Characteristics of Heavy-Ion Fragmentation Reactions at Fermi Energies

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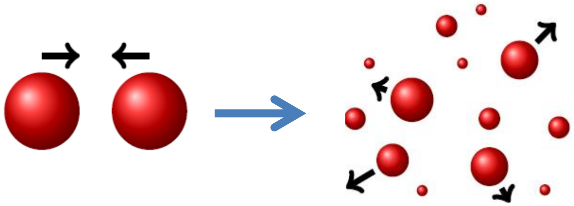
Outline

- Motivation
- Transport approach
- Remarks on solution of transport equation
- Primary (hot) and final (cold) fragments,
  evaluation of excitation energy
- Comparison with experimental data
- Conclusion

Nucleus-2021, 22/09/2021

Fragment production in heavy ion collisions



large part of final state in clusters and fragments.

Production mechanism of interest,
also for applications

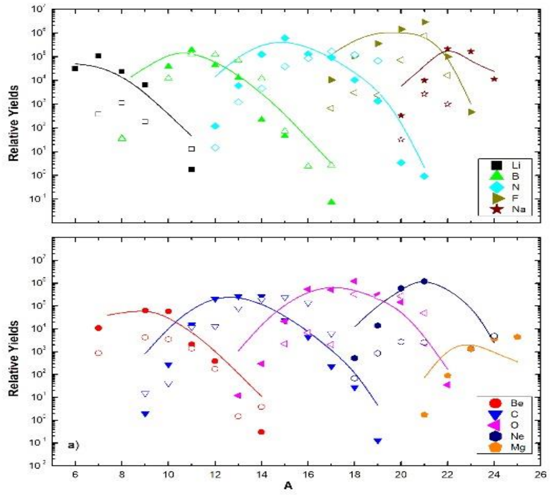
Partitioning of protons

	Xe + Sn 50 MeV/u	Au + Au 250 MeV/u
p	≈10%	21%
α	≈20%	20%
d, t, ^{3}He	≈10%	40%
$A > 4$	≈60%	18%

INDRA data, Hudan et al., PRC67 (2003) 064613.

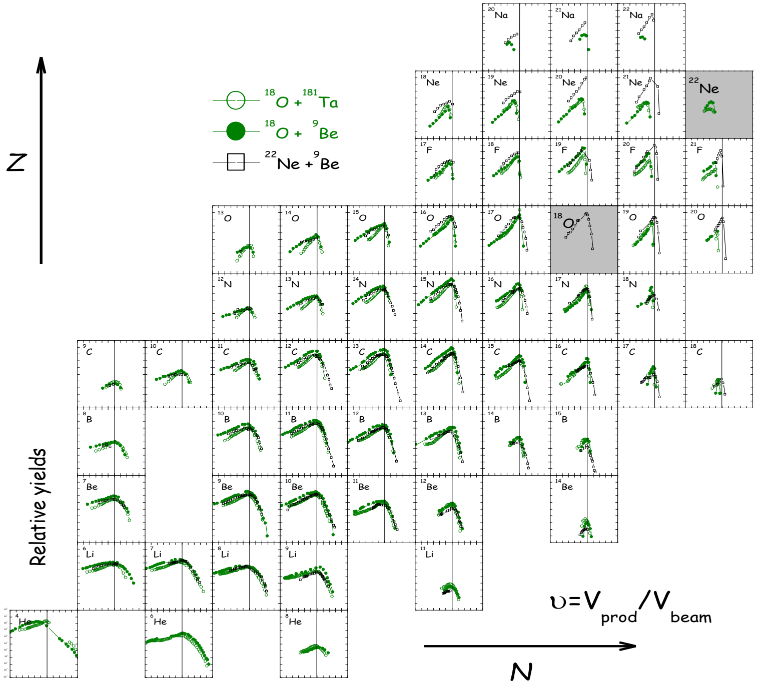
FOPI data, Reisdorf et al., NPA 848 (2010) 366.

Isotope distributions obtained at Combass set-up in FLNR: to be shown in the poster of B. Erdemchimeg during the poster session



Forward-angle inclusive isotope distributions (relative yields) of isotopes produced in (full) ^{22}Ne(42Mev/nucleon)+^{9}Be reactions and (open) ^{22}Ne(42Mev/nucleon)+^{181}Ta reactions. The solid curves present the LISE code fit for ^{22}Ne(42 A Mev)+^{9}Be

velocity distributions for different isotopes



15'ая научная конференция ОМУС, Дубна, Россия *ДИССИПАТИВНЫЕ ПРОЦЕССЫ В ПЕРЕФЕРИЧЕСКИХ СТОЛКНОВЕНИЯХ ТЯЖЕЛЫХ ИОНОВ ПРИ ЭНЕРГИЯХ ФЕРМИ,* Б. Эрдэмчимэг, Т.И. Михайлова, Г. Каминьски, А.Г. Артюх, М. Колонна, М. Ди Торо, Ю.М. Середа, Х.Х. Вольтер, 194-197, 2011

⇨ to describe fragmentation reactions microscopically we use kinetic theory:

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

(also called the Botzmann-Ühling-Uhlenbeck (BUU) approach)

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

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

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

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

Density functional

U(ρ(r)) = Nuclear Mean Field + Symmetry terms + Coulomb

$$U(\rho)=A\left[\frac{\rho}{\rho_0}\right]+B\left[\frac{\rho}{\rho_0}\right]^d+C(-1)^k(\rho_n-\rho_p)/(\rho_n+\rho_p)+U_{\mathrm{coul}}$$

$$A=-356MeV,B=303MeV,d=7/6,k=1(p),2(n),C=36MeV$$

Collision term

$$I_{coll}[f_1,\sigma]=\frac{g}{h}\int d^3p_2\,d^3p_3\,d^3p_4\;\sigma(12,34)\,\delta(\vec{p}_1+\vec{p}_2-\vec{p}_3+\vec{p}_4)\,\delta(\varepsilon_1+\varepsilon_2-\varepsilon_3+\varepsilon_4)\left[\bar{f}_1\bar{f}_2f_3f_4-f_1f_2\bar{f}_3\bar{f}_4\right]$$

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

Collision term: treatment by stochastic simulation

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

Computationally most expensive part of calculation

Remarks on Solution of Transport equation

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

$$f(\vec{r},\vec{p},t)=\frac{1}{N}\sum_{i}\delta(\vec{r}-\vec{r}_i(t))\,\delta(\vec{p}-\vec{p}_i(t))$$

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

Equations of motion of TP (Hamiltonian EoM‘s):

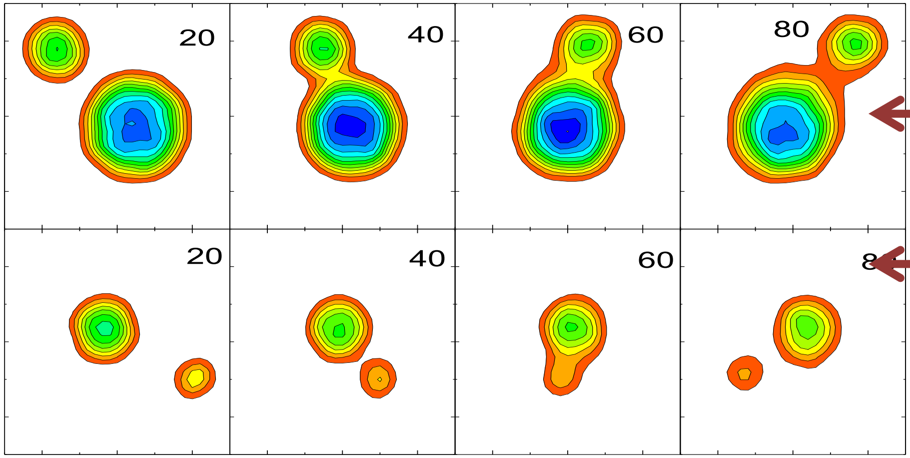
$$\frac{\partial\vec{p}_i(t)}{\partial t}=-\vec{\nabla}_r U(r_i,t) \qquad \frac{\partial\vec{r}_i(t)}{\partial t}=\frac{\vec{p}_i(t)}{m}$$

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

Initialization of test-particles is calculated filling the potential well of Woods-Saxon shape. Coulomb and symmetry energy are taken into account.

$$V(r)=-\frac{V_0}{1+\exp(\frac{r-R}{a})}+E_{\mathbf{coul}}+E_{\mathbf{symm}}$$

As a result when the dynamical calculations starts this initial state of nucleus doesn‘t represent its ground state.



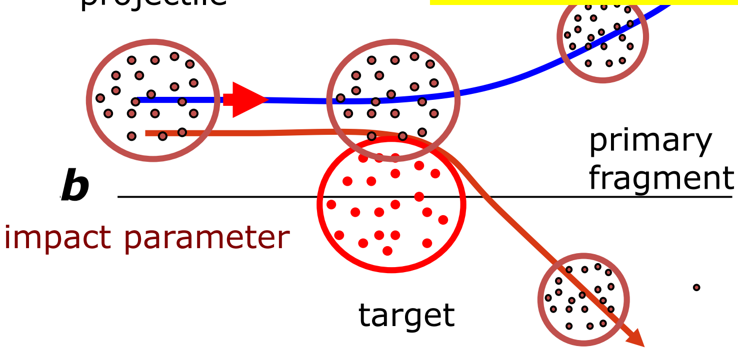
Density contour plots in the reaction

^{40}Ar(57A MeV)+^{181}Ta

^{40}Ar(57A MeV)+^{9}Be

Four times (t=20,40,60,80 fm/c) are shown

Impact parameter dependence



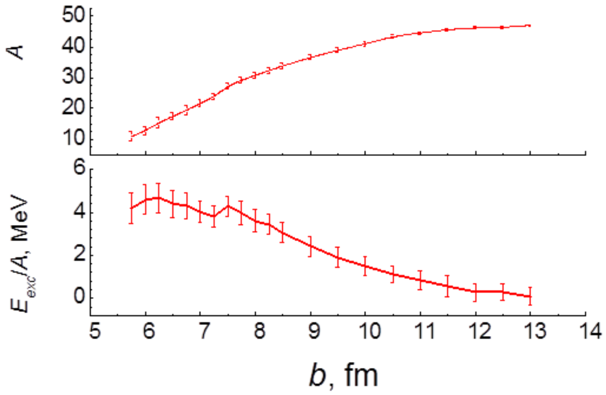
50 calculations for each value of b_i ,
b_{min} =0, b_{max}=1.2*(R_{proj} + R_{tag})
δb= 0.25 - 0.5 fm
integration over ***b*** for a quantity Φ

$$\Phi_{tot} = \sum_{i=k}^{k+N} b_i (b_{i+1} - b_i) \Phi_i$$

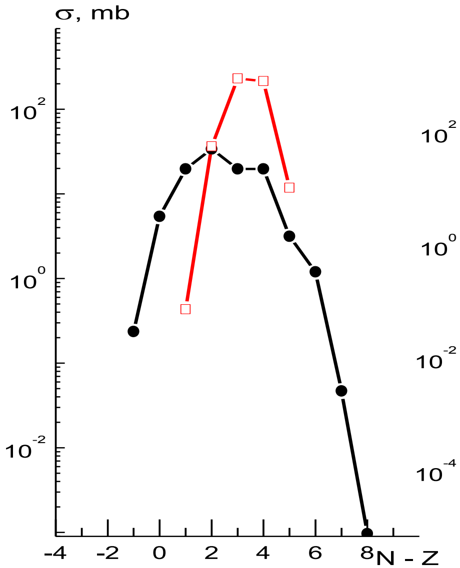
Results for the reaction ^{40}Ar on ^{181}Ta at 57 AMeV.

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

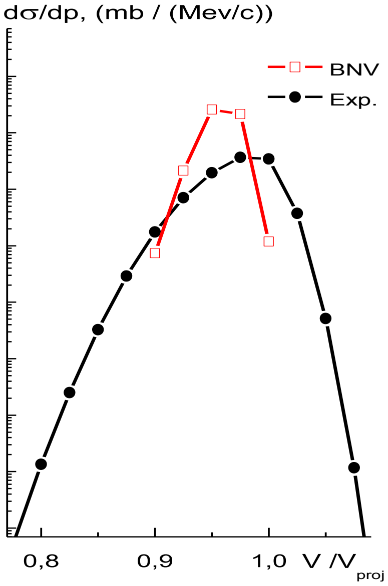
^{48}Ca + ^{181}Ta, 140 *A* MeV



Isotope distributions for the element S



Velocity distributions for S summed over isotopes



--X. H. Zhang, *et al.*,
PRC 85,
024621 (2012)

-Hot fragments have rather narrow distributions
- centered around *N-Z* of the projectile
-The width of the velocity distributions is too narrow
- and sometimes shifted to lower velocities
--> need to de-excite fragments to compare to experiment

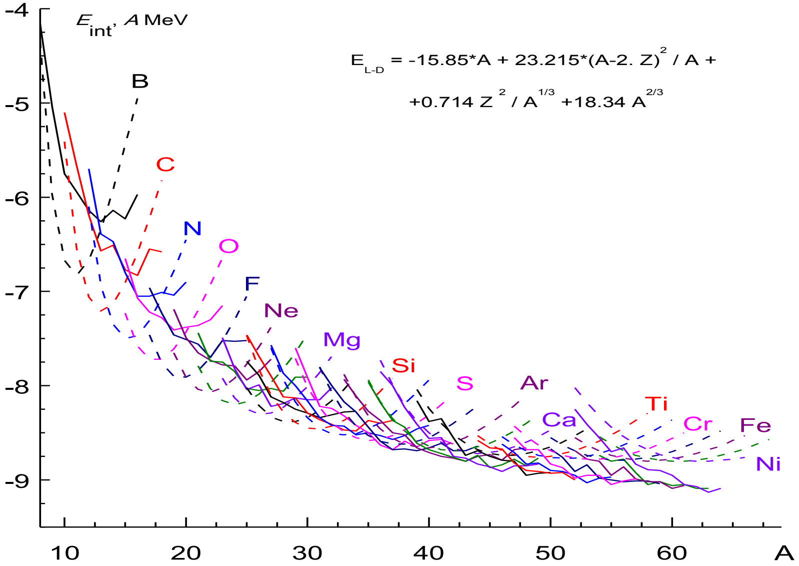
From hot fragmets – to cold ones

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

Calculation of the energy of a nucleus or fragment with the same density functional U(r) as used in the transport equation (t_i kinetic energy)

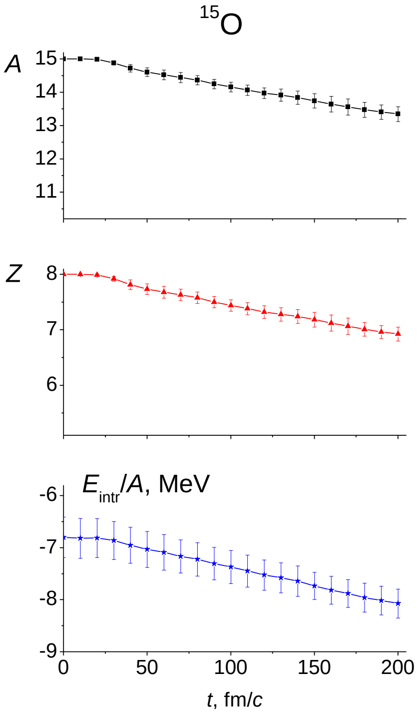
$$E = \sum_{(TP)} t_i + \tfrac{1}{2}\int d\vec{r}\,\rho(r)U(\rho)$$

Excitation energy of primary fragment $E_{exc} = E_{frag}(A,Z)-E_{g.s}(A,Z)$ at freeze-out time (no interaction)
$E_{g.s.}$ ground state energy for initialized nucleus



G.S. binding energies for isotopic chains of the intialized nuclei (solid lines) with a liquid-drop formula (dashed lines).
--> reasonable agreement

However, phenomenologically initalized nuclei are not very stable and loose particles during the evolution



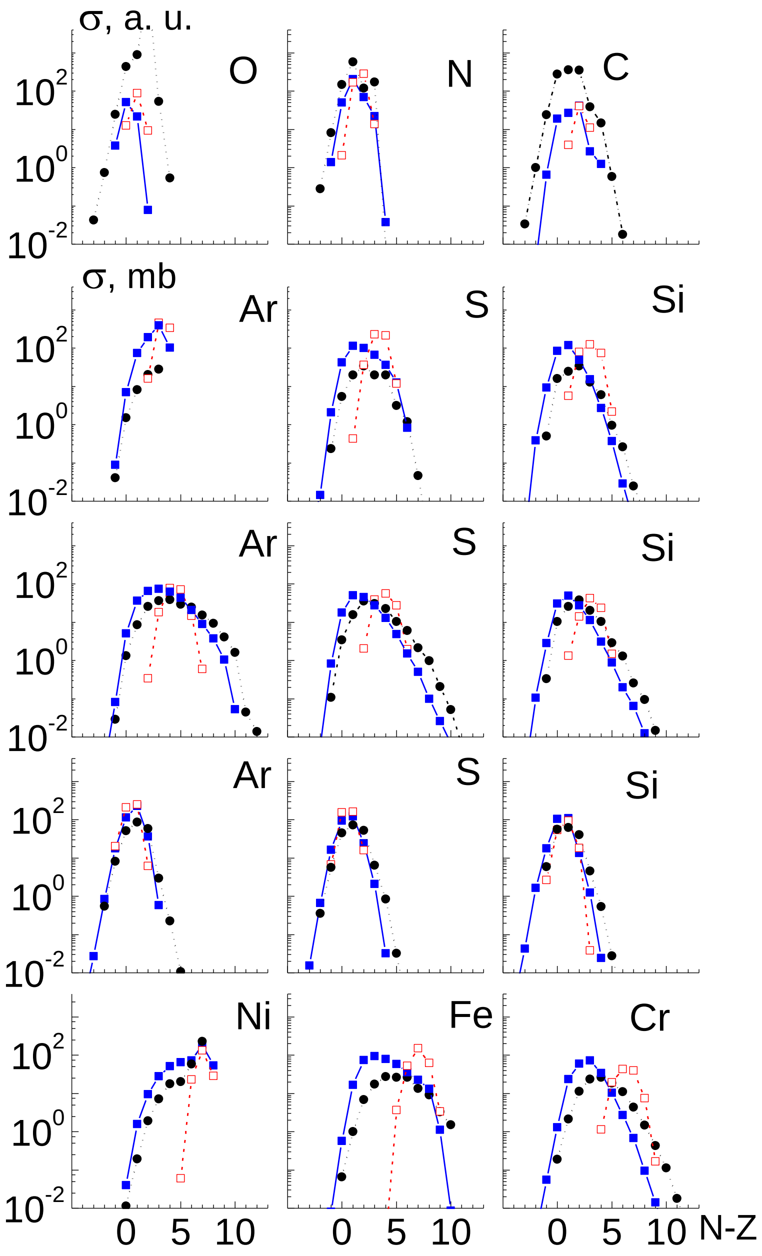
Results: Isotope distributions for selected elements

^{18}O+^{181}Ta, 35 AMeV
Exp - A.G.Arthuk, et al., NPA 701(2002) 96c
BNV - T.I.M, et al. PHPL 12 (2015)409

^{40}Ar+^{181}Ta, 57 AMeV
Exp - X. H. Zhang, *et al.,* PRC 85, 024621 (2012)
BNV -T.I.M, et al., BRAS 78(2014)1131

^{48}Ca+^{181}Ta, 140 AMeV
^{40}Ca+^{181}Ta, 140 AMeV
Exp-M. Mocko *et al.*
PRC **74**, 054612 (2006),
BNV,
T.I.M,et al.,PHAN 79(2016)604

^{64}Ni+^{181}Ta, 140 AMeV
Exp. -M. Mocko *et al.*,
Phys. Rev. C **74**, 054612 (2006),
(EPJ Web of Conf. **173**, 04010 (2018)



☐ hot fragments (BNV)

■ cold fragments (SMM)

● experimental data

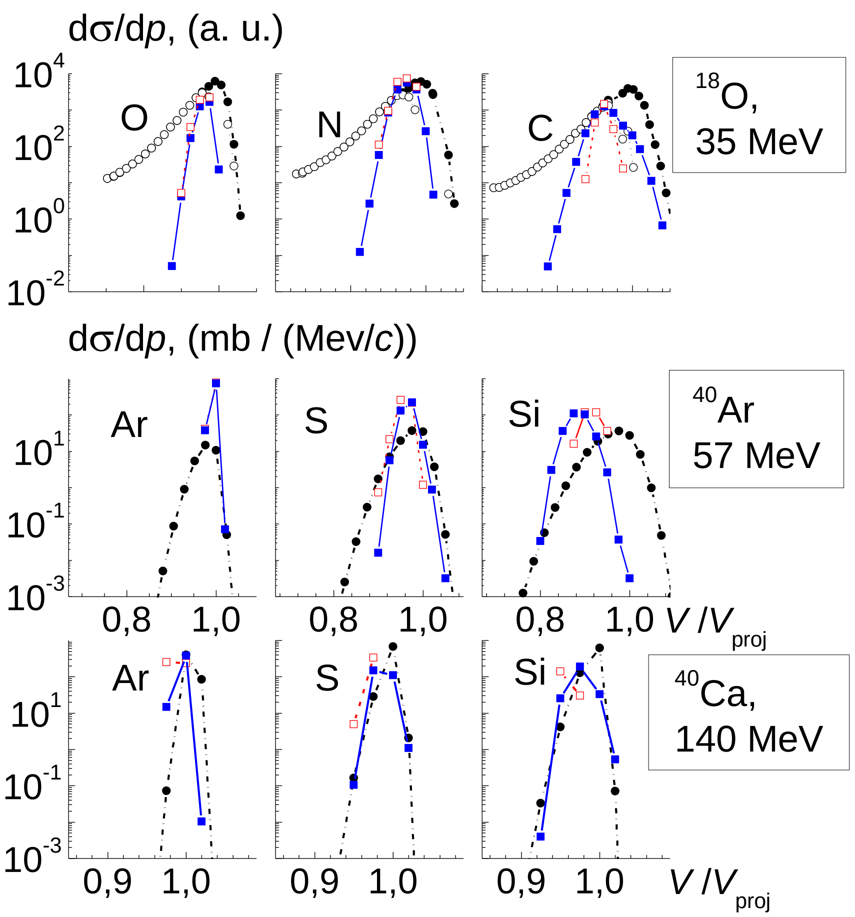
Comments:

- de-exitation (SMM) important for agreement with data

- agreement with the data ok (no parameter adjustment)

- slightly shifted to smaller neutron excess (probably due to spurious emission of neutrons).

Results: Velocity distributions for selected isotopes



☐ hot fragments (BNV)

■ cold fragments (SMM)

● experimental data

○ exp. data, dissipative comp. (for 18O)

Comments:

-effect of de-excitation not large for velocities, some widening

- maxima are shifted somewhat to lower energies relative to the data

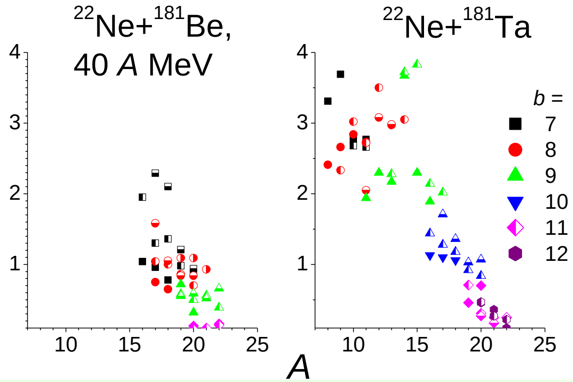
-widths too small, esp. for lower energies. not enough fluctuation?

- there is a direct breakup component close to beam velocities, esp. for low energies

- velocity spectra are helpful to understand reaction mechanism

Isotope distributions for reaction Ne(40 A MeV)+^{9}Be/^{181}Ta and dependence on excitation energy

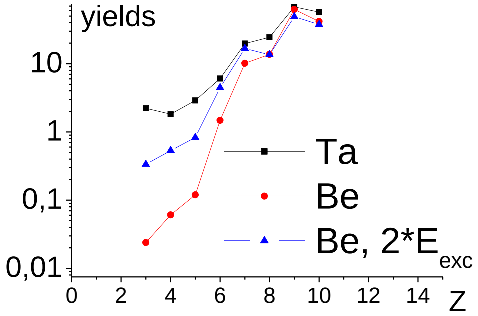
Excitation enery as a function of impact parameter for two reactions

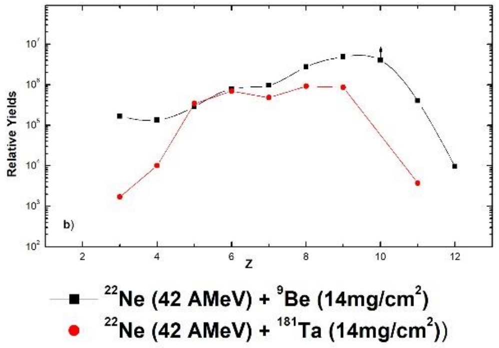


Element distributions for Ne(40 A MeV)+^{9}Be/^{181}Ta

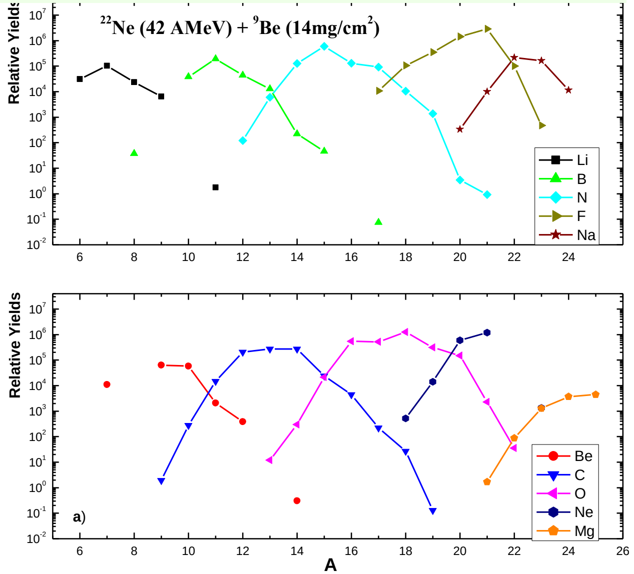
Calculations

Experiment

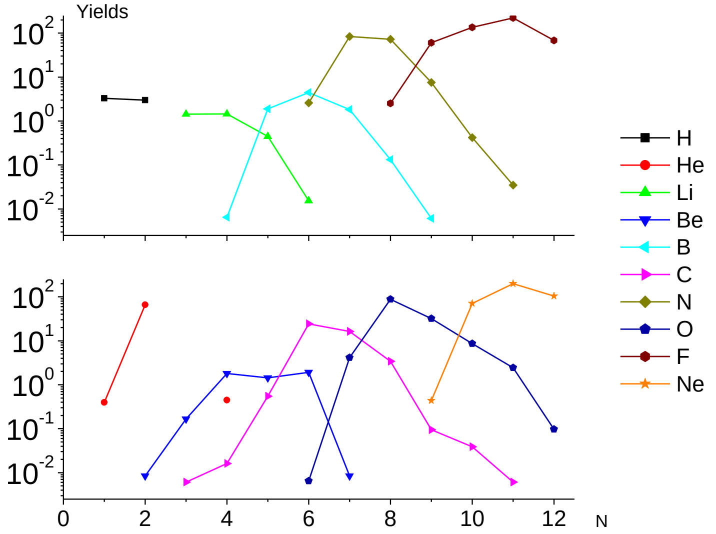




Isotope distributions in the Ne(40 A MeV)+^{9}Be experiment



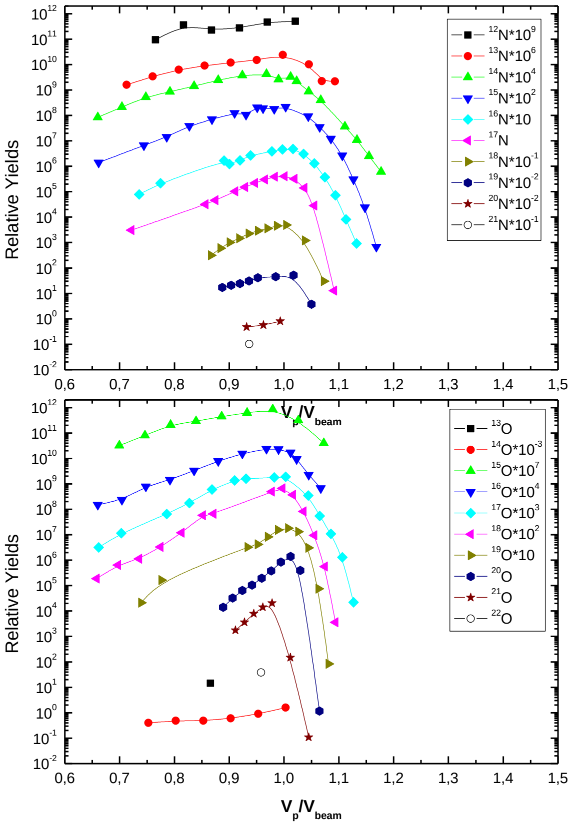
Isotope distributions in the Ne(40 A MeV)+^{9}Be calculations

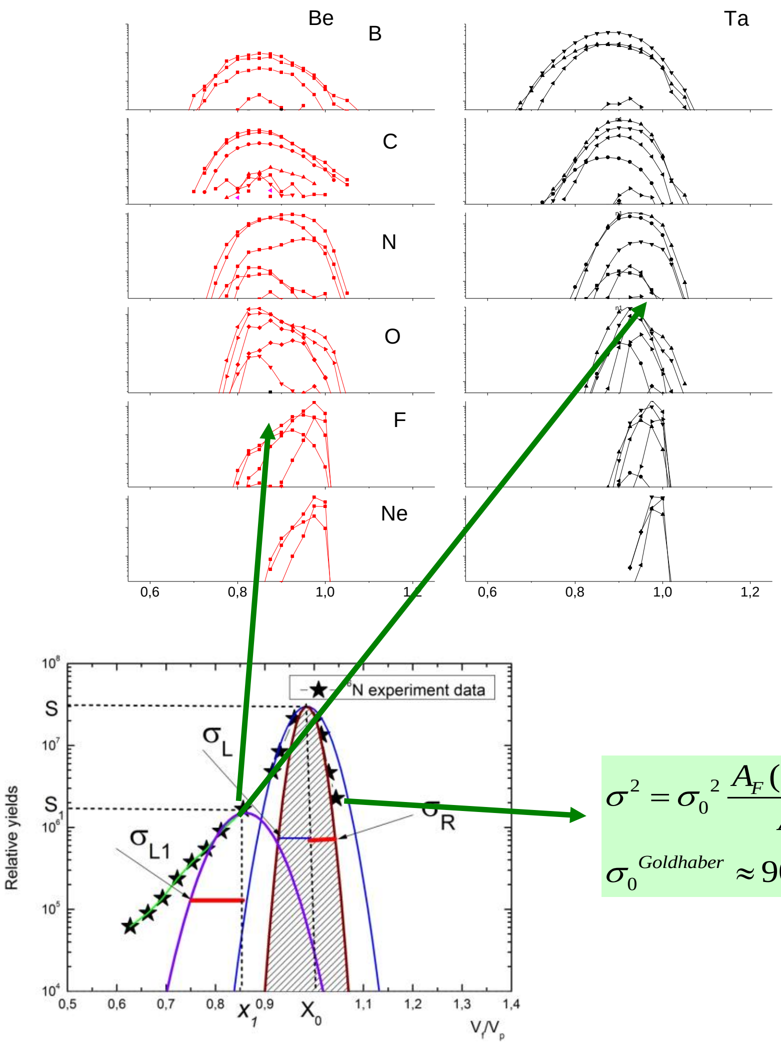


Velocity distributions of fragments

Experimental results (COMBASS group, FLNR)

Calculations





$$\sigma^2 = \sigma_0{}^2 \frac{A_F(A_P - A_F)}{A_P - 1},$$

$$\sigma_0^{Goldhaber} \approx 90\ MeV/c^{-1}$$

Velocity distributions calculated in combined Transport+Statistical moment gives dissipative component, the maxima is shifted to lower velocities.

In collaboration with:

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M. Di Toro, LNS-INFN, Catania, Italy
H.H. Wolter, Univ. of Munich, Germany

Conclusions

Heavy-ion fragmentation reactions are interesting for physics and important for applications. A microscopic understanding is desirable.

Here we use transport theory. The solution of the highly non-linear transport equation is mathematically challenging. We solve it by simulations.

The transport approach results in „hot“ fragments. Their de-excitation has to be included to obtain the final outcome and compare to experiment. We use a statistical decay code, and determine the input (excitation energy) consistently.

We apply the method to reactions from low to intermediate energies, also extensively to experimental results obtained at the FLNR.

Results for isotope distributions are ok. Velocity spectra are often too narrow (not enough fluctuations?) . Velocity spectra contains more information about the mechanism.

Future developments:
- improve the initialization of the colliding nuclei
- study the effect of fluctuations on the fragmentation.

Thank you for the attention