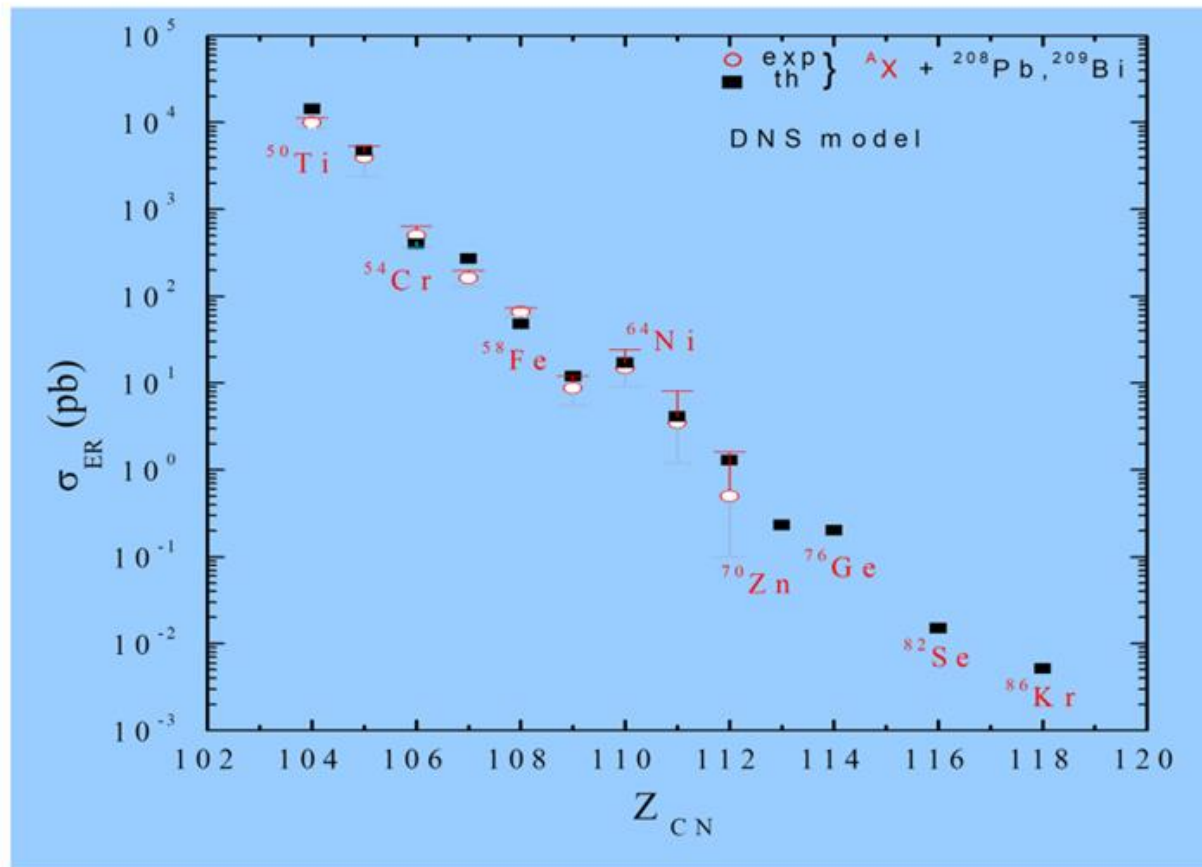


Perspectives for Cold and Hot Fusion Reactions

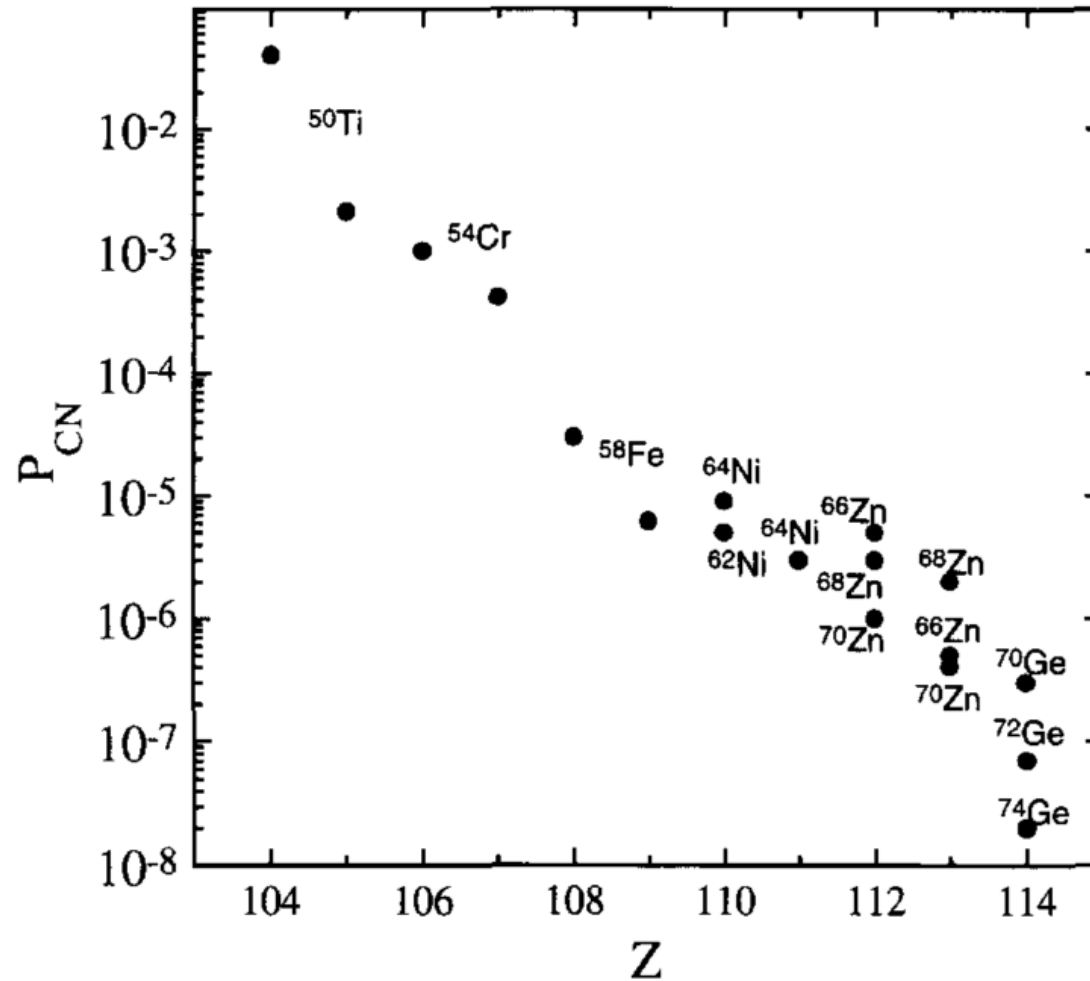
G.G.Adamian and N.V.Antonenko

What interesting fusion reactions can still be done with Pb and actinide targets?

Evaporation residue cross sections



Fusion probability (NPA633(1998)409)



Due to the increase in Coulomb repulsion with raising projectile charge number, the formation probability of compound nucleus decreases strongly.

There is a strong correlation between fusion probability and the entrance channel mass (charge) asymmetry

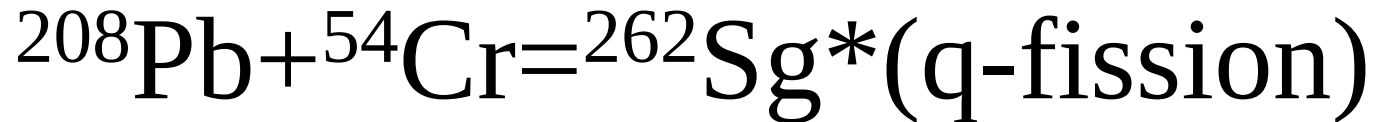
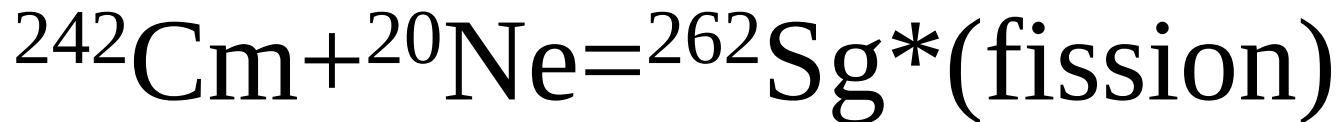
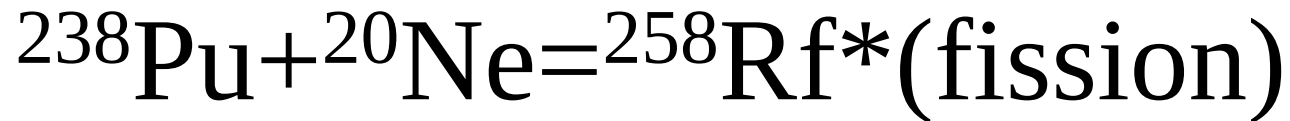
Quasifission probability is almost equal to unity

Quasifission as a signature of dinuclear system (DNS)

The role of Quasifission seems to be strongly increased with decreasing charge asymmetry in the entrance channel of the reaction.

The reaction combinations with large and small charge asymmetries would have different characteristics of fission-type products.

1. Comparison of quasifission and fission mass (charge) distributions



The production of the exotic nucleus is treated as a 4-step process:

- 1) the initial dinuclear system with light nucleus (Z_i, N_i) is formed in the collision;**
- 2) the dinuclear system with light exotic nucleus (Z, N) is produced by nucleon transfers;**
- 3) this dinuclear system separates into two fragments;**
- 4) neutron emission from these fragments.**

$$\begin{aligned}
\frac{d}{dt}P_{Z,N}(t) = & \Delta_{Z+1,N}^{(-,0)}P_{Z+1,N}(t) + \Delta_{Z-1,N}^{(+,0)}P_{Z-1,N}(t) \\
& + \Delta_{Z,N+1}^{(0,-)}P_{Z,N+1}(t) + \Delta_{Z,N-1}^{(0,+)}P_{Z,N-1}(t) \\
& - \left(\Delta_{Z,N}^{(-,0)} + \Delta_{Z,N}^{(+,0)} + \Delta_{Z,N}^{(0,-)} + \Delta_{Z,N}^{(0,+)} \right) P_{Z,N}(t) \\
& - (\Lambda_{Z,N}^{qf} + \Lambda_{Z,N}^{fis})P_{Z,N}(t)
\end{aligned}$$

Rates Δ depend on single-particle energies and temperature related to excitation energy.

Only one-nucleon transitions are assumed.

$\Lambda_{Z,N}^{qf}$: rate for decay of dinuclear system

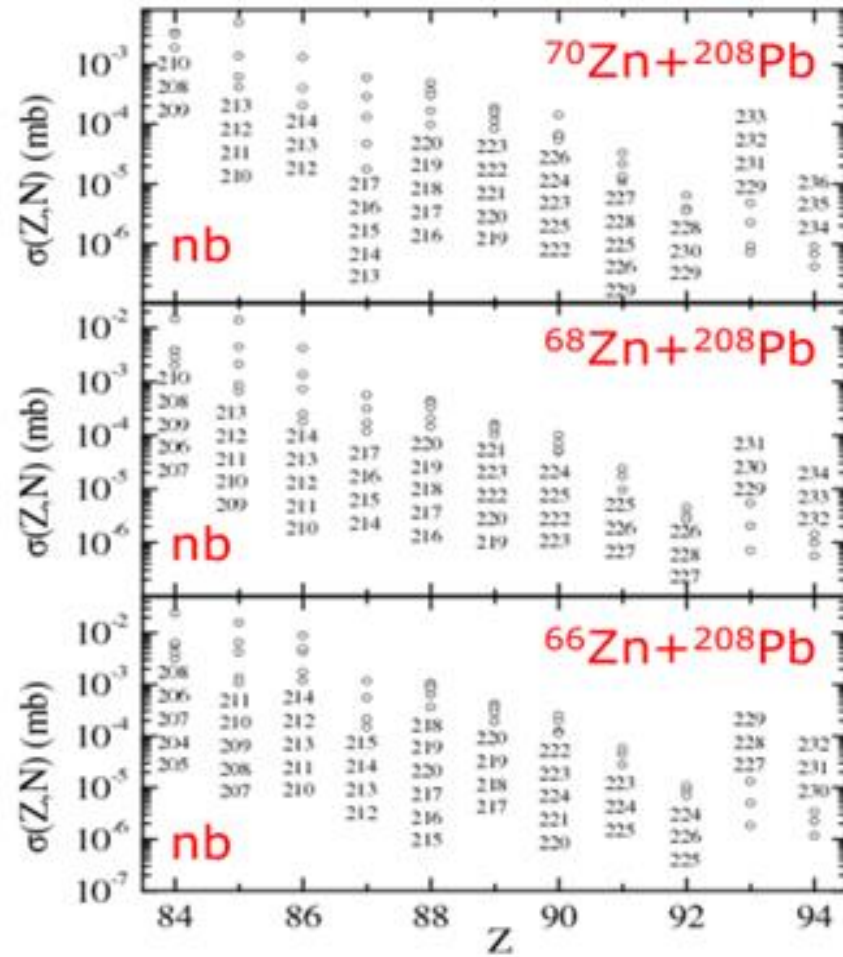
$\Lambda_{Z,N}^{fis}$: rate for fission of heavy nucleus

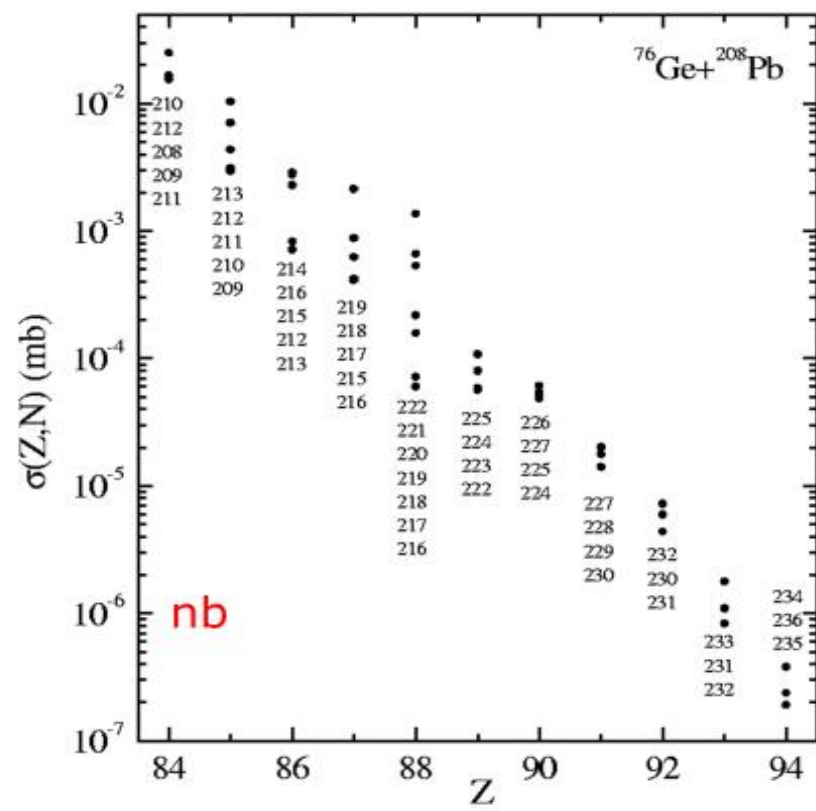
2. Transfer-type products accompanying cold fusion (asymmetry-exit-channel quasifission)

Transfer to more asymmetric systems

It would confirm the fusion in the mass asymmetry coordinate

15/11/2024

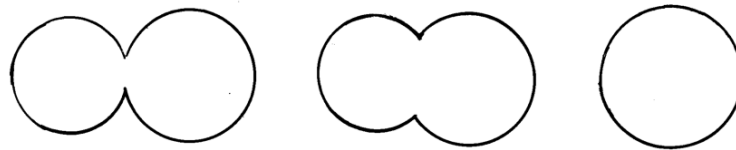




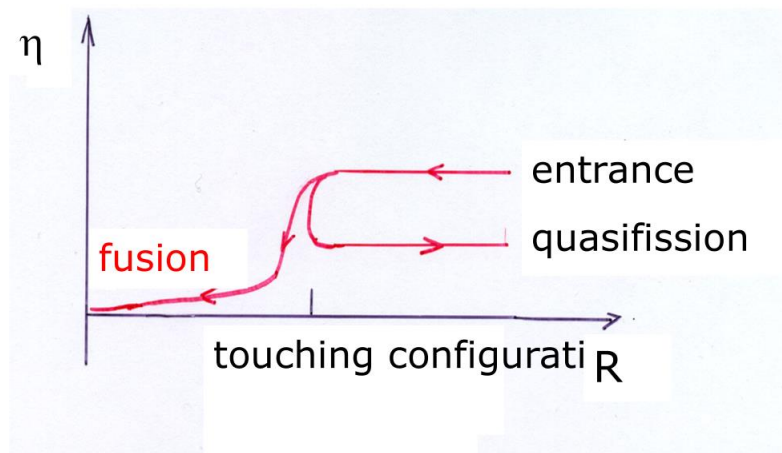
3. Neck dynamics in cold fusion or Role of neck in cold fusion

a) Models using adiabatic potentials

Minimization of potential energy, essentially adiabatic dynamics in the internuclear distance, nuclei melt together.

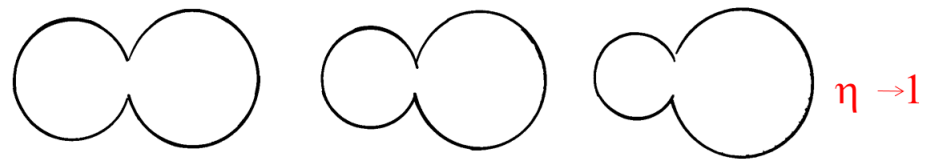


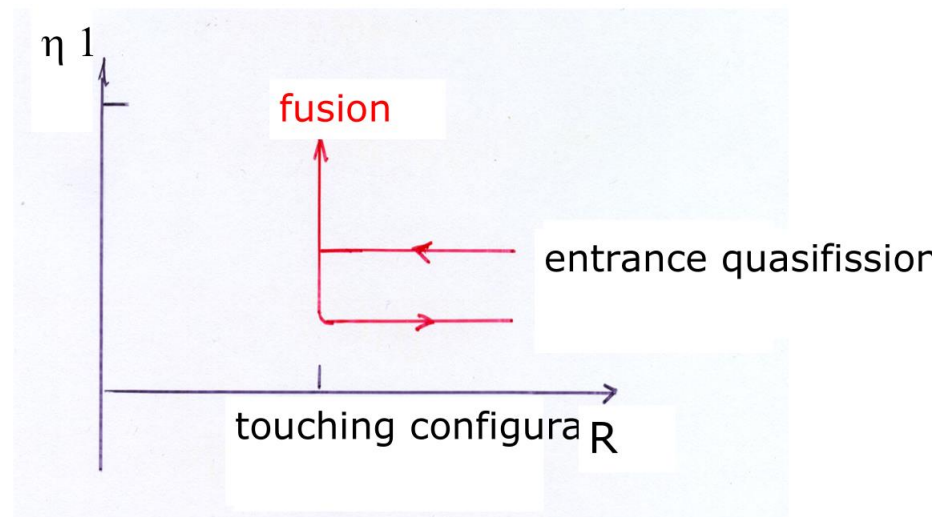
Large probabilities of fusion for producing nuclei with similar projectile and target nuclei.



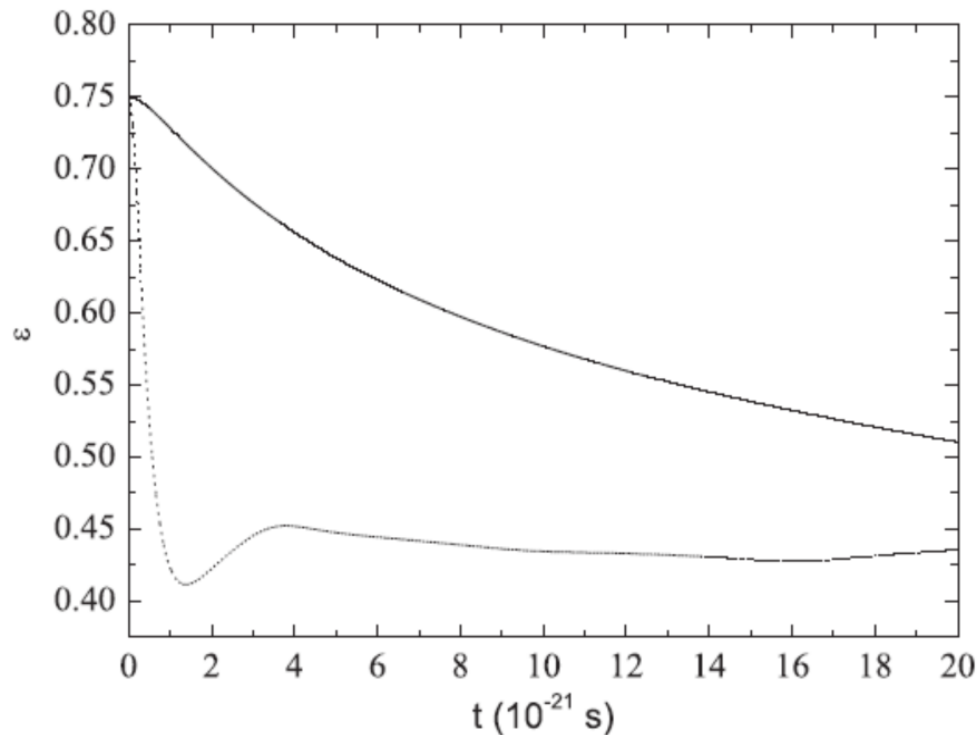
b) Dinuclear system (DNS) concept

Fusion by transfer of nucleons between the nuclei
(idea of V. Volkov, also von Oertzen),
mainly dynamics in mass asymmetry degree
of freedom, use of diabatic potentials,
calculated with the diabatic two-center shell model.

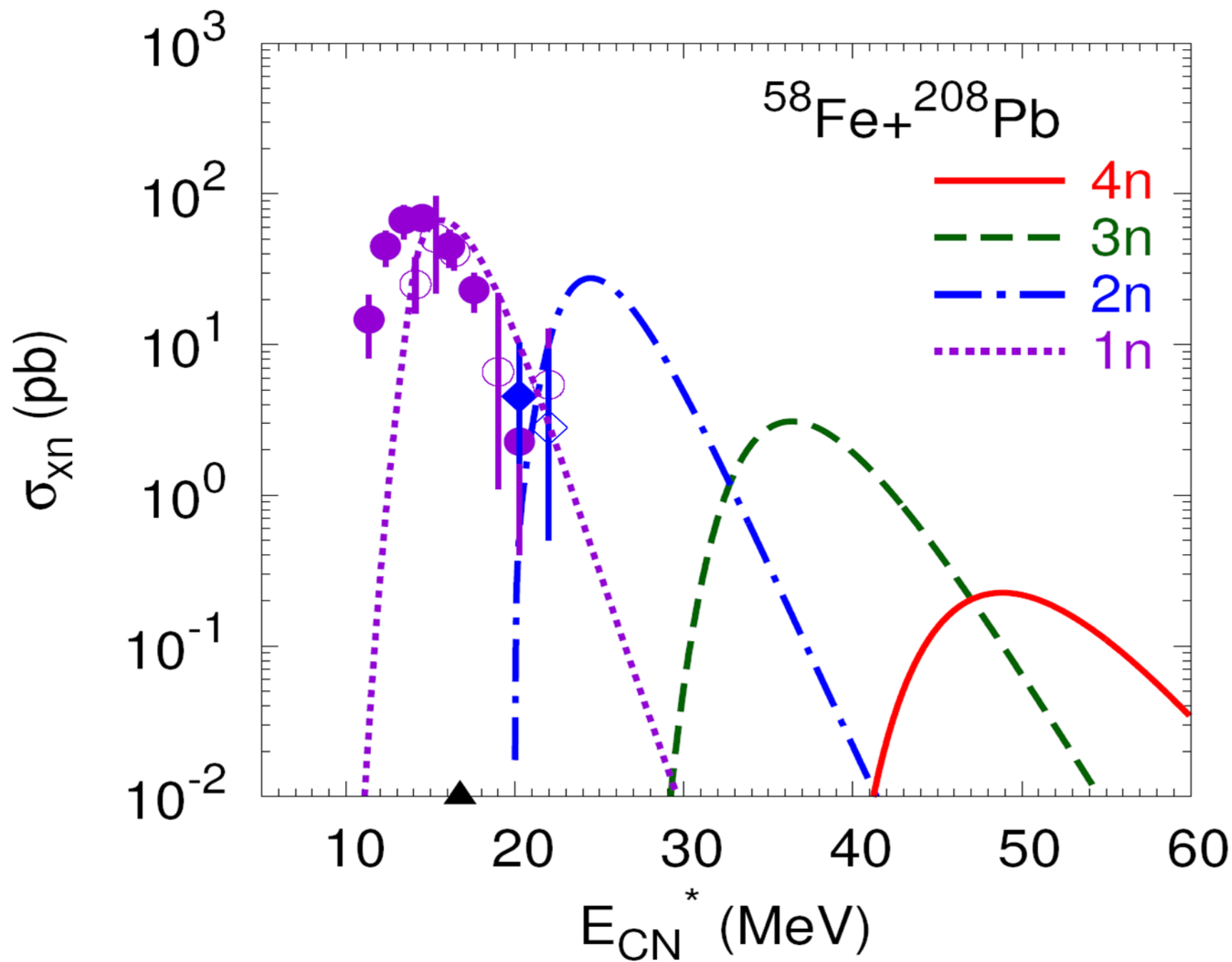


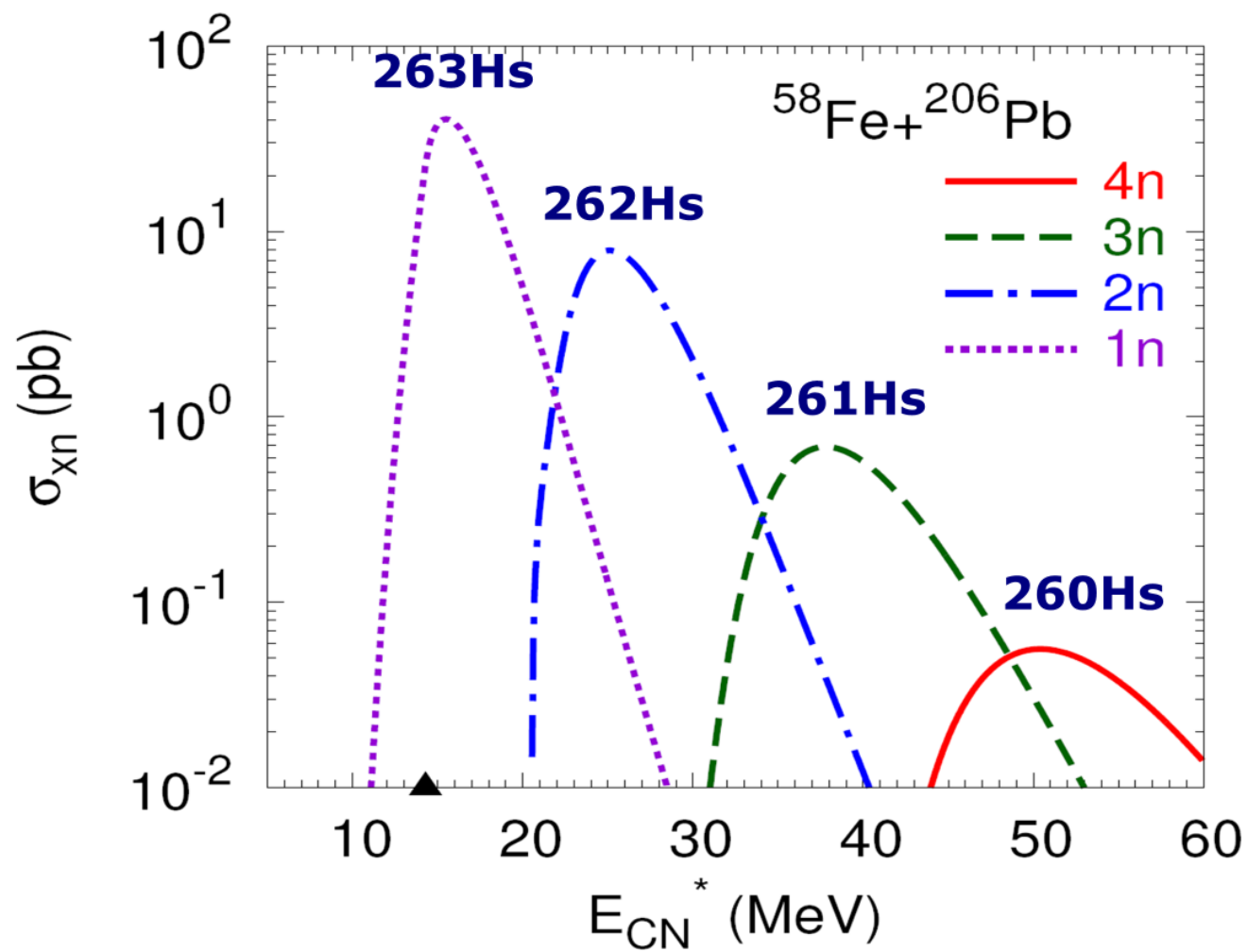


3. Neck dynamics in cold fusion or Role of neck in cold fusion



4. Study of xn -channels with $x > 1$, 2





4. Dependence of fission barrier on spin
or
Population of the yrast rotational band
of SHN produced in cold fusion

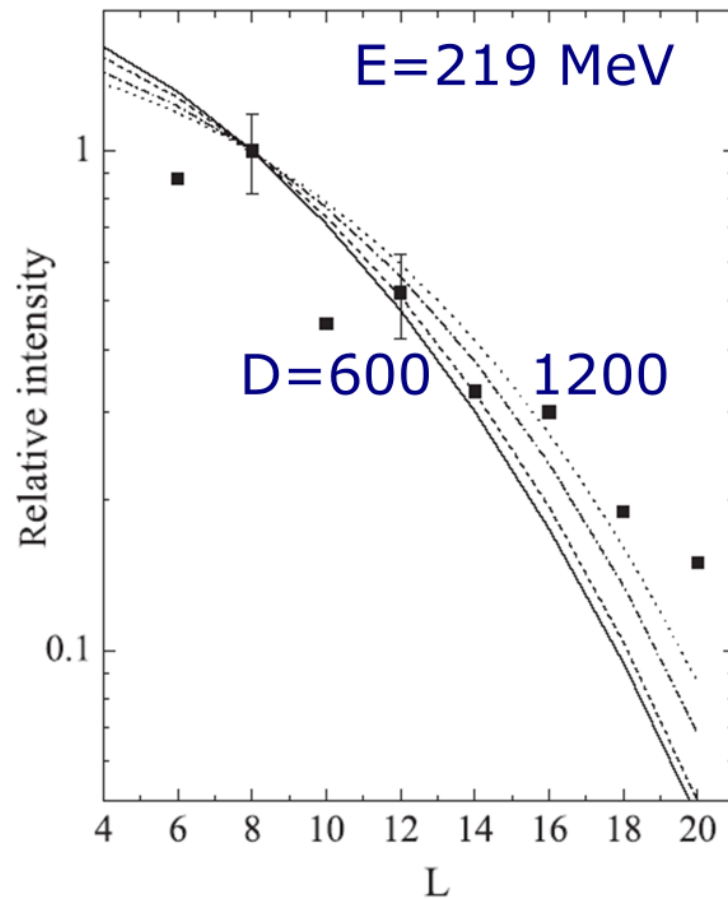
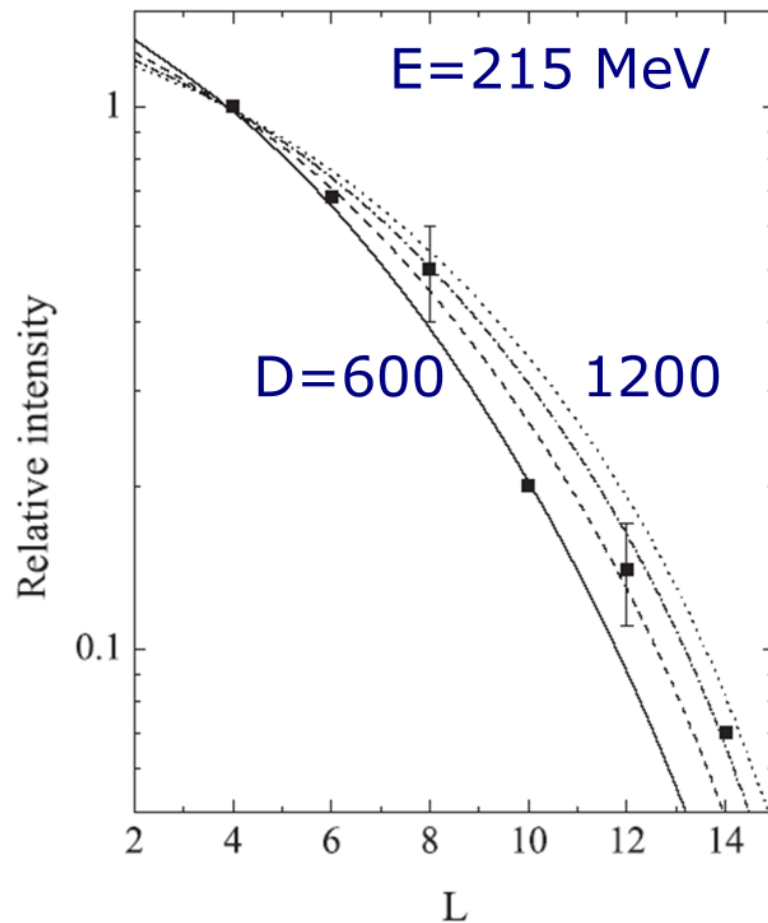
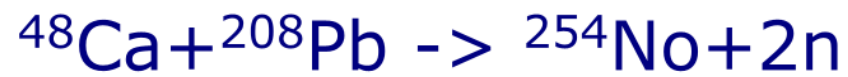
Dependence of fission barrier on spin

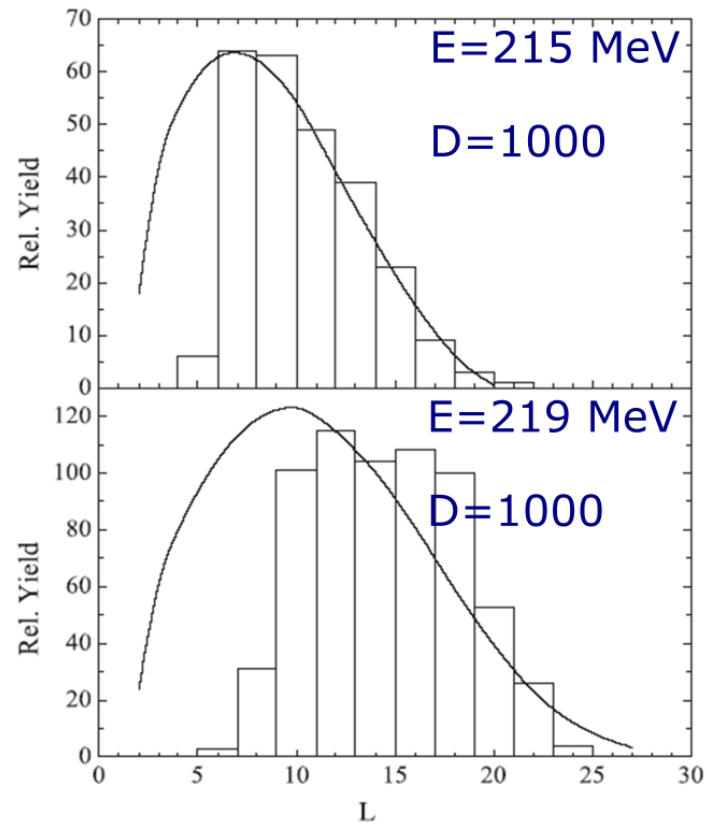
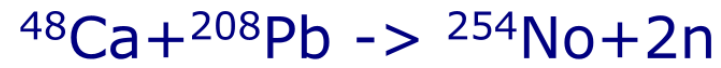
$$B_f(E_{CN}^*, J) = B_f^{LD}(J) + B_f^M(E_{CN}^* = 0) \\ \times \exp[-E_{CN}^*(J)/E_D] \exp[-J(J+1)/D]$$

Damping parameter **D from exper. data**

$$E_D = \alpha_0 A^{4/3}/a,$$

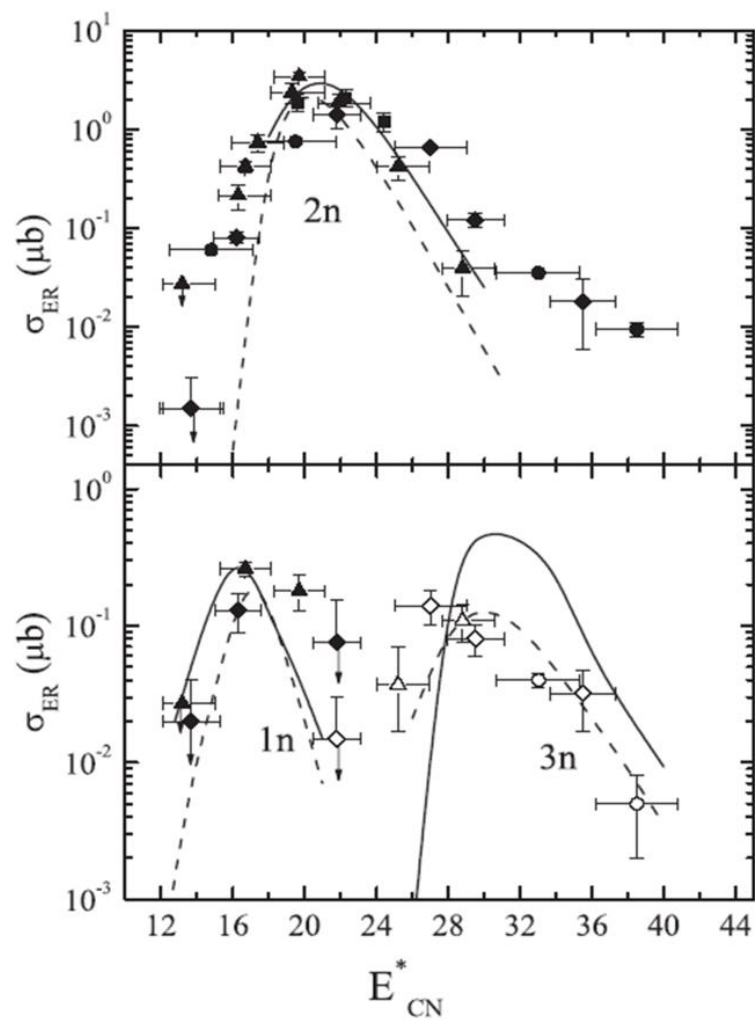
where $\alpha_0 = 0.4$.

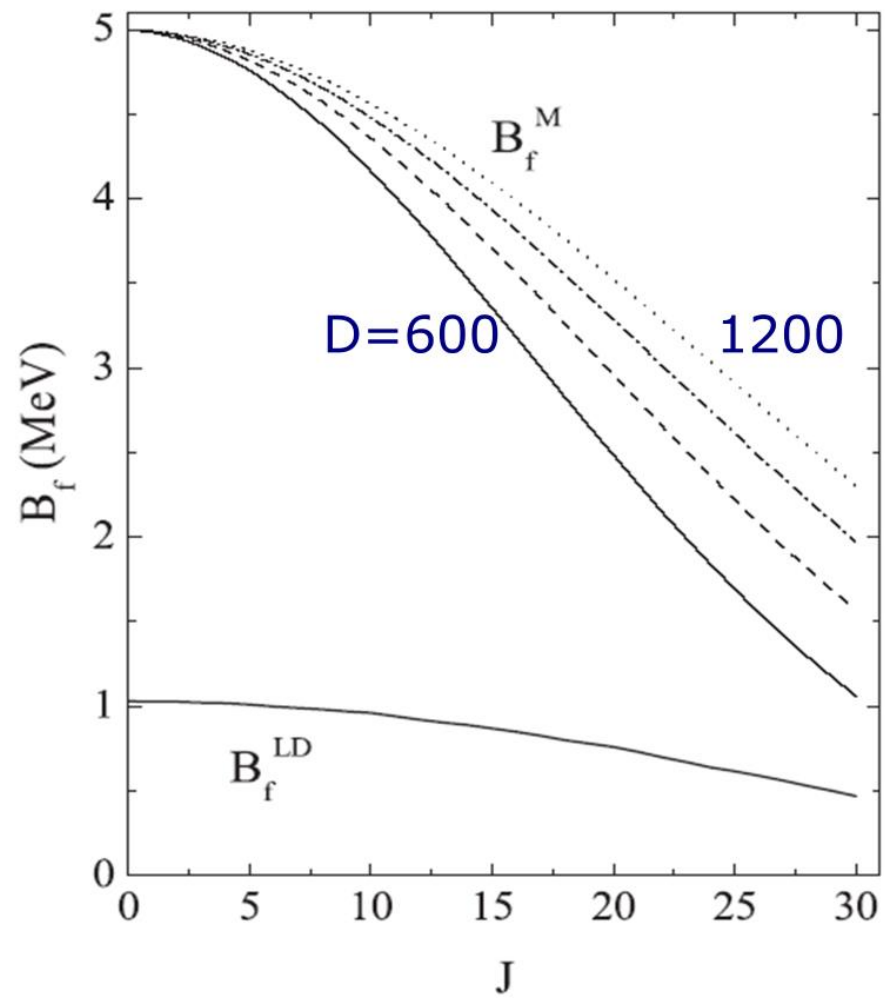




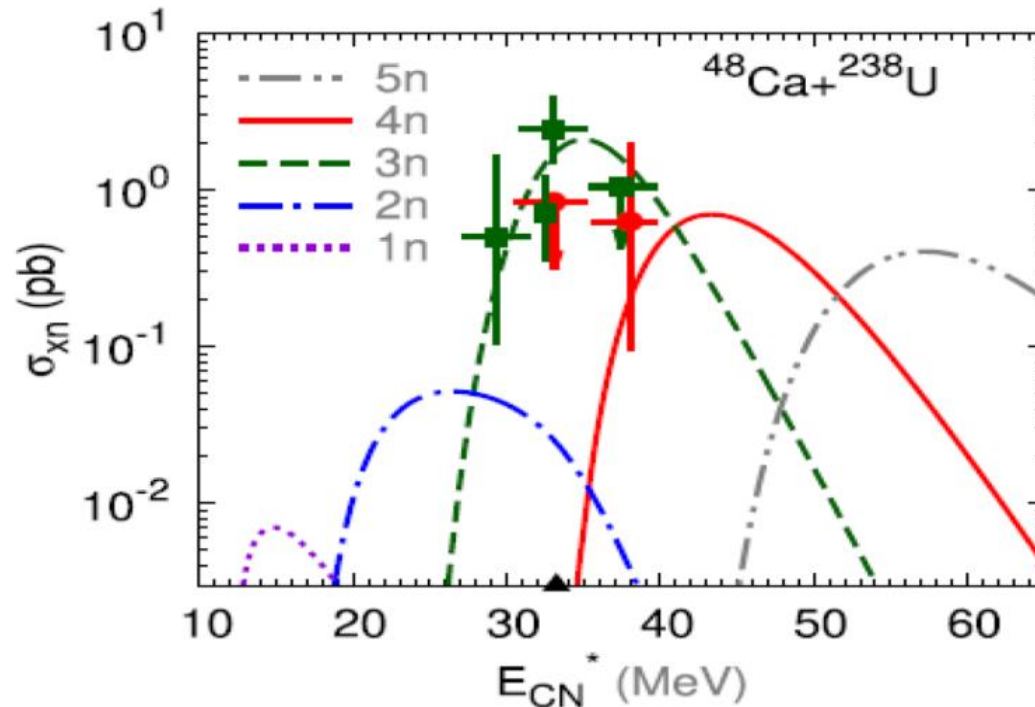
$^{48}\text{Ca} + ^{208}\text{Pb}$

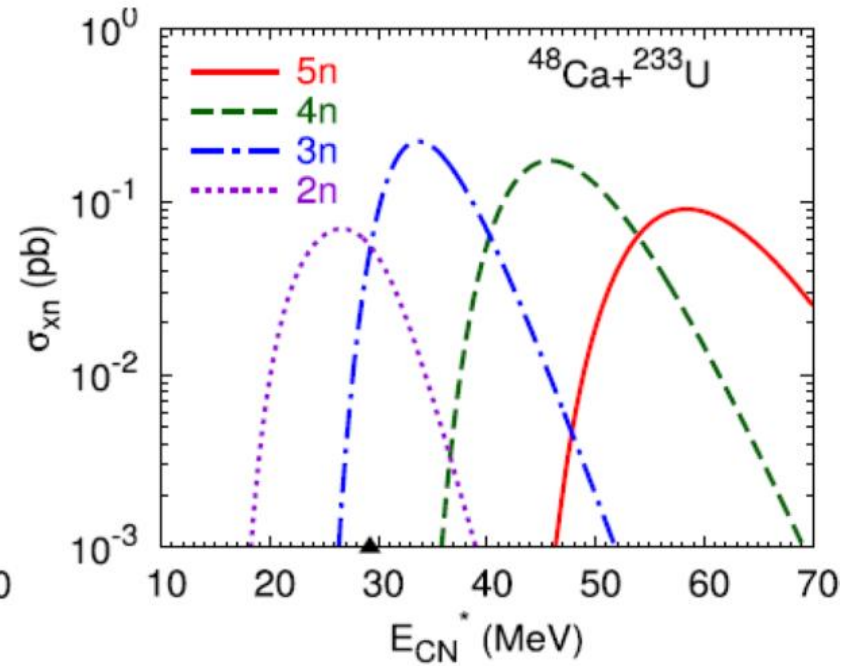
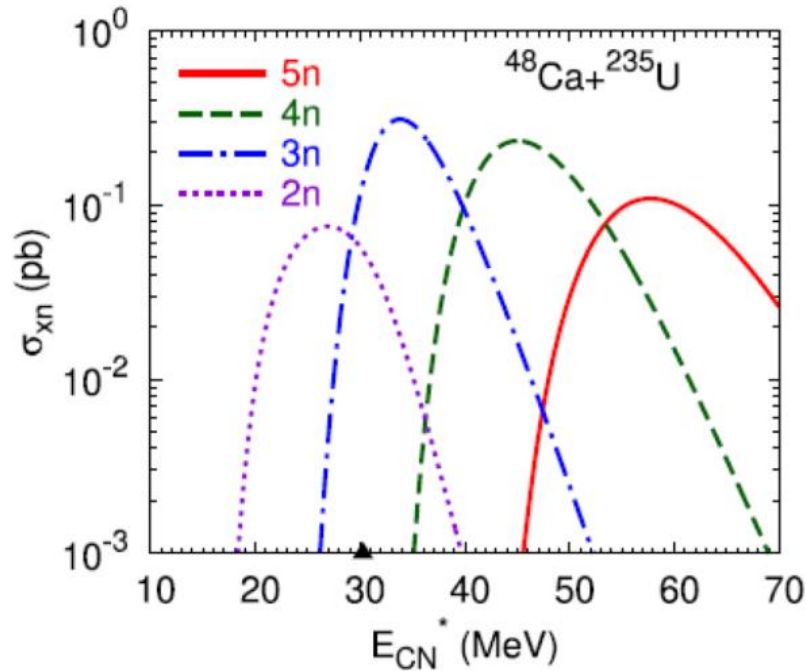
$D=1000$





5. Hot & cold fusion reactions leading to the same SH evaporation residue





Cross section in $^{48}\text{Ca} + ^{233}\text{U} \rightarrow ^{277}\text{Cn} + 4n$ is comparable to one in $^{70}\text{Zn} + ^{208}\text{Pb} \rightarrow ^{277}\text{Cn} + 1n$, in which is 0.5 pb

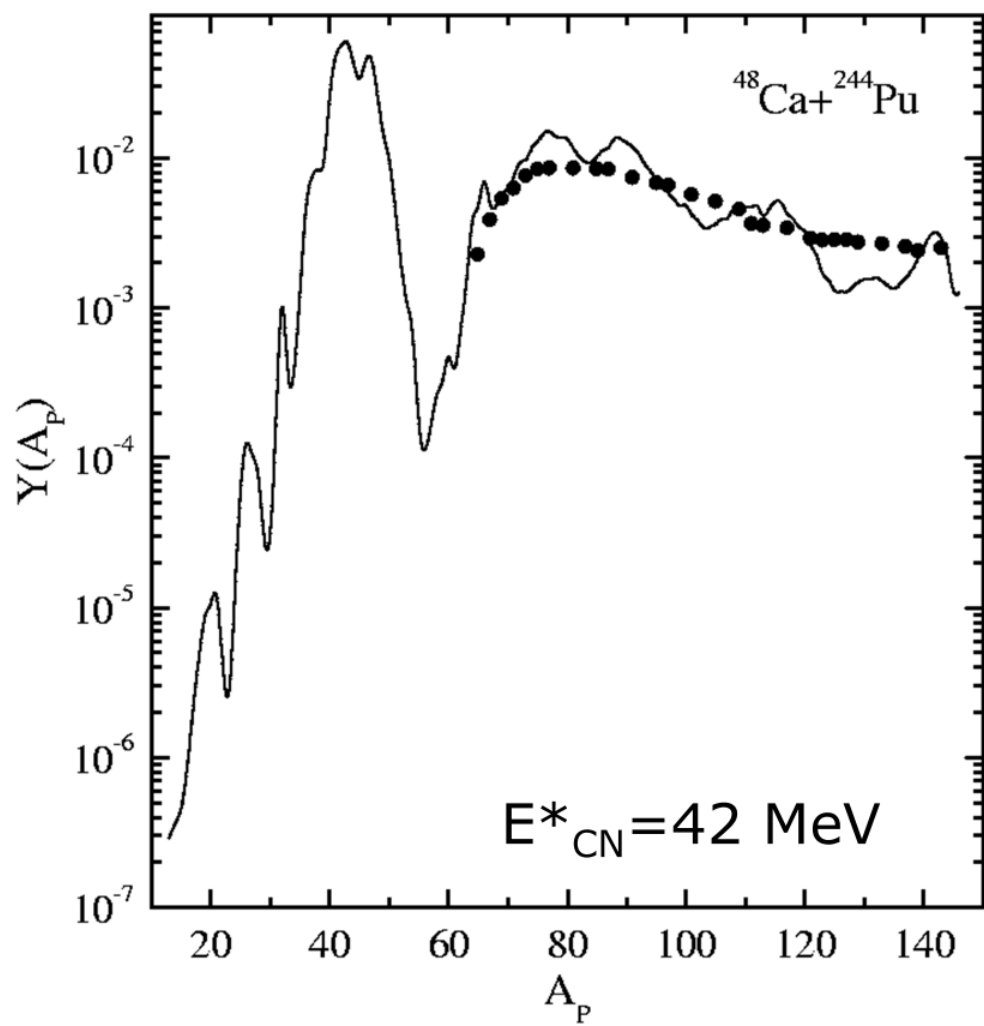
$$\frac{P_{CN}(4n)}{P_{CN}(1n)} \approx \frac{W_{1n}}{W_{4n}} \approx 10^4$$



$$\frac{P_{CN}(1n)}{P_{CN}(4n)} \approx \frac{W_{sur}^{4n}}{W_{sur}^{1n}}$$



6. *Asymmetry-exit-channel* quasifission



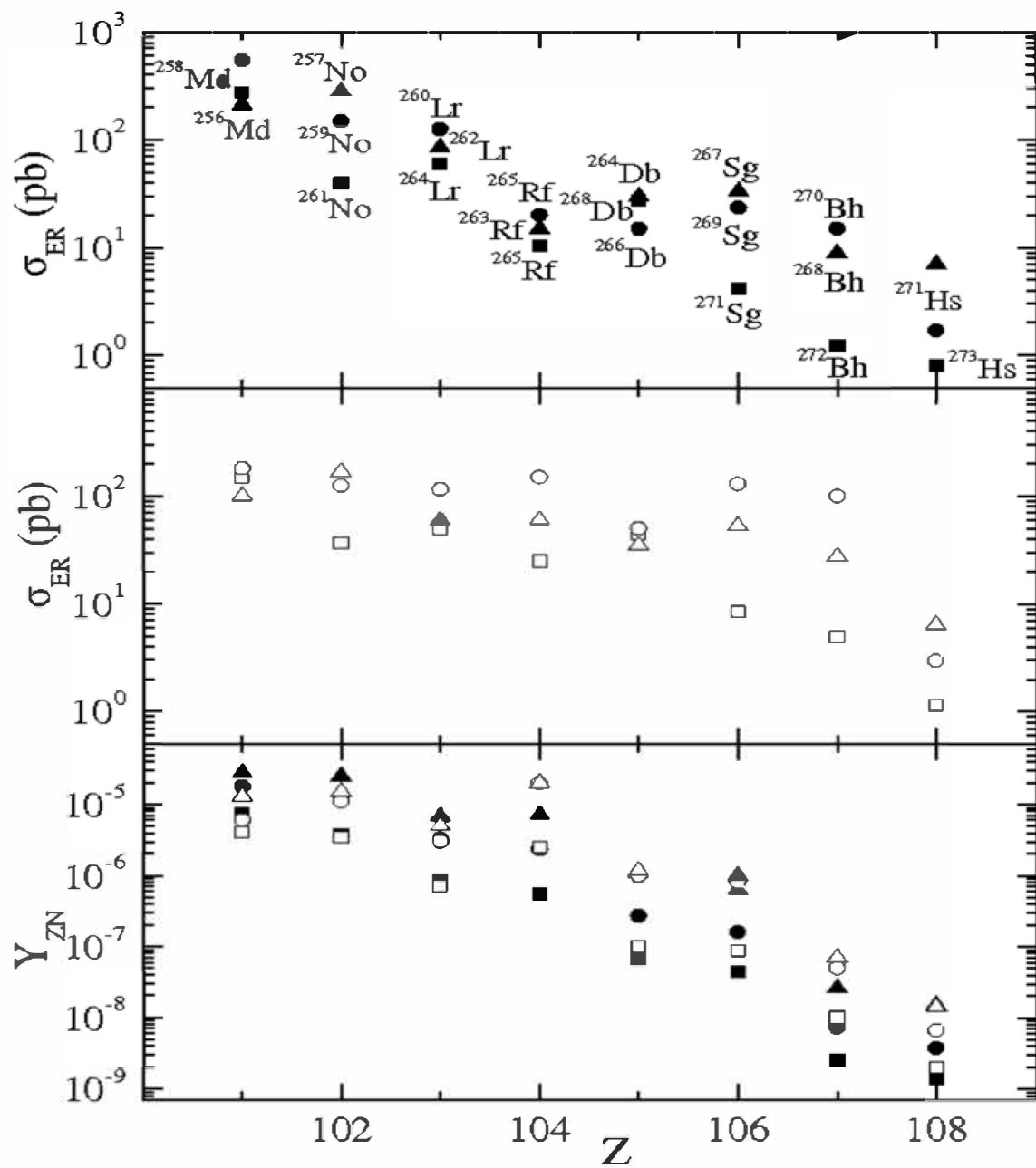
The measurement of the small yields of the products with $Z = 6 - 16$ in $^{48}\text{Ca} + ^{244}\text{Pu}$ reactions can give the complementary information about the QF process and fusion path.

It would confirm the evolution of the DNS to the compound nucleus in the mass asymmetry coordinate.

The yield of light products is larger for larger beam energies.

The quasifission barrier increases for Z values smaller than the atomic number of projectile, which hinders the decay of asymmetric DNS.

$^{48}\text{Ca} + ^{244}\text{Cm}$ ▲
 $^{48}\text{Ca} + ^{246}\text{Cm}$ ●
 $^{48}\text{Ca} + ^{248}\text{Cm}$ ▣

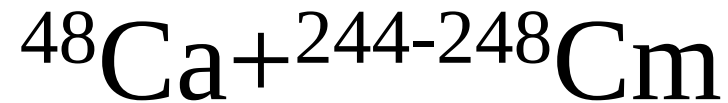


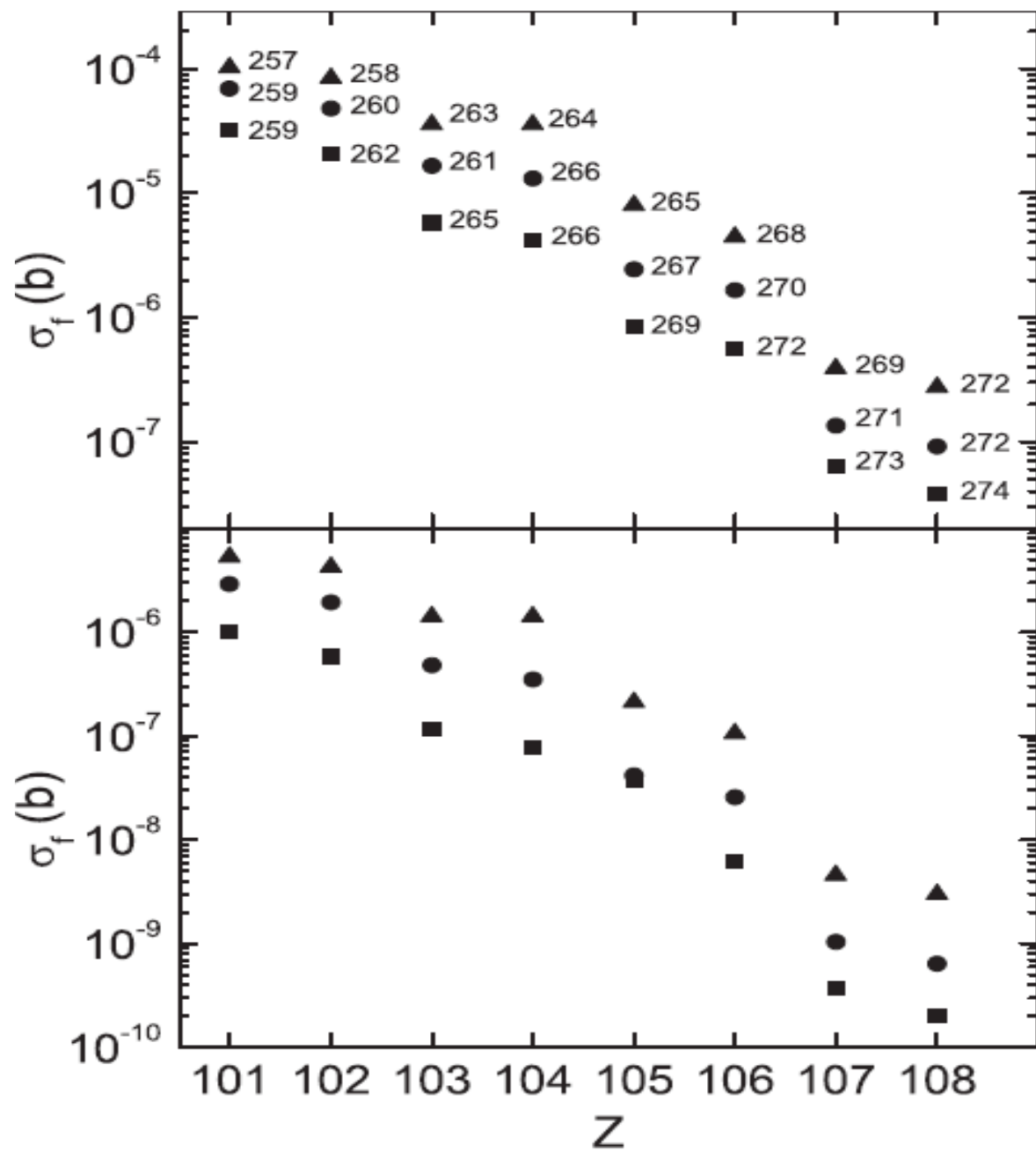
In the asymmetry-exit-channel quasifission reactions $^{48}\text{Ca} + \text{Actinides}$ one can produce new isotopes of SHN with $Z=104-108$, which are not reachable in the hot and cold complete fusion reactions with the stable nuclei.

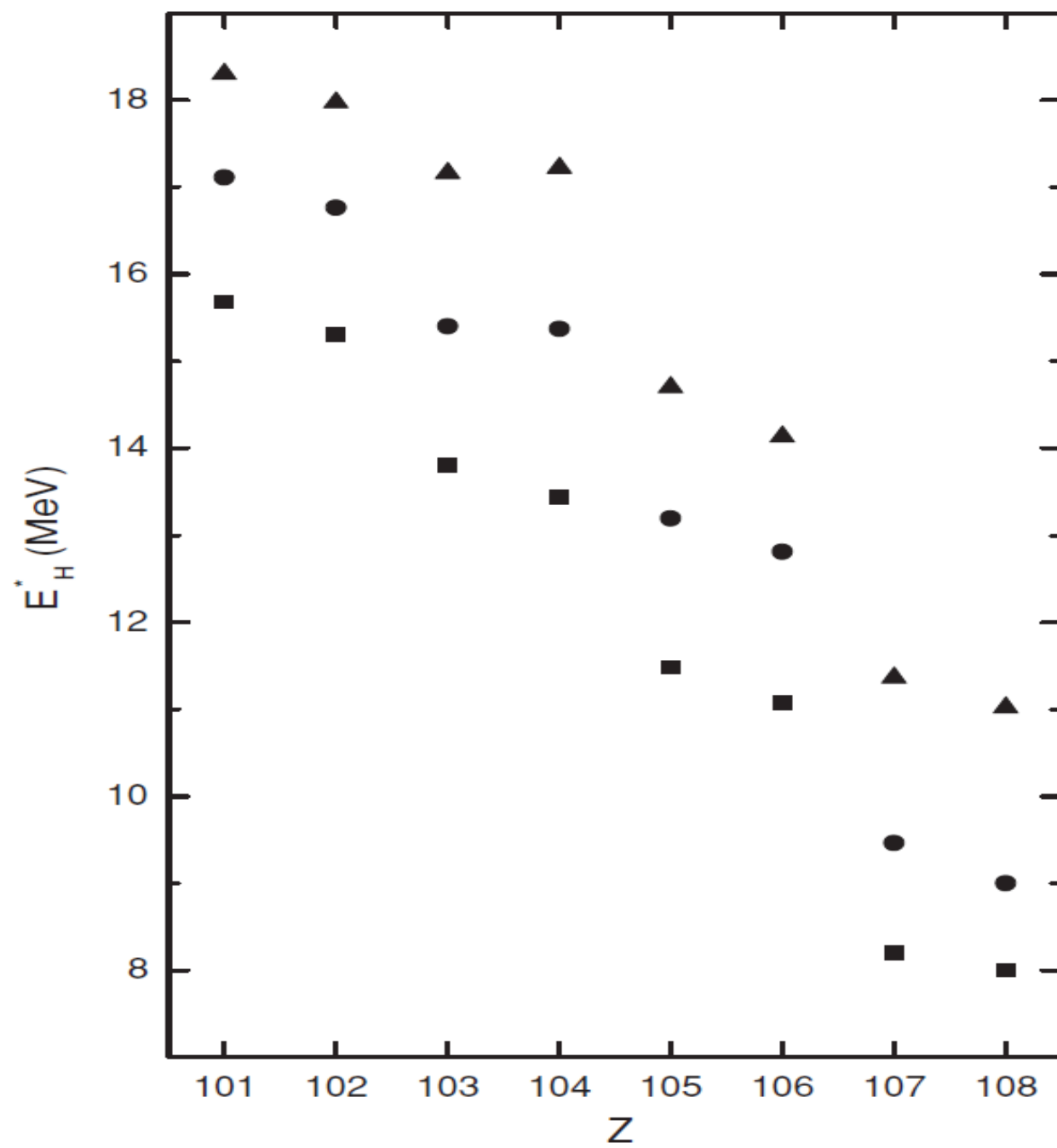
The production of these isotopes is important for the experimental identification of superheavy nuclei which alpha-decay chains end in the unknown isotope.

For example, for the complete fusion reaction $^{48}\text{Ca} + ^{243}\text{Am} = ^{291-x}\text{n}115 + x\text{n}$ alpha-decay chains end at unknown nucleus $^{267,268}\text{Db}$ ($Z=105$).

Study of transfer-induced fission of SHN







Theory expects remarkable
experimental results in the near
future

Thank you for your attention

7. Isotopic trends in the production of SHN in cold fusion

8. Comparison of production cross sections of nuclei with $Z=113$ and 114 in cold fusion

9. Symmetry-exit-channel quasifission

2. Possibility of production of neutron-rich isotopes of Zn and Ge ($N > 50$) in transfer reactions

$^{48}\text{Ca}(E_{\text{cm}}=190 \text{ MeV}) + ^{238}\text{U}$

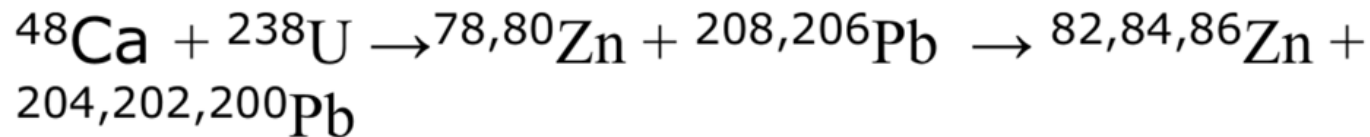
and

$^{48}\text{Ca}(E_{\text{cm}}=201 \text{ MeV}) + ^{244}\text{Pu}$

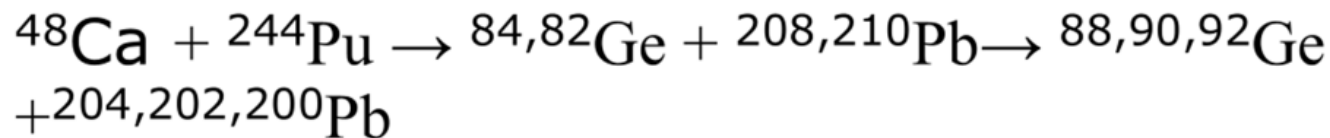
at low energies [PRC 81 (2010) 024604]

Due to the large neutron excess and smaller quasifission losses near the entrance channel, the use of ^{48}Ca is more preferable than the use of heavier projectiles to reach the neutron-rich region of nuclide in the actinide-based reactions.

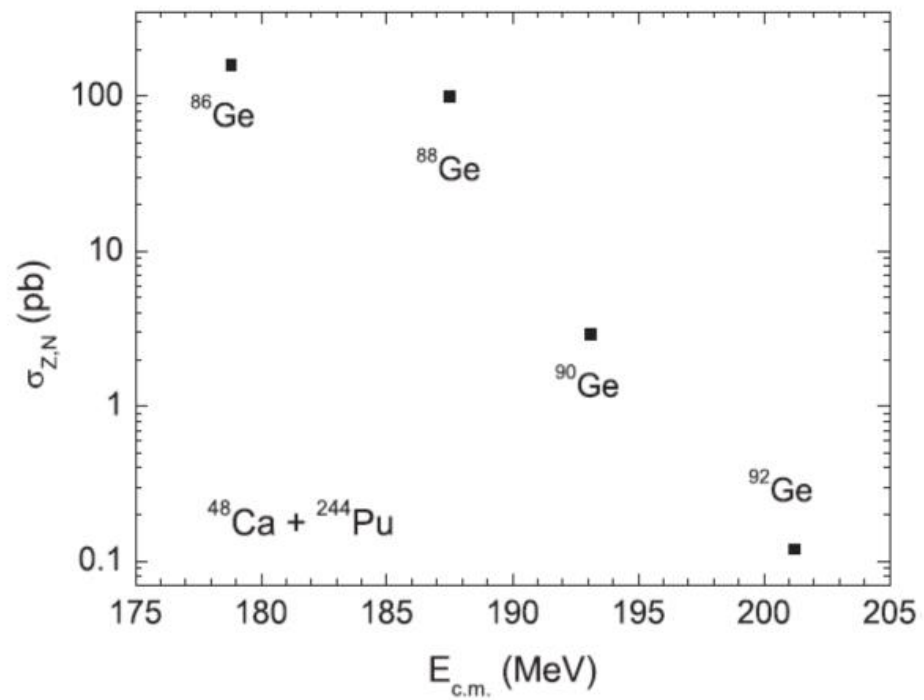
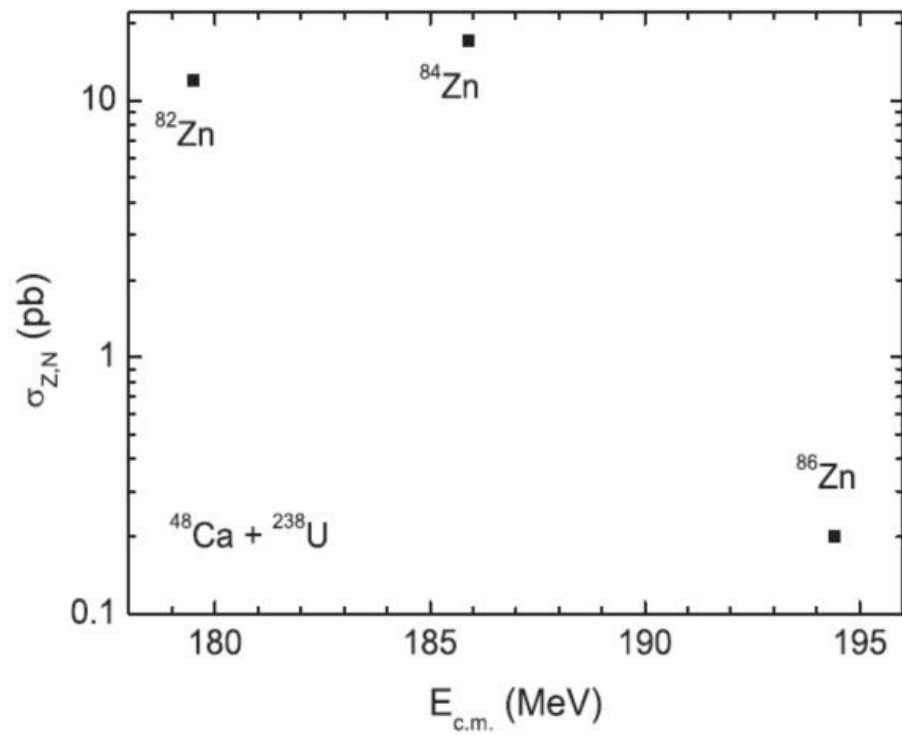
The dinuclear system (DNS) evolution in the reactions treated can be schematically presented in the following way:



and



The system initially moves to the deep minimum of the potential energy surface (energetically favorable) which is caused by the shell effects around the DNS with **magic** heavy ^{208}Pb and **magic** light ^{80}Zn or ^{82}Ge nuclei then from this minimum it reaches the DNS with exotic light nucleus by fluctuations in mass asymmetry.



Possibility of production of neutron-rich isotopes of nuclei with $Z=64-80$ as complementary to light fragments in transfer reaction

$^{48}\text{Ca}(E_{\text{cm}}=189 \text{ MeV}) + ^{238}\text{U}$ at low energies

It should be noted that these isotopes can not be reliably identified among the products of induced fission of actinides and can not be produced in the complete fusion reaction with available stable beams.

