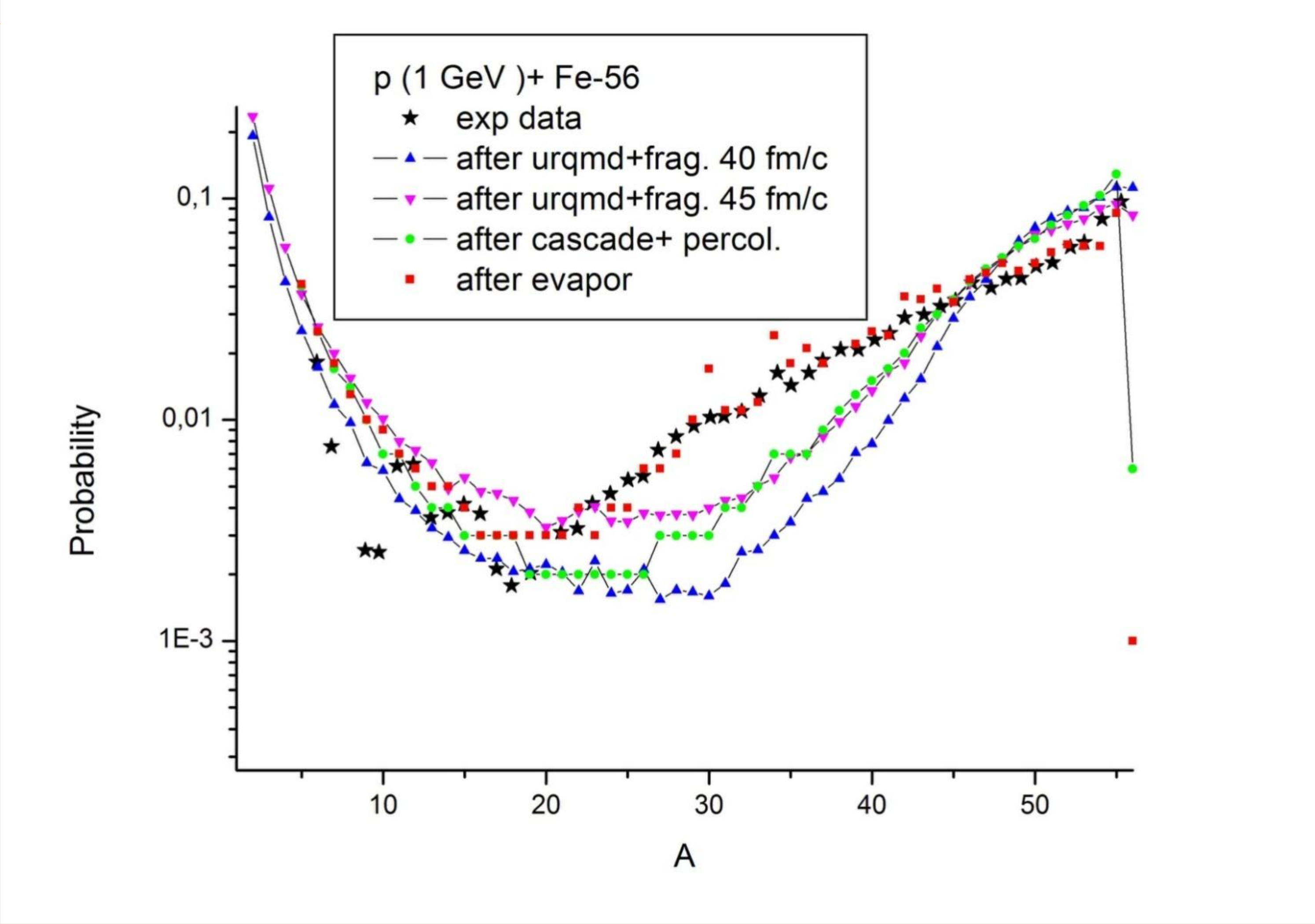
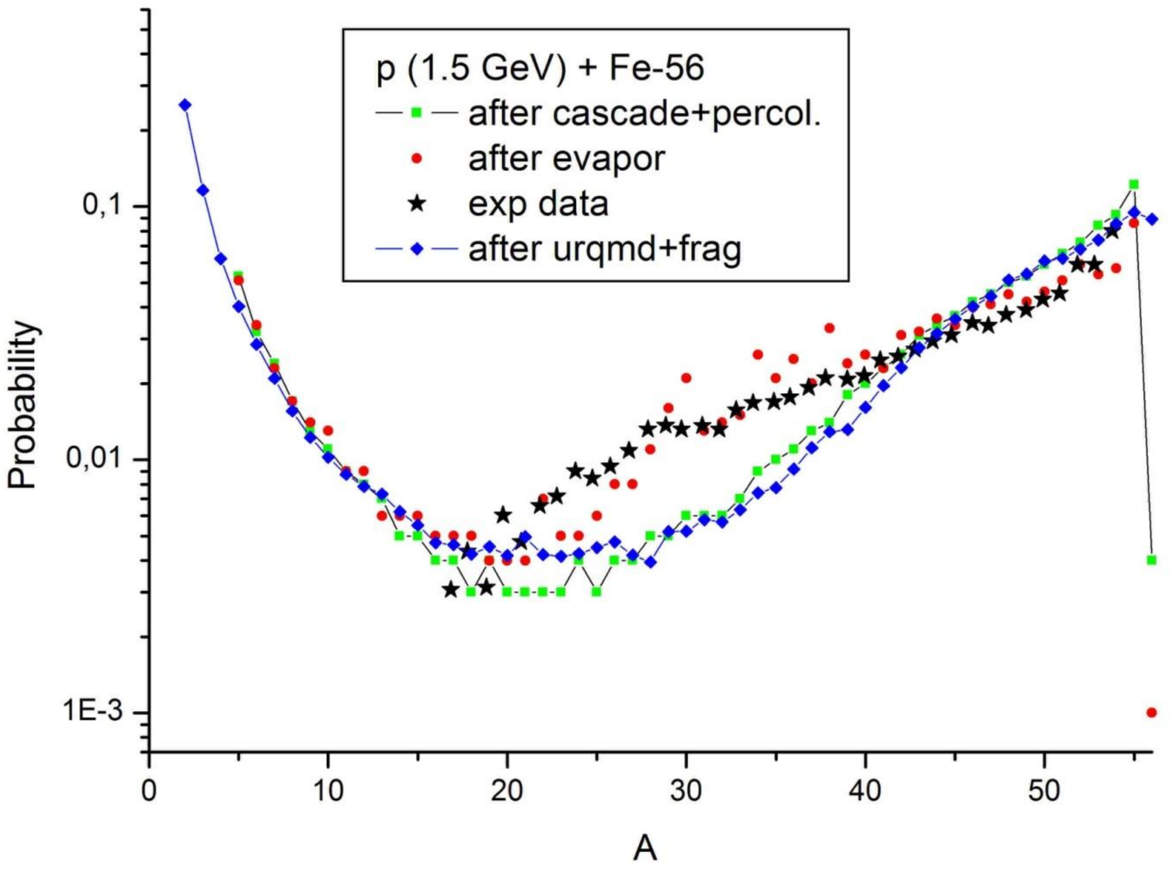


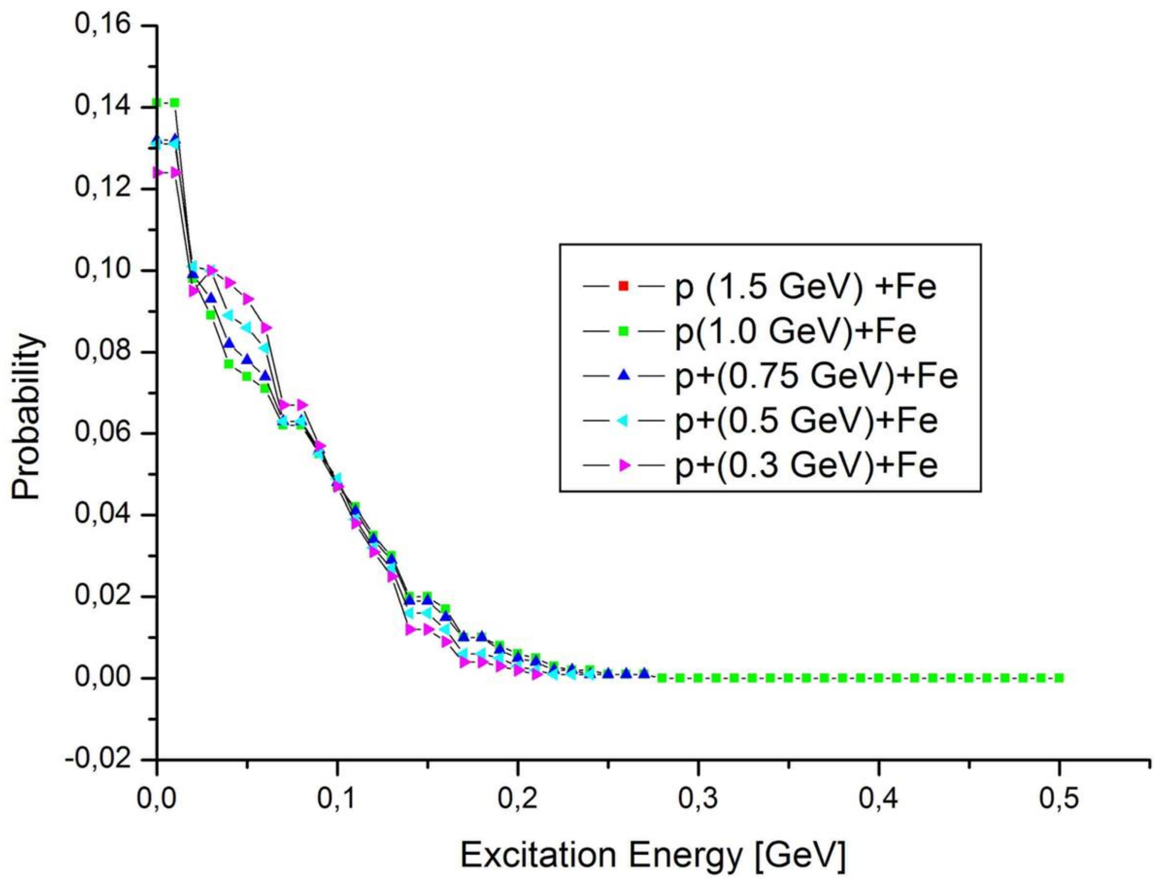
# Mass distribution of fragments in the reaction p + Fe-56 at 1 GeV.



# Mass distribution of residues



# Exitation Energy from INC Model



# Conclusion.

- Dynamical models can be useful for calculations of fragments production.
- The UrQMD model can be modified for description of fragments in nuclear interactions by including dynamical formation of clusters and decay of them.