Transport Description of Heavy Ion Fragmentation Reactions at Energies of 35-140 MeV

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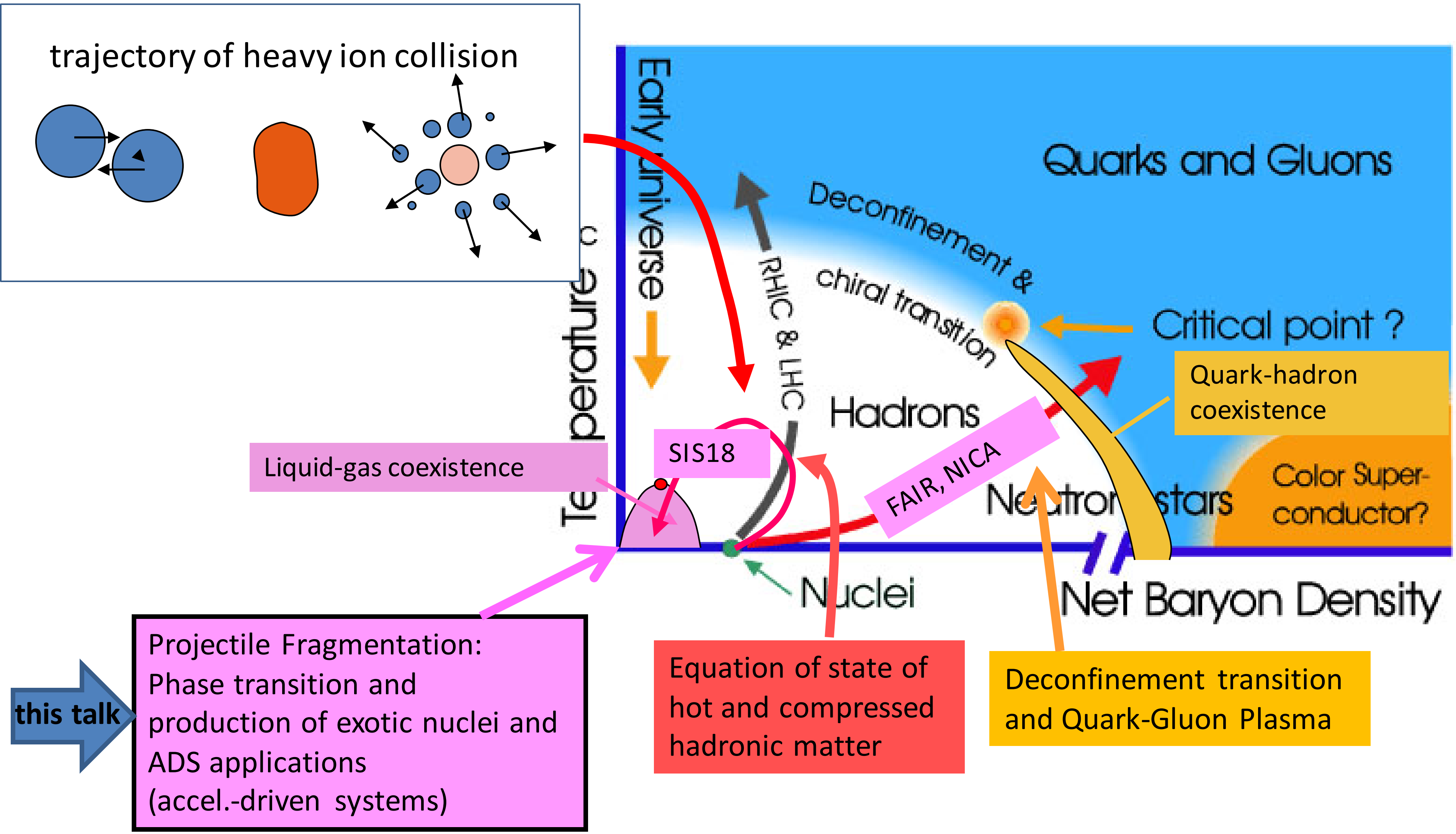
Outline

- **Motivation of the research**
- **Transport calculations of nuclear reactions at energies from the Fermi energy (~35 MeV) to a few 100 MeV per nucleon**
- **Fragmentation of projectile residues. De-excitation of excited residue by statistical evaporation (with consistent calculation of ground state energies of nuclei)**
- **Isotope and velocity distributions for different combinations of nuclei at different energies**
- **Conclusion**

Motivation: Exploration of the Phases of Strongly Interacting Matter



Note: Heavy ion collisions are non-equilibrium processes
→ transport theory is necessary

Transport theory: Boltzmann-Nordheim-Vlasov (BNV) approach

time evolution of the one-body phase space density: f(r,p;t)

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\vec{\nabla} f - \vec{\nabla} U \vec{\nabla}_p f = I_{coll}[f,\sigma]$$

$$I_{coll}[f_1,\sigma] = \frac{g}{h}\int dr^3 p_2 dr^3 p_3 dr^3 p_4 W(12,34)\left[\bar{f}_1 \bar{f}_2 f_3 f_4 - f_1 f_2 \bar{f}_3 \bar{f}_4\right]$$

$$W(12,34) = \sigma(12,34)\,\delta(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\,\delta(\varepsilon_1+\varepsilon_2-\varepsilon_3-\varepsilon_4)$$

Pauli blocking factors for final state $(1-f(r,v_i;t)) \equiv (1-f_i) := \bar{f}_i$

Physical input: mean field potential U (→equation of state) and in-medium elastic cross section σ

Partial integro-differential equation for f(r,p;t) solved by simulation with the test particle method:
N finite element test particles (TP) per nucleon

$$f(\vec{r},\vec{p},t) = \frac{1}{NA}\sum_i \delta(\vec{r}-\vec{r}_i(t))\,\delta(\vec{p}-\vec{p}_i(t))$$

$$\rho(r;t) = \int d\vec{p}\; f(\vec{r},\vec{p};t)$$

Equations of motion of TP (Hamiltonian):

$$\frac{\vec{p}_i(t)}{\partial t} = -\vec{\nabla}_r U(r_i,t) \qquad \frac{\vec{r}_i(t)}{t} = \frac{\vec{p}_i(t)}{M}$$

$$\vec{p}_i(t+\tfrac{1}{2}\Delta t) = \vec{p}_i(t) - \tfrac{1}{2}\Delta t\,\vec{\nabla}_r U(r_i,t)$$

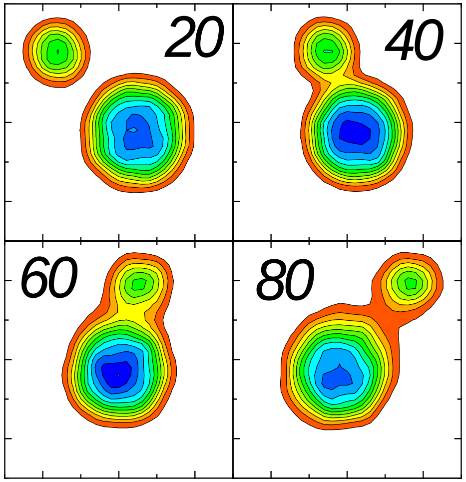
$$\vec{r}_i(t+\Delta t) = \vec{r}_i(t) + \Delta t\;\vec{p}_i(t+\tfrac{1}{2}\Delta t)/M$$

Collision term: stochastic simulation

1. Select in each time step δt TP with distance $d \le \sqrt{\sigma/\pi}$
2. Collide with probability $P=\sigma_{el}/\sigma_{max}$ with random direction
3. Check Pauli blocking of final state in phase space

Computationally most expensive part of calculation

Density contour plots Ar(57*A* MeV)+Ta at four different times



Identify final fragments by coalescence method
Here: Cut-off criterion in density $(\rho(r;t_{freeze\text{-}out})<0.17\ \rho_0)$
Primary fragments are still **excited!**

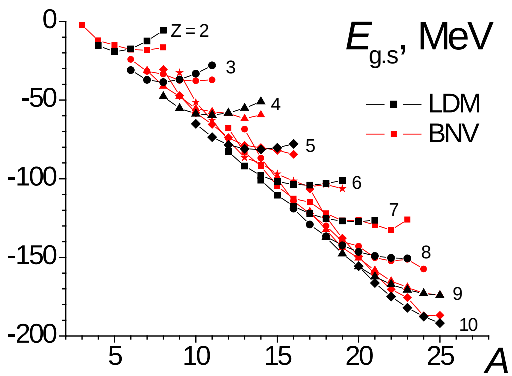
F. Bertsch, S. Das Gupta , , Phys. Rep. **160** (1988) 189
V. Baran, M. Colonna, M. Di Toro, Phys. Rep., **410** (2005) 335

Fragment identification and de-excitation

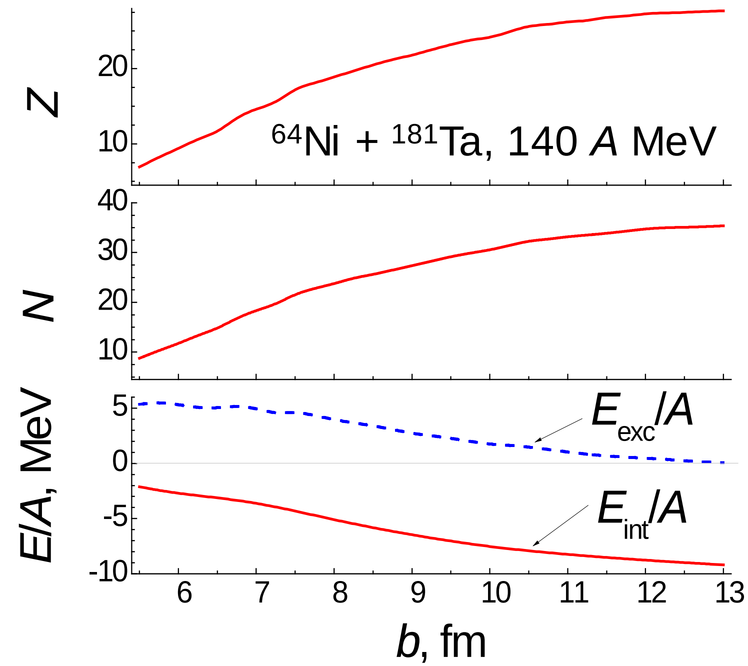
Calculation of the energy of a nucleus or fragment with the same density functional U(r) as used in the transport equation $E = \sum_{(TP)} t_i + \frac{1}{2}\int d\vec{r}\,\rho(r)U(\rho)$

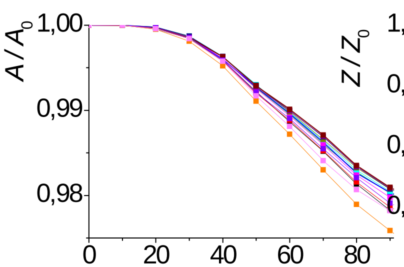
Excitation energy of primary) fragment $E_{exc} = E_{frag}(A,Z) - E_{g.s}(A,Z)$ at freeze-out time

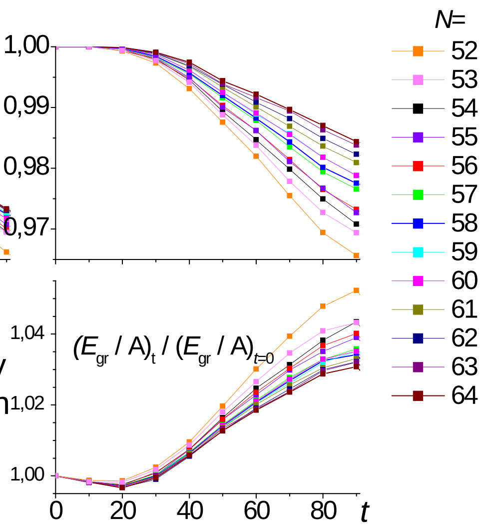
Comparison of the ground state energies calculated with transport approach with LD formula



Average charge, mass and excitation energy of primary fragments as function of impact parameter b





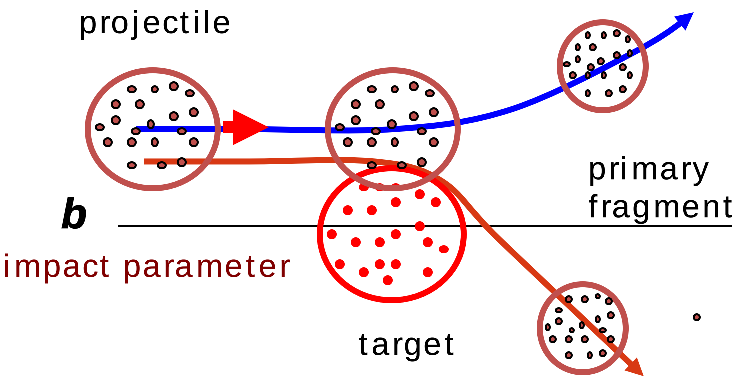


Loss of particles and energy with time in free propagation due to spurious TP evaporation for ^{52}Ni – ^{64}Ni

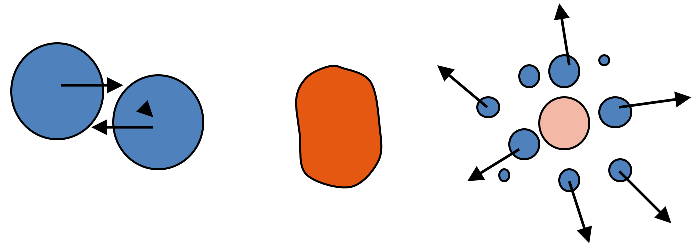
Calculating cold evaporation residues:
SMM code, P. Bondorf, et al.,Phys. Rep. 257, 133 (1995)
Input parameters: A_{fr}, Z_{fr}, E_{exc} from BNV calculation

Evolution of type of reaction with incident energy

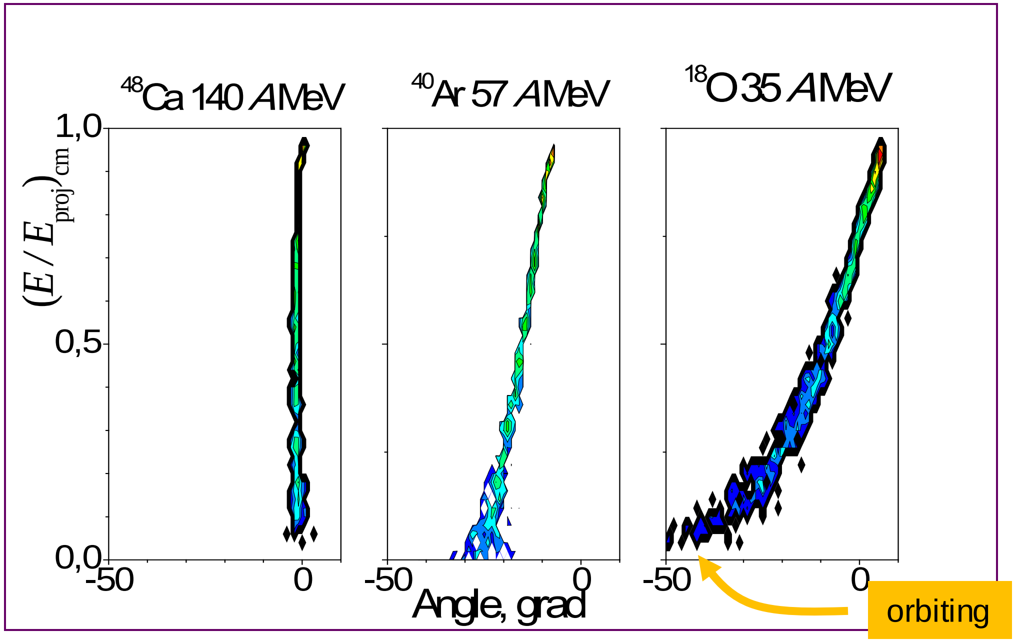
Lower energy E_{inc}~30-50 AMeV:
deep inelastic, friction like



Higher energy E_{inc}>60 AMeV:
fragmentation, abrasion like

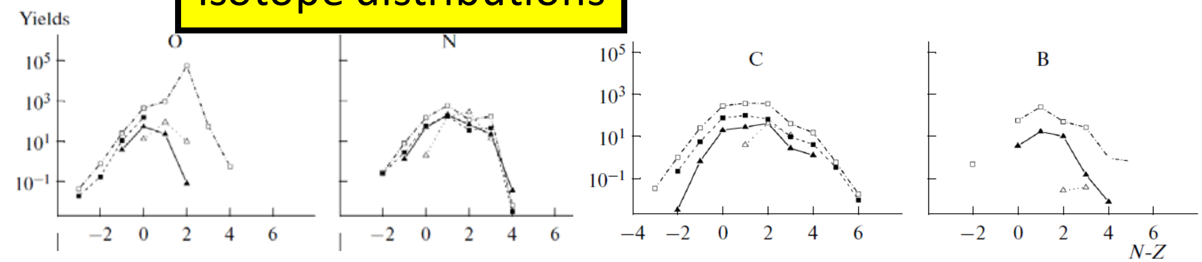


Can be seen in „Wilczynski plot“: Energy loss vs. deflection angle

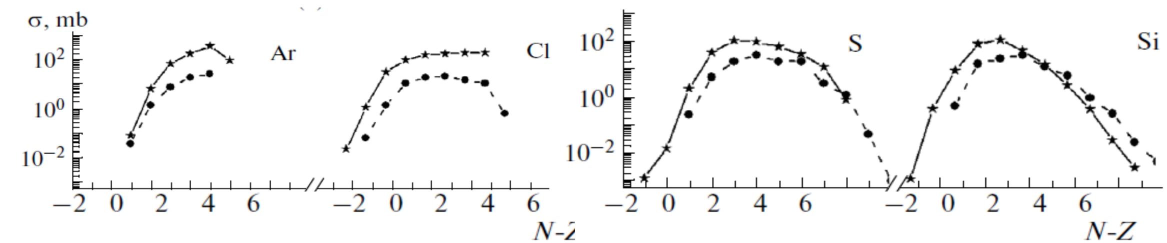


Isotope distributions

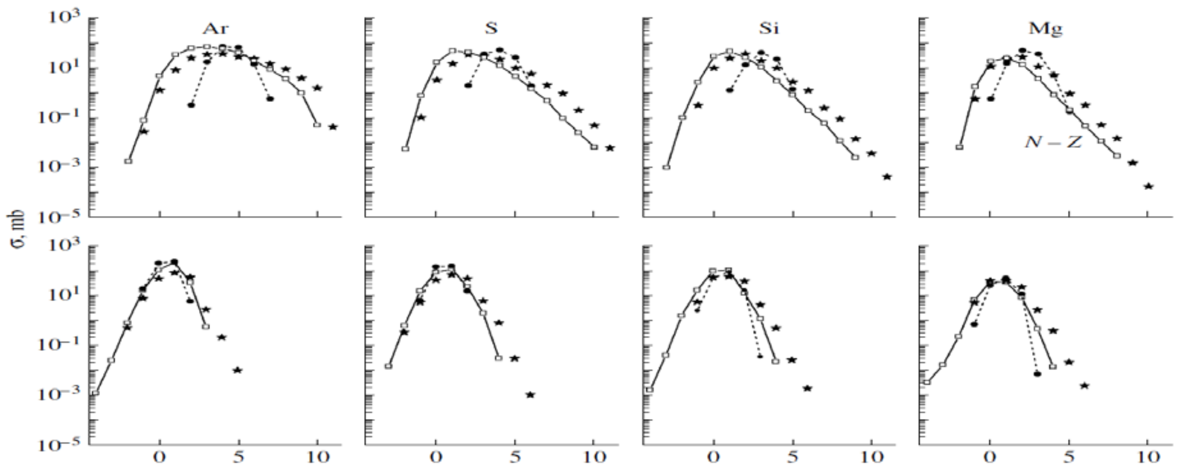
18O+181Ta, 35 AMeV
exp(full)-open square
(A.G.Arthuk, et al., NPA 701(2002) 96c)
exp(diss)-full square
BNV,hot-open triangle
SMM,cold-full triangle
T.I.M, et al. PHPL 12 (2015)409



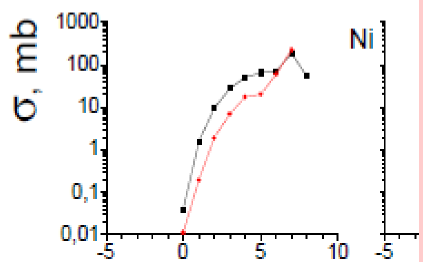
40Ar+181Ta, 57 AMeV
exp-solid circ
(X. H. Zhang, *et al.*, PRC 85, 024621 (2012)) ,
SMM,cold-stars,
T.I.M, et al., BRAS 78(2014)1131



48,40Ca+181Ta, 140 AMeV
exp-stars (M. Mocko *et al.* PRC **74**, 054612 (2006))),
BNV, hot-solid circ
SMM, cold-open squares
T.I.M,et al.,PHAN 79(2016)604



64Ni+181Ta, 140 AMeV
exp-red (M. Mocko *et al.*, Phys. Rev. C **74**, 054612 (2006)),
SMM,cold-black
(this work)



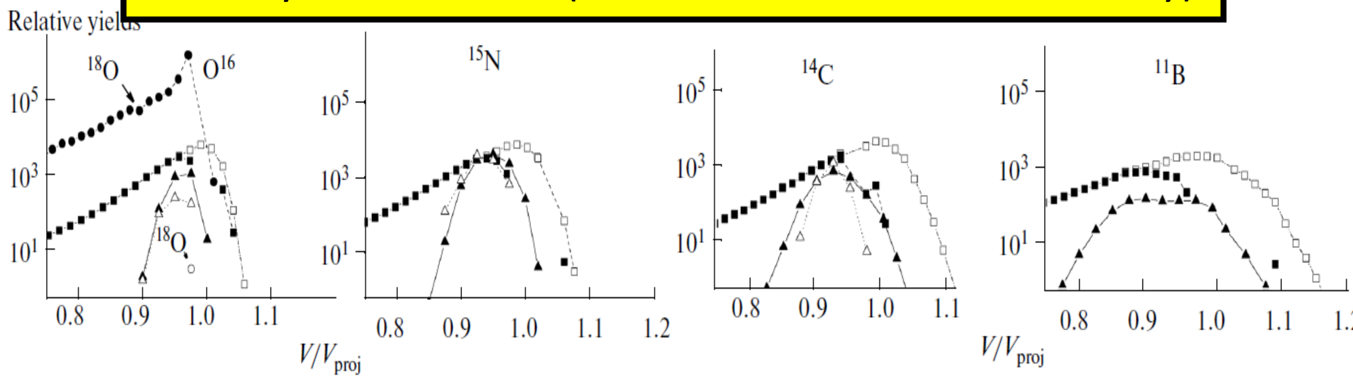
N - Z

- secondary evaporation shifts the distributions towards lower mass and widens it (large shift for 48Ca because of large neutron excess

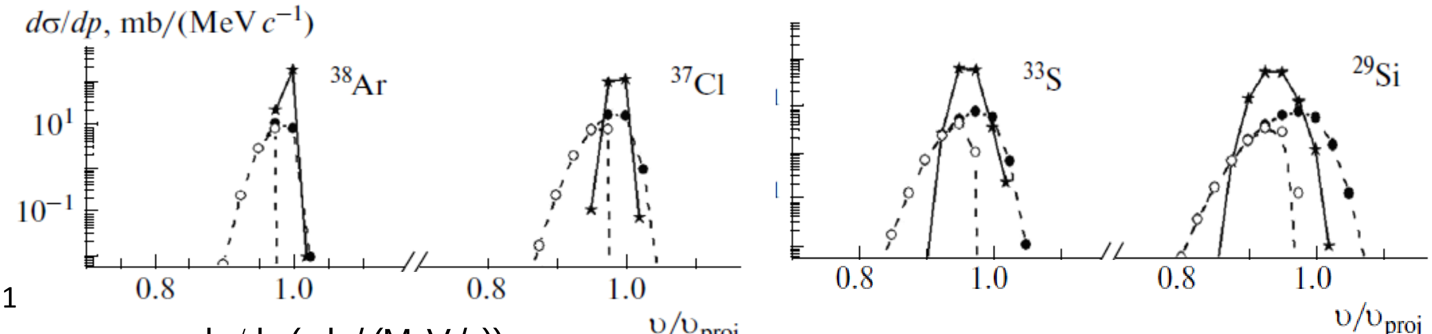
- reasonable agreement with the data, but somewhat shifted to smaller neutron excess (probably due to spontaneous emission of neutrons).

Velocity distributions (normalized to incident velocity)

18O+181Ta, 35 AMeV
exp(full)-open square
(A.G.Arthuk, et al., NPA 701(2002) 96c)
exp(diss)-full square
BNV,hot-open triangle
SMM,cold-full triangle
T.I.M, et al. PHPL 12 (2015)409



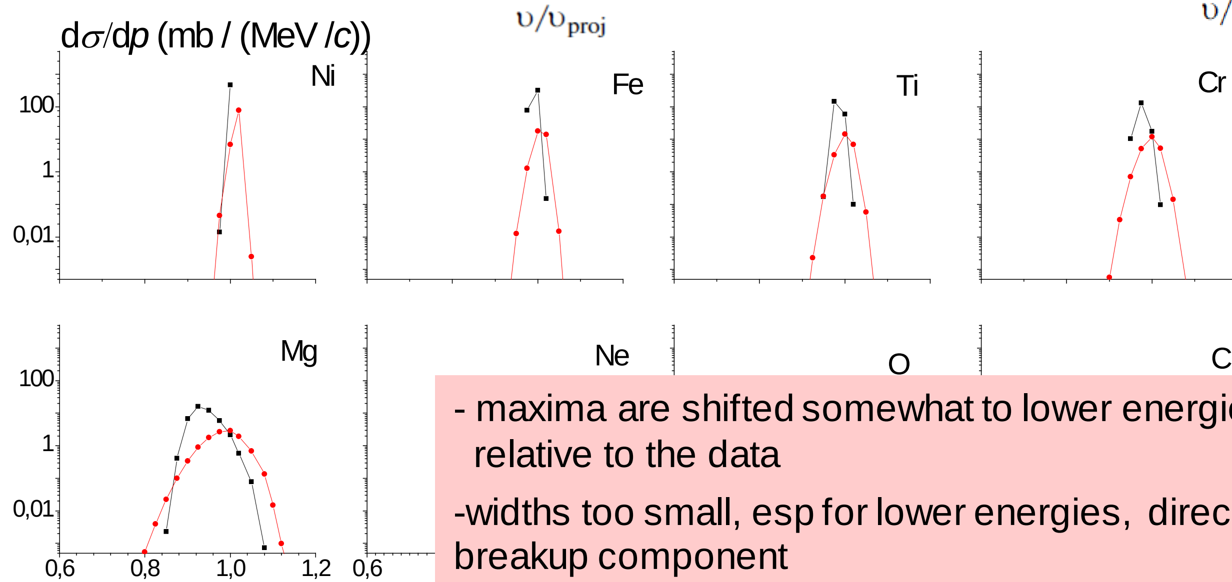
40Ar+181Ta, 57 AMeV
exp(full)-solid circles
(X. H. Zhang, *et al.*, PRC 85, 024621 (2012)),
exp(diss)-open circles
SMM,cold-stars,
T.I.M, et al., BRAS 78(2014)1131



^{64}Ni+181Ta, 140 AMeV
exp-red (M. Mocko *et al.*, PRC **74**, 054612 (2006)),
SMM,cold-black
(this work)

elements near proj (upper)

lighter elements (lower)



- maxima are shifted somewhat to lower energies relative to the data
- widths too small, esp for lower energies, direct breakup component
- probably not enough fluctuation?

Results

- The transport approach was applied for modeling and studying projectile fragmentation at Fermi energies. It allows us to predict the hot fragments produced in the reaction.

- A method of calculation of excitation energy of hot fragments was developed. We use SMM statistical evaporation code to calculate the final cold fragment production in the collision.

- Out model was used to describe available experimental data. It shows that due to particle evaporation the calculated isotope distributions are shifted slightly to lower masses in comparison to experiment. The calculated velocity distributions at energies in the range 35—60 *A* MeV only describe the dissipative part, at higher energies the coincidence of calculated velocity distributions with the experimental one is much better.

- The width of both isotope and velocity distributions produced in our calculations are lower than those obtained from experimental data. This is probably due to too small fluctuations in the approach.

Thank you for attention