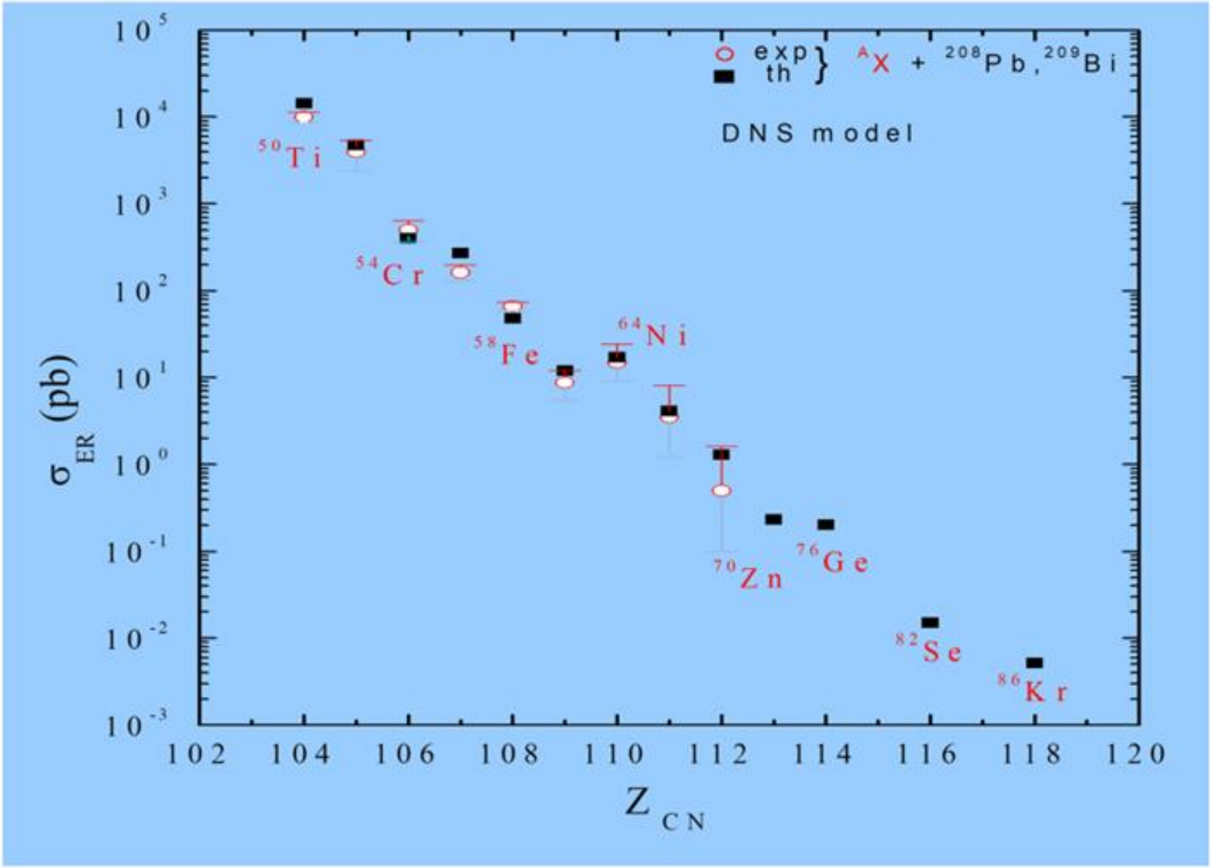
New Perspectives for Cold and Hot Fusion Reactions

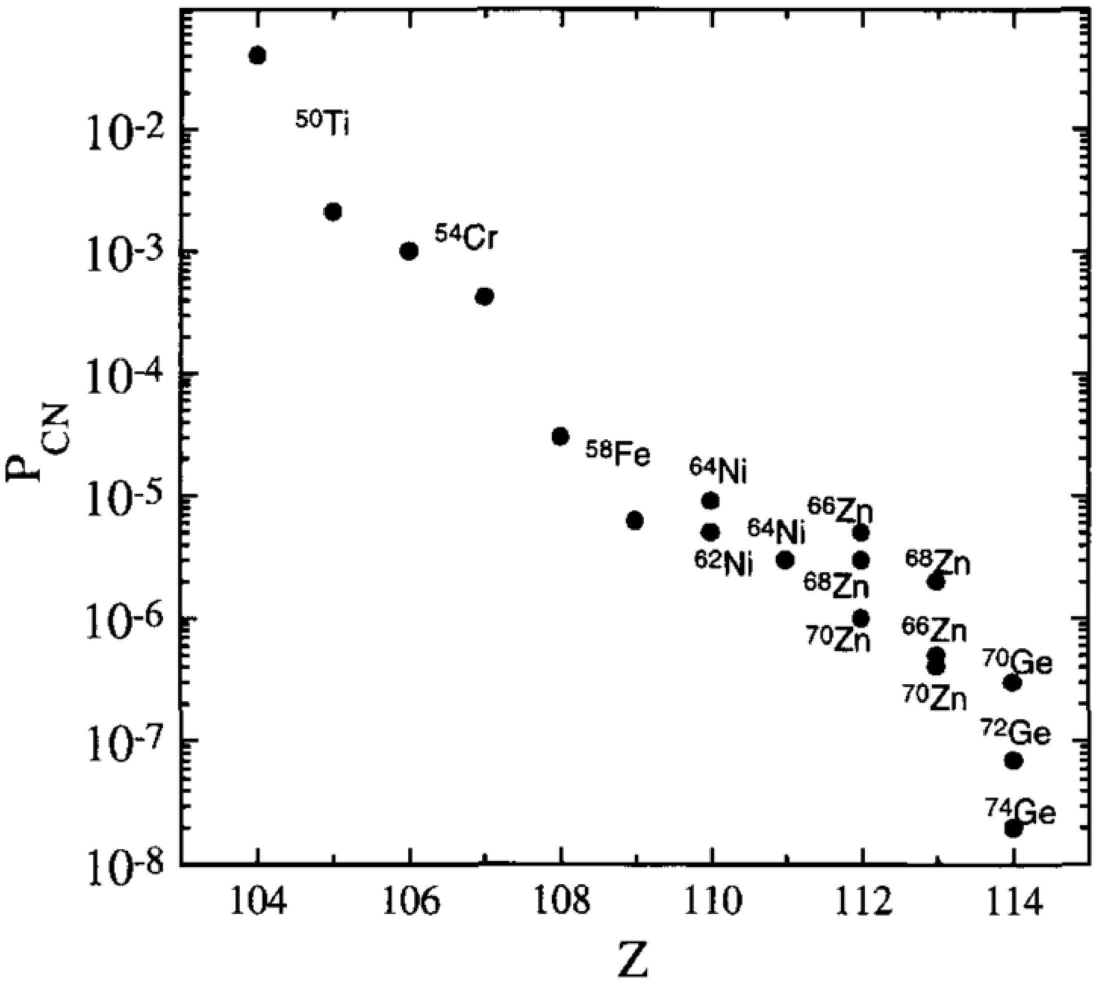
G.G.Adamian and N.V.Antonenko

What interesting fusion reactions can still 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

Qusifission 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

238Pu+20Ne=258Rf*(fission)
208Pb+50Ti=258Rf*(q-fission)

242Cm+20Ne=262Sg*(fission)
208Pb+54Cr=262Sg*(q-fission)

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.

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

Rates Δ depend on single-particle energies

and temperature related to excitation energy.

Only one-nucleon transitions are assumed.

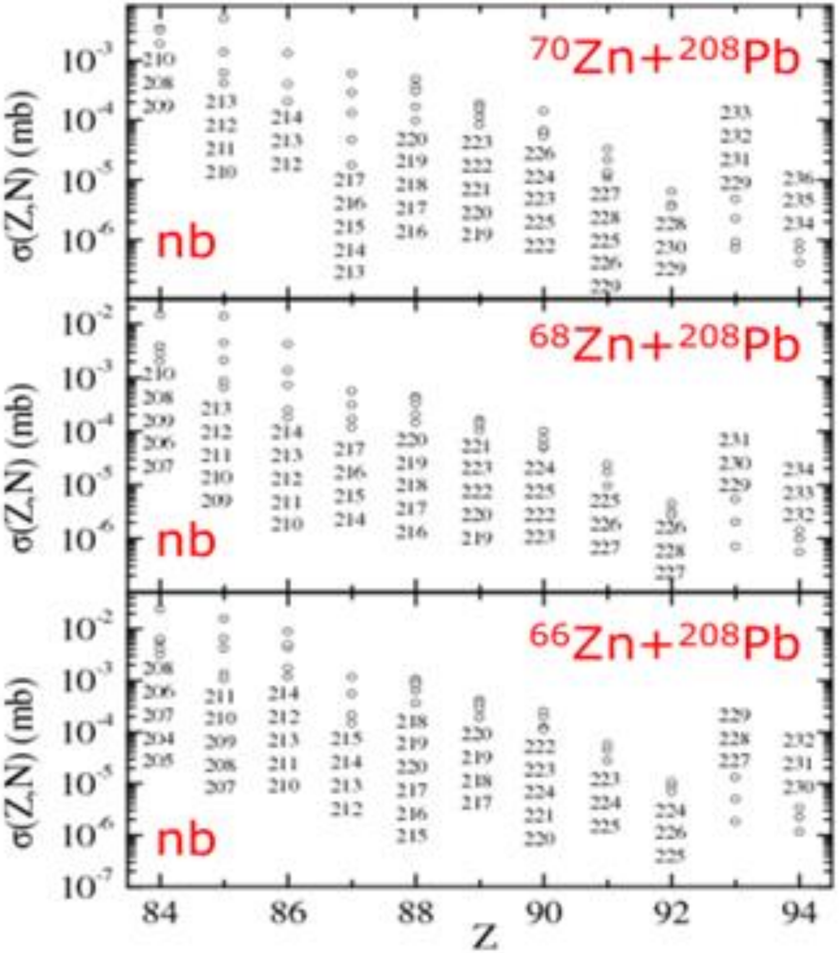
$\Lambda^{qf}_{Z,N}$: rate for decay of dinuclear system

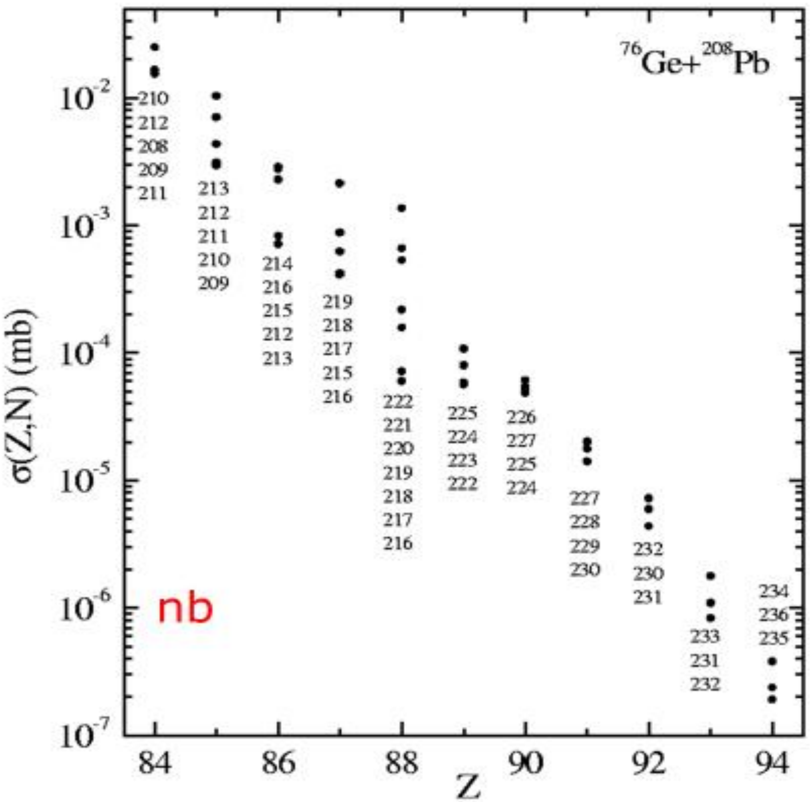
$\Lambda^{fis}_{Z,N}$: rate for fission of heavy nucleus

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

Transfer to more asymmetric systems

It would confirm the fusion in the mass asymmetry coordinate


70Zn+208Pb
68Zn+208Pb
66Zn+208Pb
nb
σ(Z,N) (mb)
Z

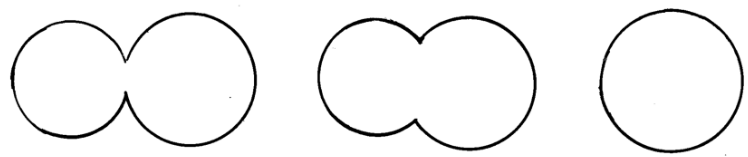


^{76}Ge+^{208}Pb
σ(Z,N) (mb)
Z
nb
210
212
208
209
211
213
212
211
210
209
214
216
215
212
213
219
218
217
215
216
222
221
220
219
218
217
216
225
224
223
222
226
227
225
224
227
228
229
230
232
230
231
233
231
232
234
236
235

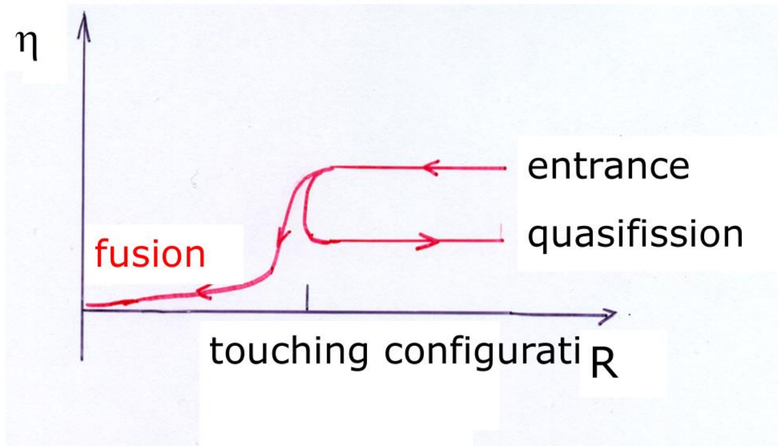
3. Neck dynamics in cold fusion
or
Role of neck in cold fusion

a)Models using adiabatic potentials

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

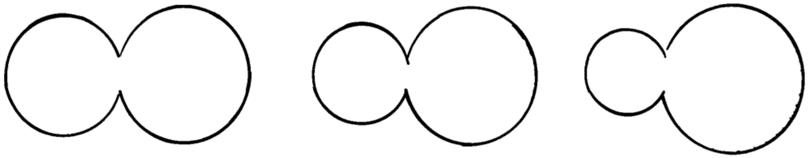


Large probabilities of fusion for producing nuclei with similar projectile and target nuclei.

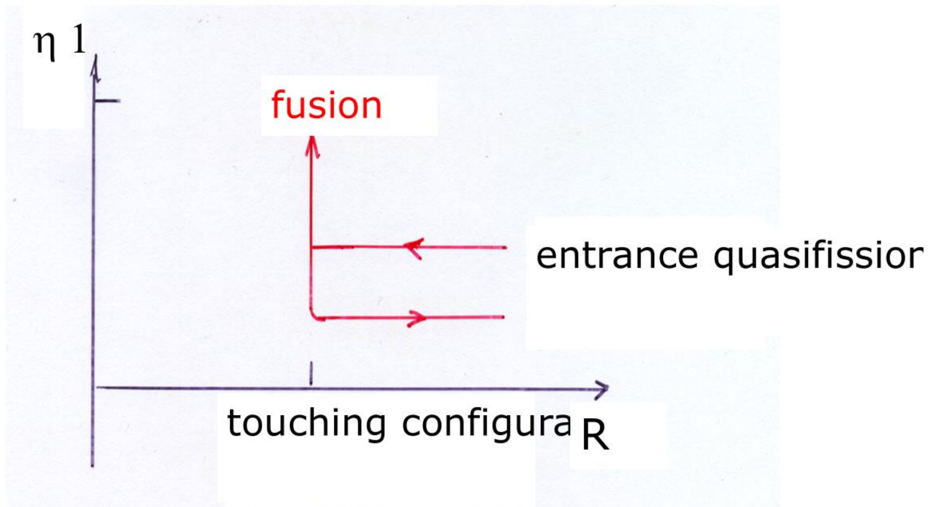

η
entrance
quasifission
fusion
touching configurati
R

b) Dinuclear system (DNS) concept

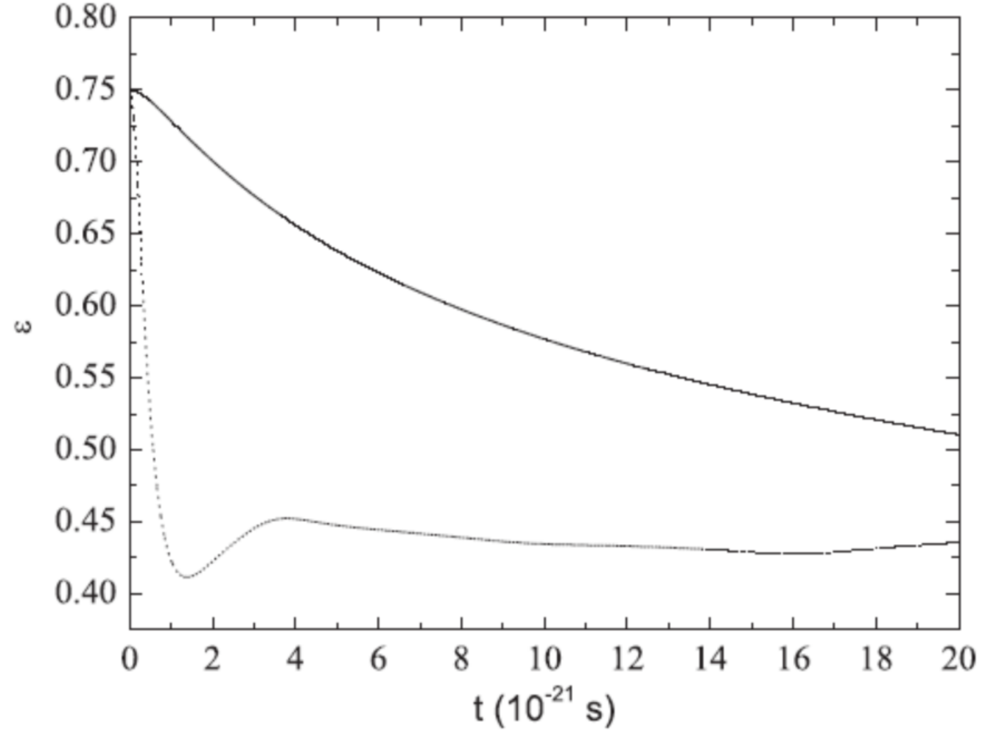
Fusion by transfer of nucleons between the nuclei (idea of V. Volkov, also von Oertzen), mainly dynamics in mass asymmetry degree of freedom, use of diabatic potentials, calculated with the diabatic two-center shell model.



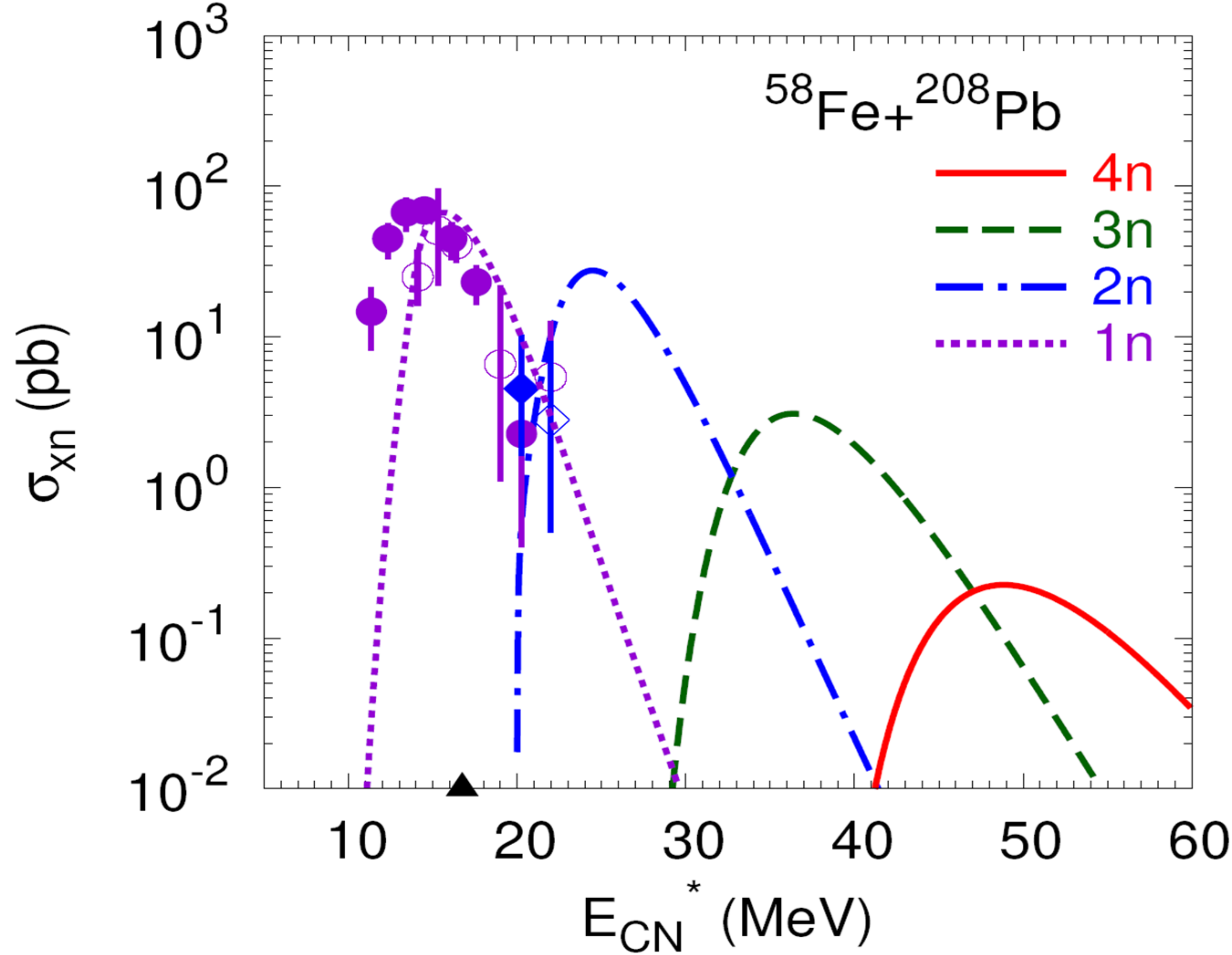
$\eta \to 1$


η 1
fusion
entrance quasifissior
touching configura
R

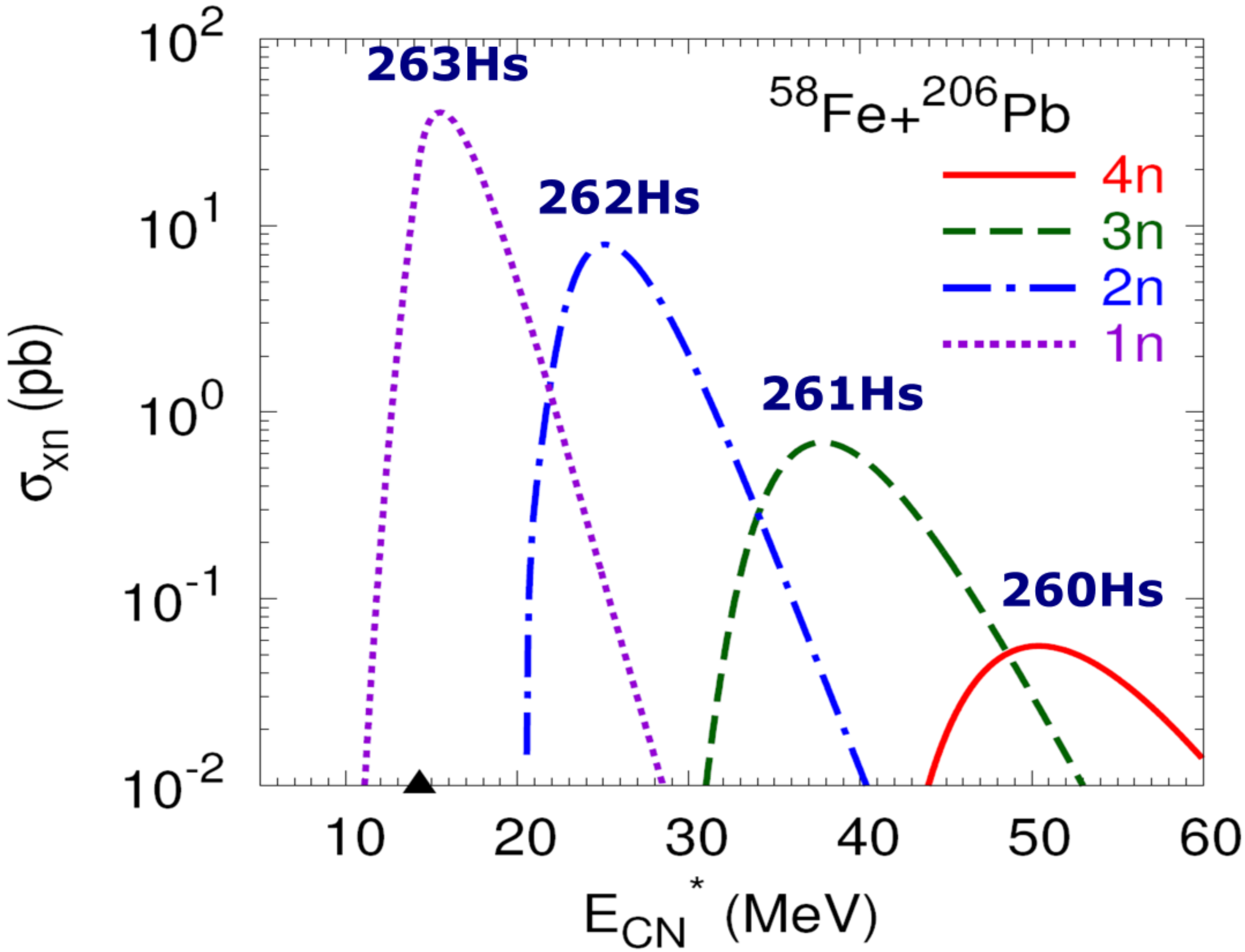
3. Neck dynamics in cold fusion
or
Role of neck in cold fusion



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



$^{58}Fe+^{208}Pb$
4n
3n
2n
1n
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^* (MeV)



263Hs
262Hs
261Hs
260Hs
58Fe+206Pb
4n
3n
2n
1n
σxn (pb)
ECN* (MeV)
10
20
30
40
50
60
10^2
10^1
10^0
10^-1
10^-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

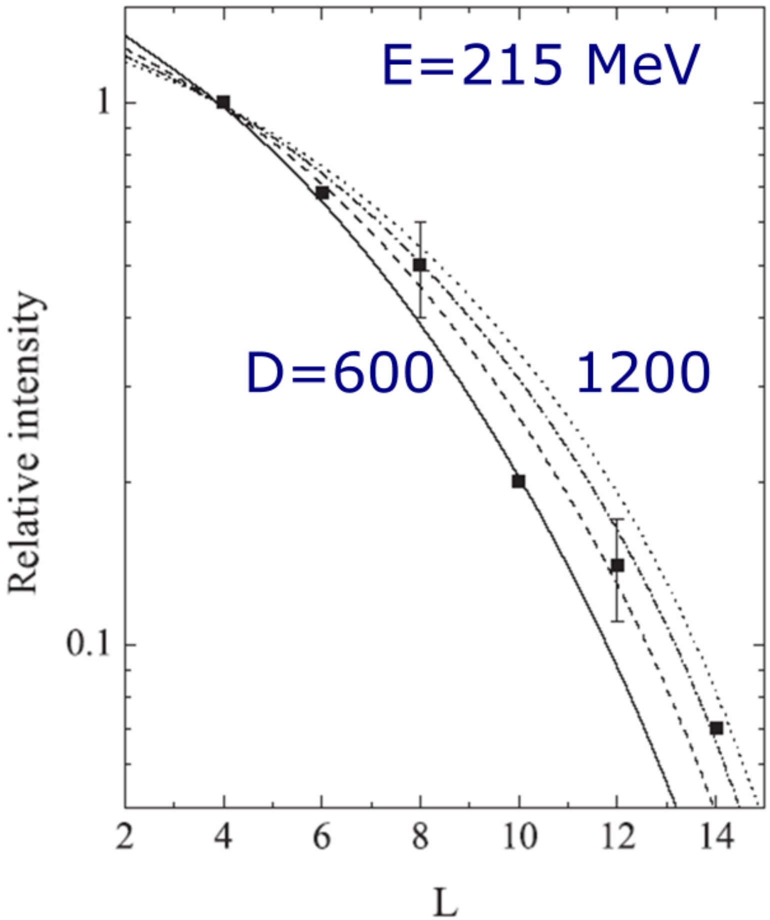
$$B_f(E^*_{CN}, J) = B_f^{LD}(J) + B_f^{M}(E^*_{CN} = 0)$$
$$\times \exp[-E^*_{CN}(J)/E_D] \exp[-J(J+1)/D]$$

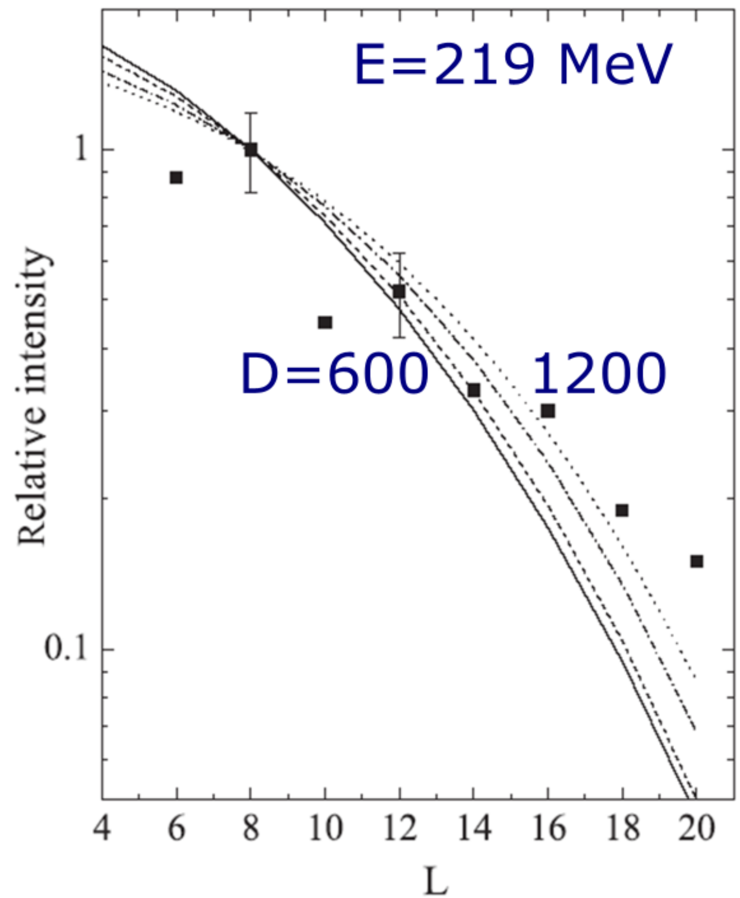
Damping parameter D from exper. data

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

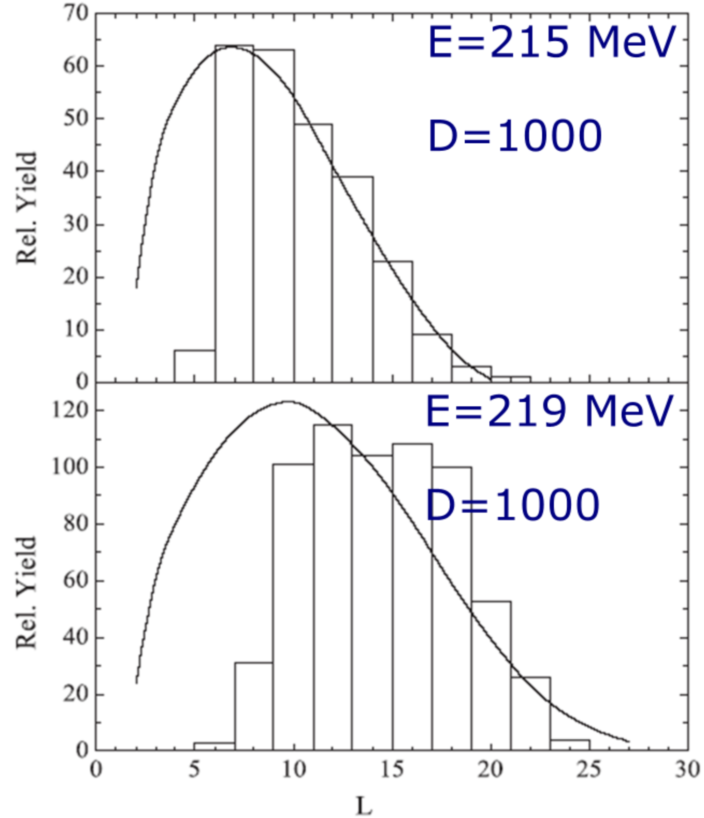
where $\alpha_0 = 0.4$.

$^{48}Ca+^{208}Pb$ -> $^{254}No+2n$



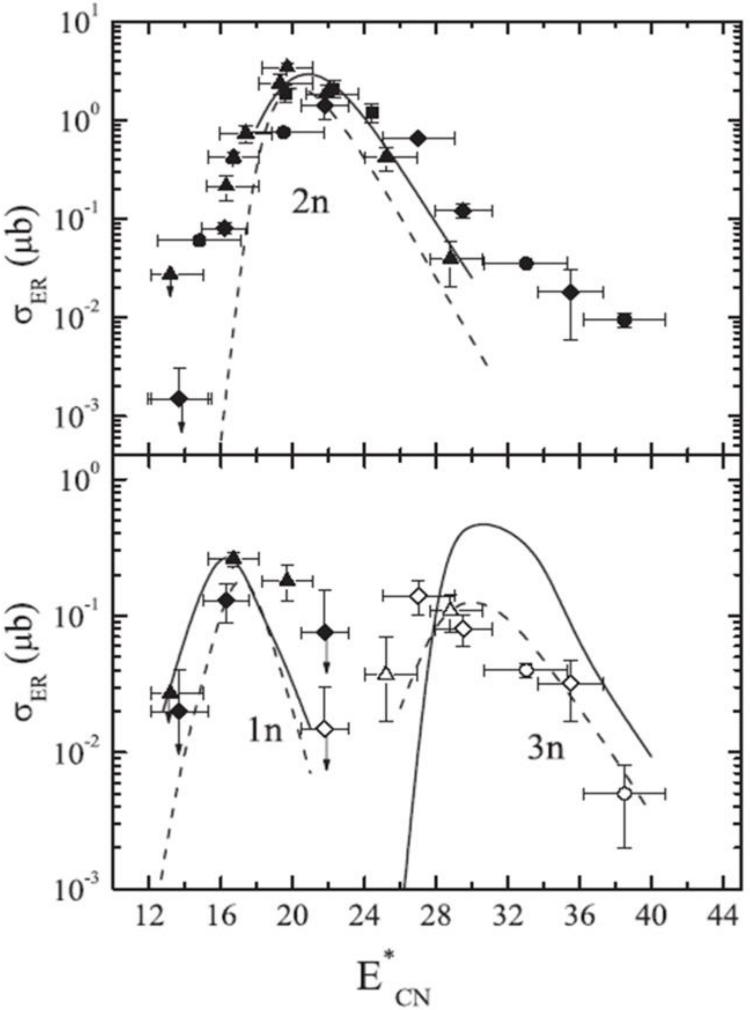


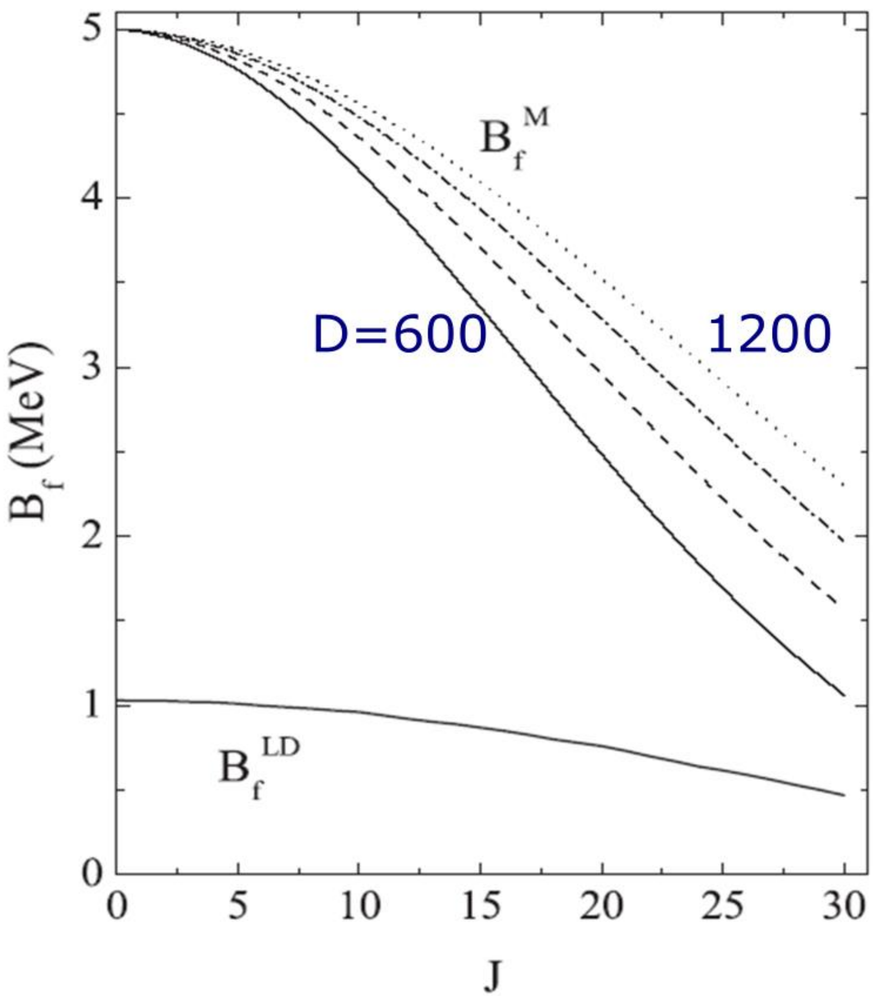
$^{48}Ca+^{208}Pb$ -> $^{254}No+2n$



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

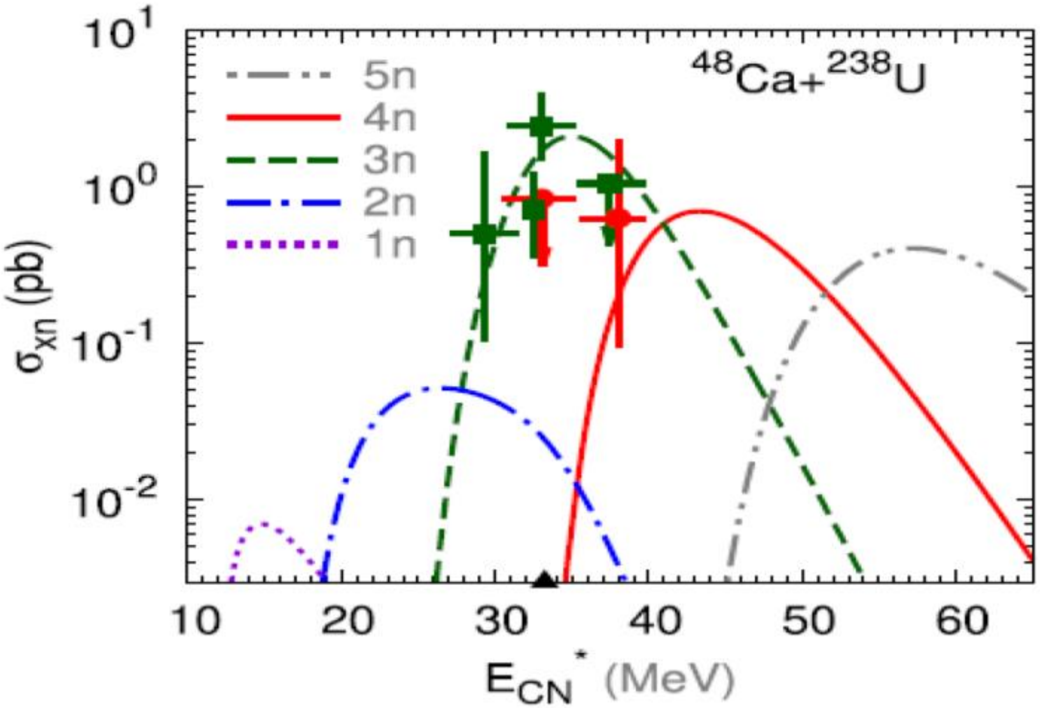
D=1000

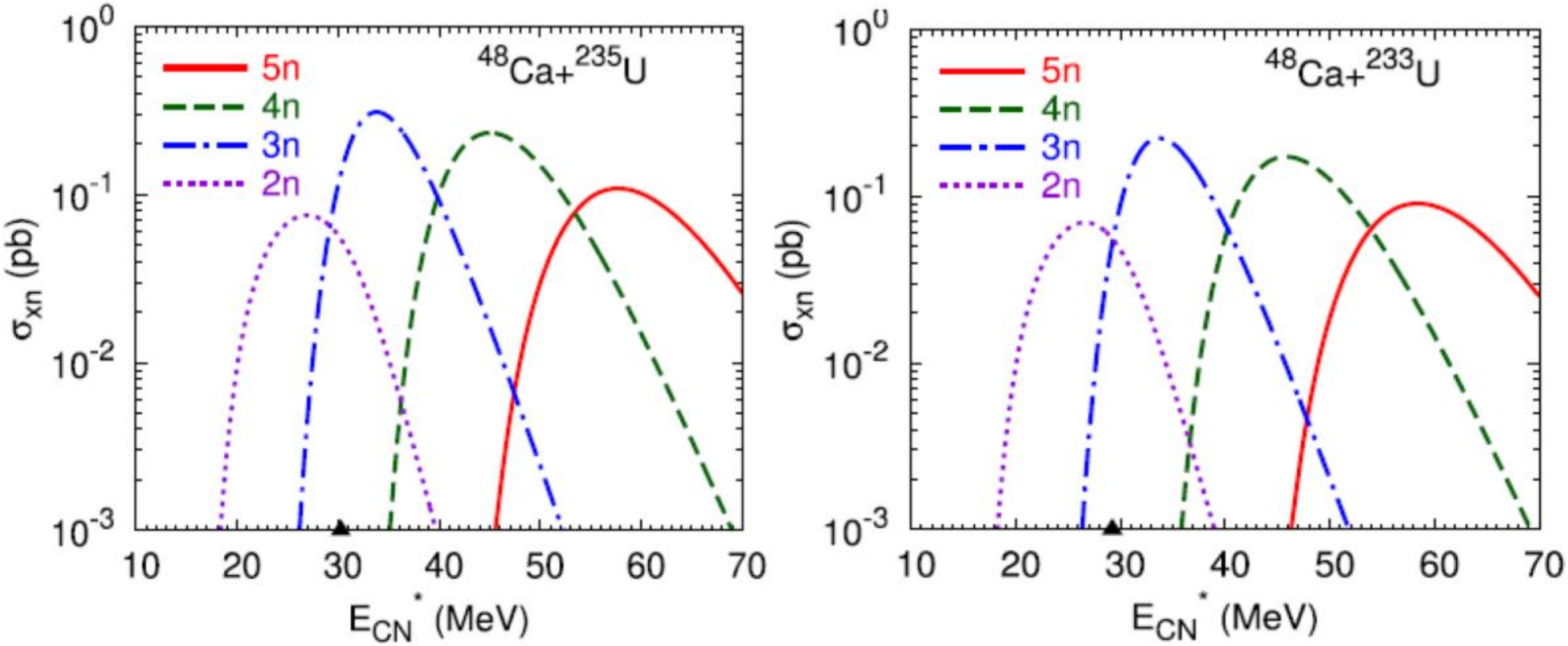




B_f^M
D=600
1200
B_f^{LD}
B_f (MeV)
J
0
1
2
3
4
5
0
5
10
15
20
25
30

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





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

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

$^{48}Ca+^{239}Pu \rightarrow {}^{283}Fl+4n$

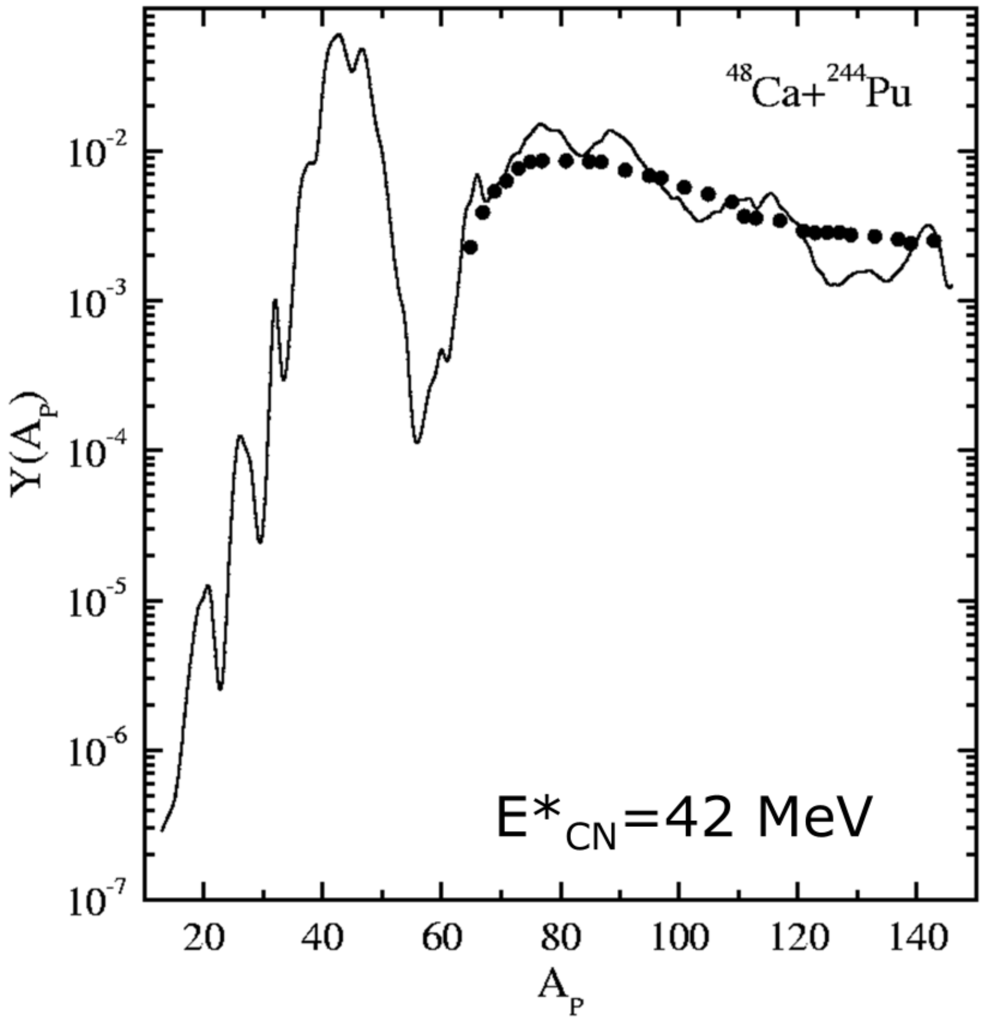
$^{76}Ge+^{208}Pb \rightarrow {}^{283}Fl+1n$

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

$^{48}Ca+^{233}U \rightarrow {}^{277}Cn+4n$

$^{70}Zn+^{208}Pb \rightarrow {}^{277}Cn+1n$

6.Asymmetry-exit-channel quasifission



$^{48}Ca+^{244}Pu$
E^*_{CN}=42 MeV
$Y(A_P)$
A_P
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
20 40 60 80 100 120 140

The measurement of the small yields of the products with Z = 6 – 16 in 48Ca+244Pu 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.

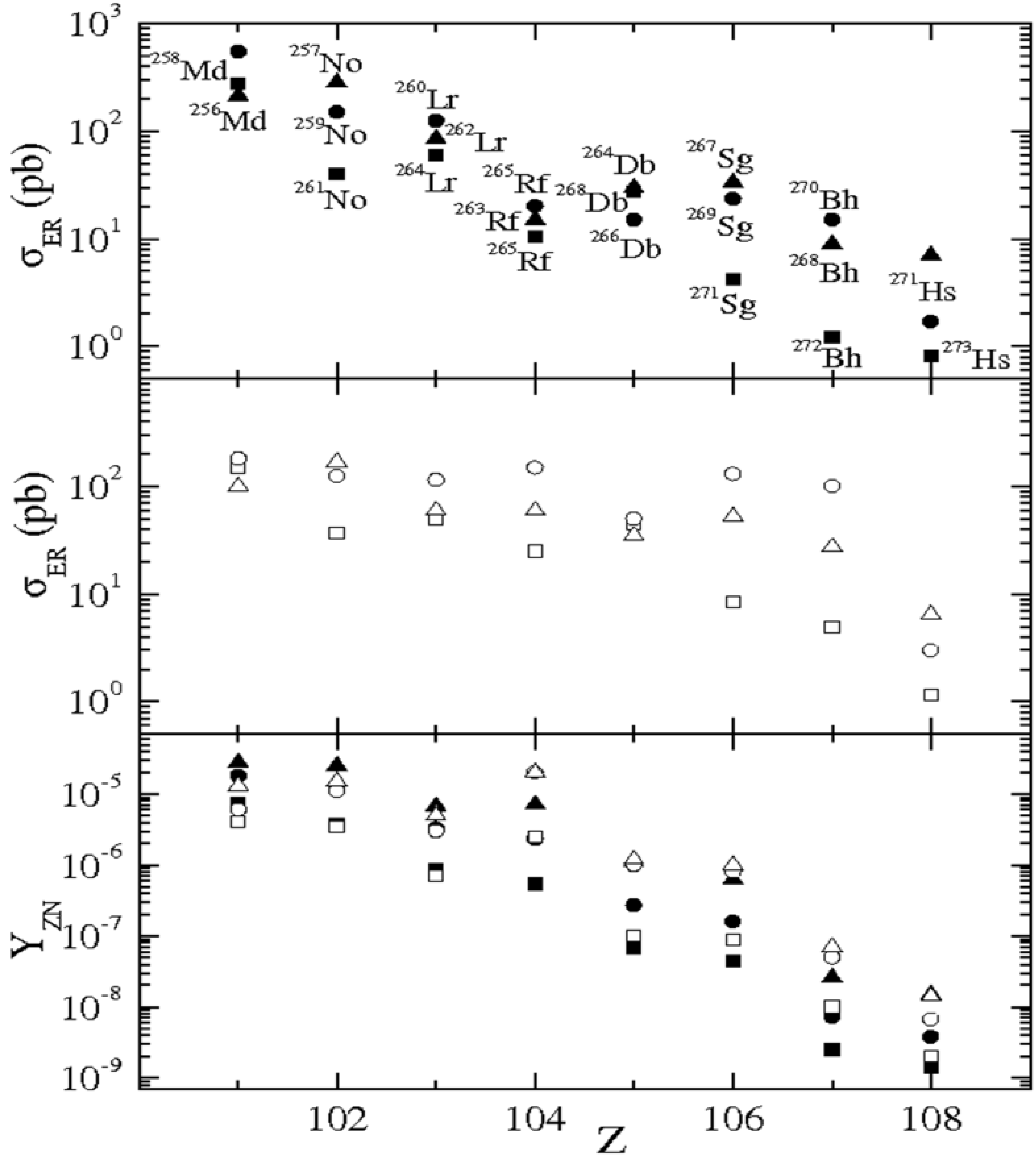
The yield of light products is larger for larger beam energies.

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

$^{48}Ca+^{244}Cm$ ▲ E

$^{48}Ca+^{246}Cm$ ● E$_{c}$

$^{48}Ca+^{248}Cm$ ■ E$_{cr}$

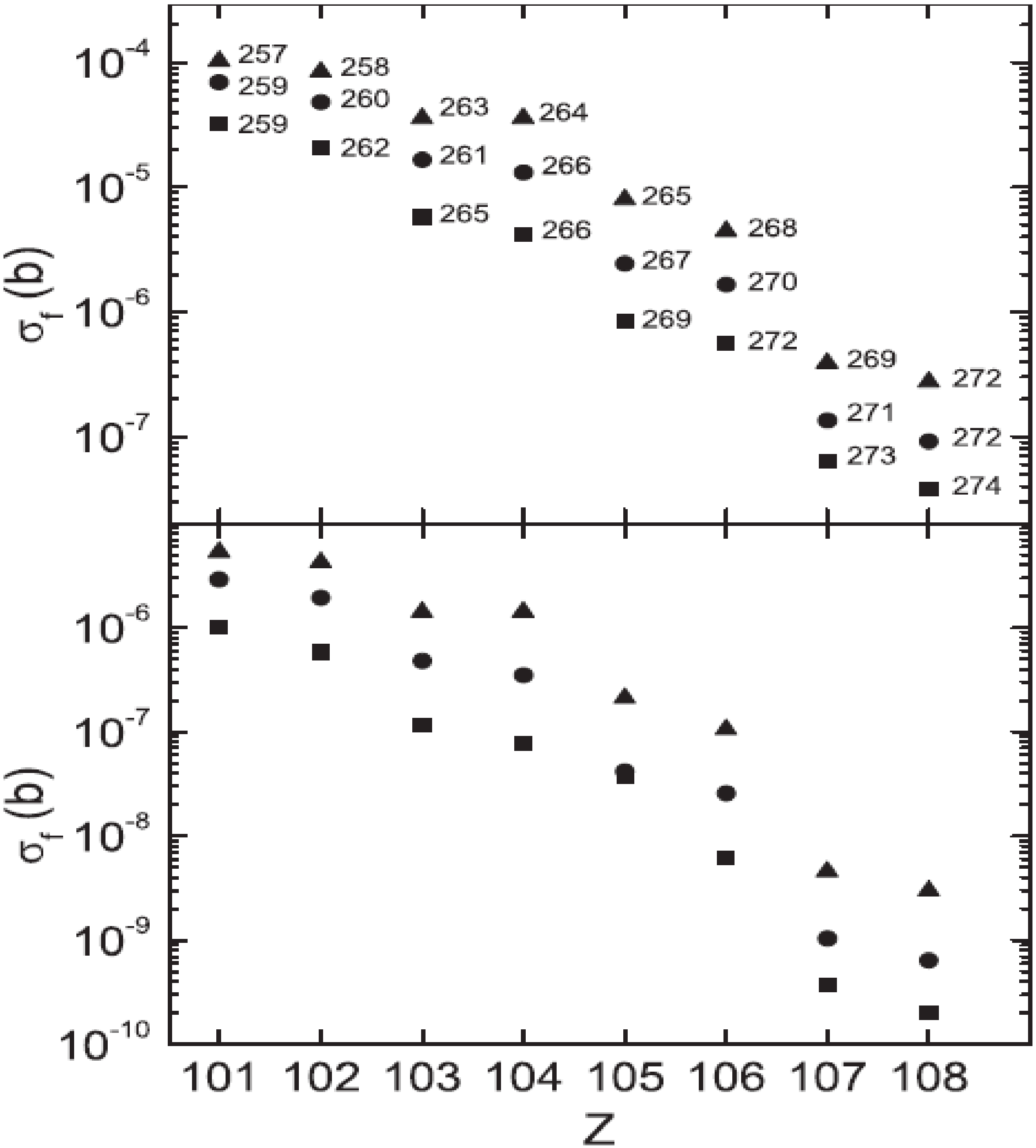


In the asymmetry-exit-channel quasifission reactions ^{48}Ca+Actinides one can produce new isotopes of SHN with Z=104-108, which are not reachable in the hot and cold complete fusion reactions with the stable nuclei.
The production of these isotopes is important for the experimental identification of superheavy nuclei which alpha-decay chains end in the unknown isotope.

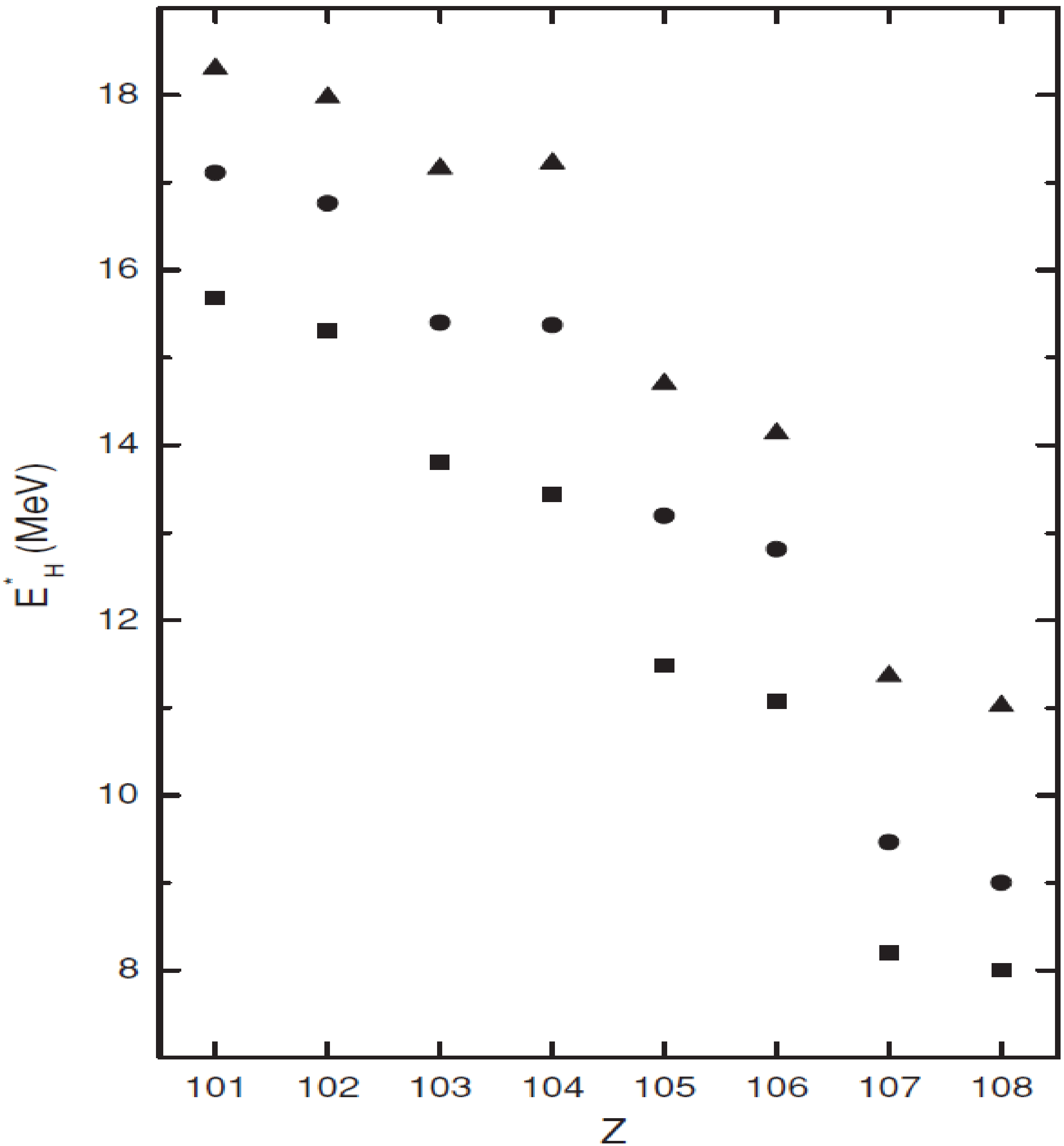
For example, for the complete fusion reaction $^{48}Ca+^{243}Am=^{291-xn}115+xn$ alpha-decay chains end at unknown nucleus $^{267,268}Db$ (Z=105).

Study of transfer-induced fission of SHN

48Ca+244-248Cm



257
259
259
258
260
262
263
261
265
264
266
266
265
267
269
268
270
272
269
271
273
272
272
274
σ_f (b)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
101
102
103
104
105
106
107
108
Z



18
16
14
12
10
8
E*H (MeV)
101
102
103
104
105
106
107
108
Z

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

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

and

$^{48}Ca(E_{cm}=201$ MeV) + ^{244}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.

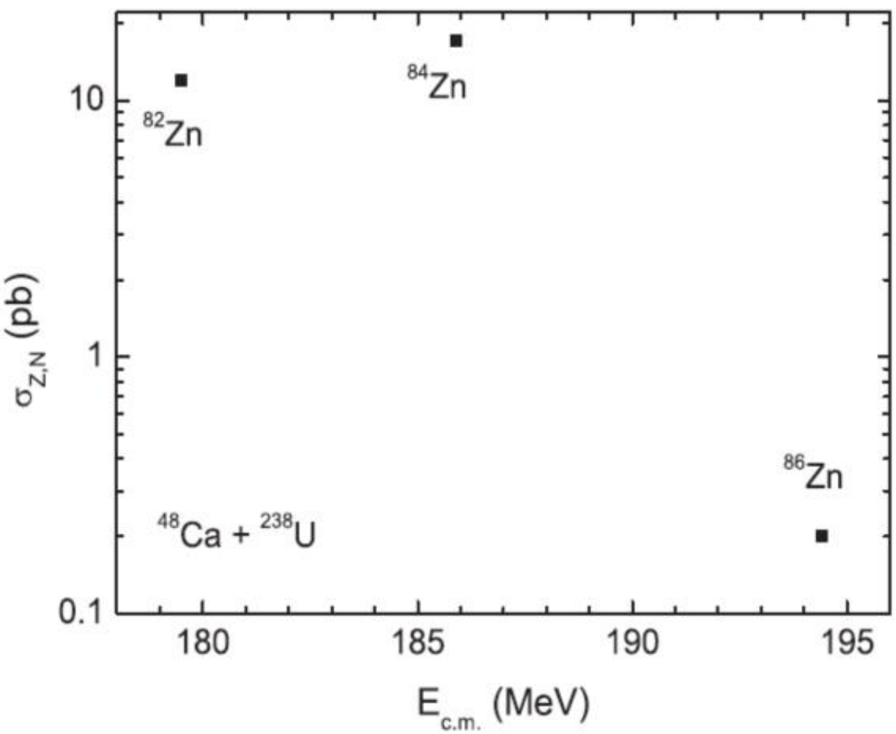
The dinuclear system (DNS) evolution in the reactions treated can be schematically presented in the following way:

$^{48}Ca + ^{238}U \rightarrow ^{78,80}Zn + ^{208,206}Pb \rightarrow ^{82,84,86}Zn + ^{204,202,200}Pb$

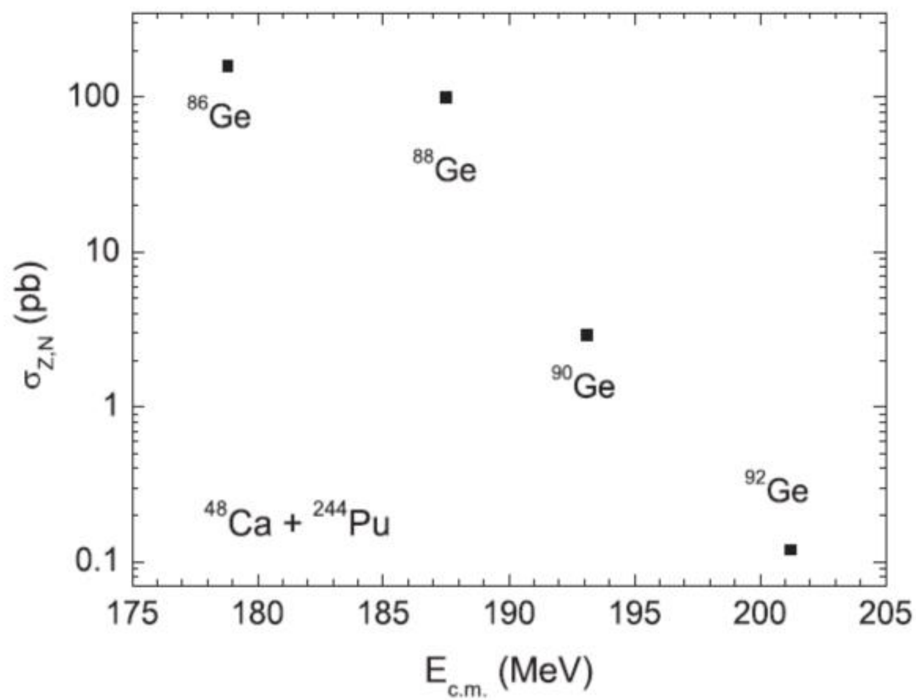
and

$^{48}Ca + ^{244}Pu \rightarrow ^{84,82}Ge + ^{208,210}Pb \rightarrow ^{88,90,92}Ge + ^{204,202,200}Pb$

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.



σZ,N (pb)
Ec.m. (MeV)
82Zn
84Zn
86Zn
48Ca + 238U

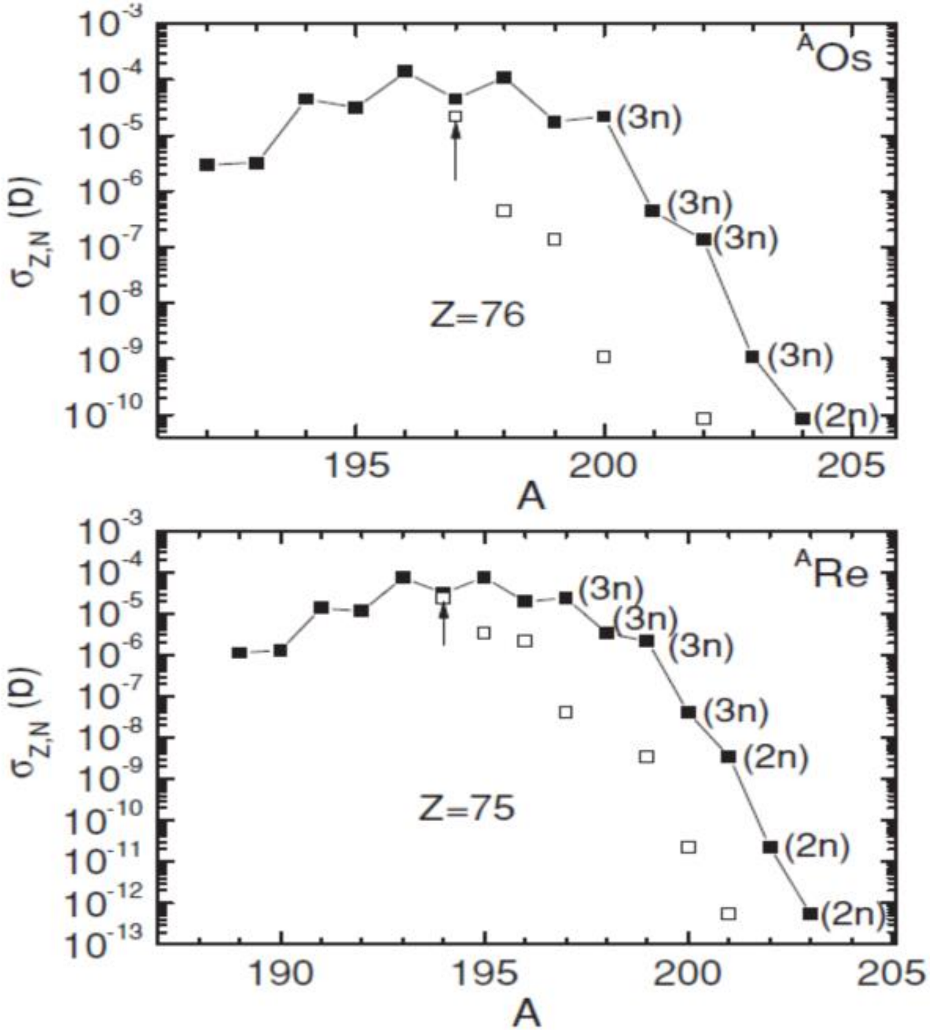


σZ,N (pb)
Ec.m. (MeV)
86Ge
88Ge
90Ge
92Ge
48Ca + 244Pu

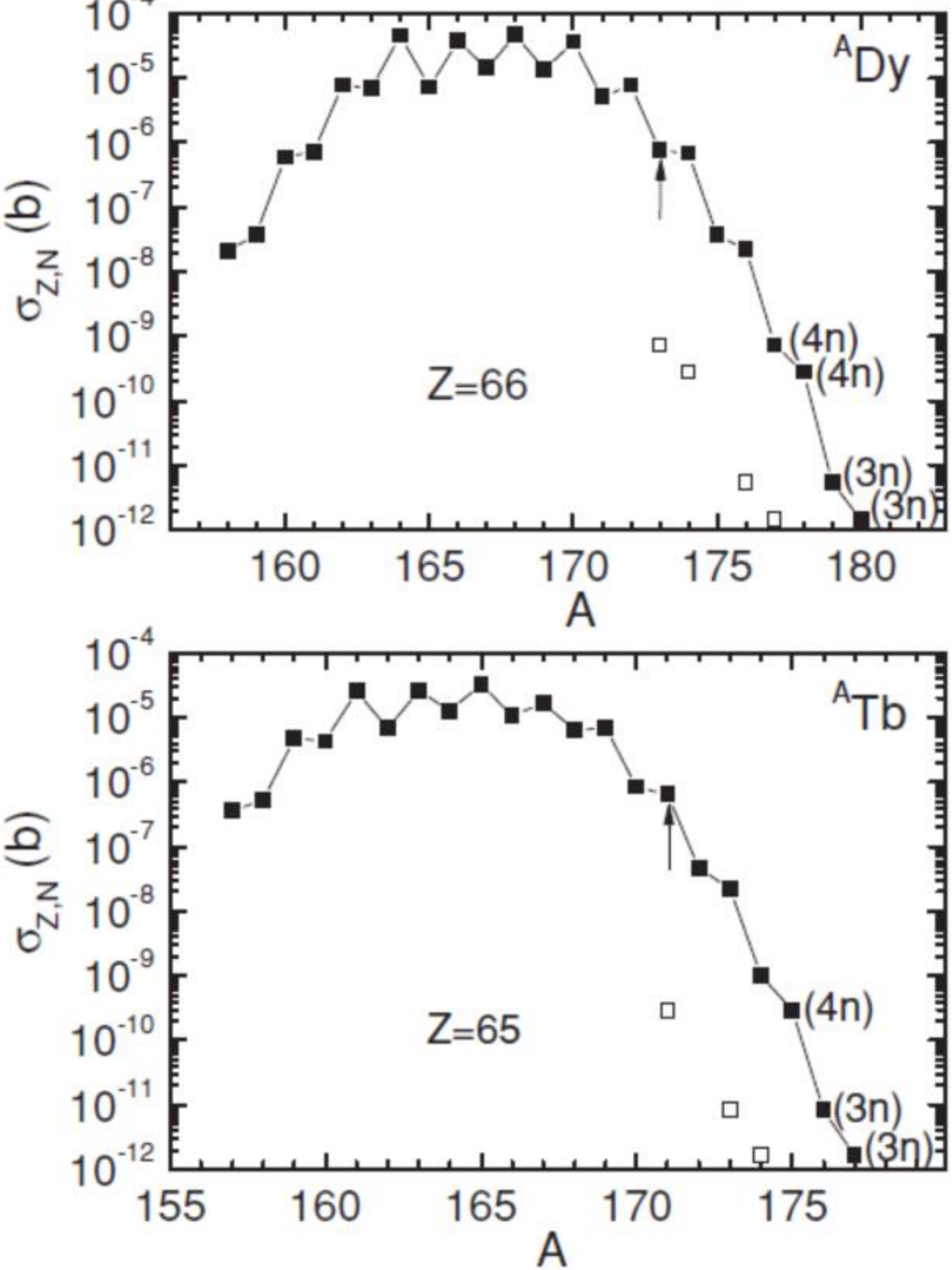
Possibility of production of neutron-rich isotopes of nuclei with Z=64-80 as complementary to light fragments in transfer reaction

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

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



^{A}Os
Z=76
(3n)
(3n)
(3n)
(3n)
(2n)
$\sigma_{Z,N}$ (b)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
195
200
205
A
^{A}Re
Z=75
(3n)
(3n)
(3n)
(3n)
(2n)
(2n)
(2n)
$\sigma_{Z,N}$ (b)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
190
195
200
205
A



^{A}Dy
Z=66
(4n)
(4n)
(3n)
(3n)
$\sigma_{Z,N}$ (b)
A
^{A}Tb
Z=65
(4n)
(3n)
(3n)
$\sigma_{Z,N}$ (b)
A