Complete Fusion

of heavy nuclei

or

fusion mechanism

Contents

Work of

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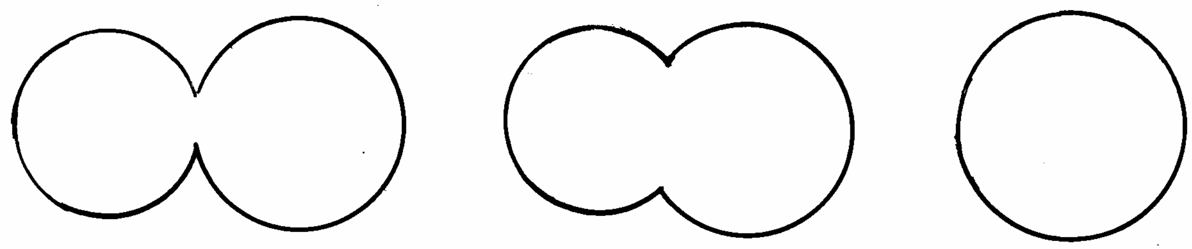
1. Fusion models with adiabatic and diabatic potentials

Main collective coordinates are used for the description of the fusion process:

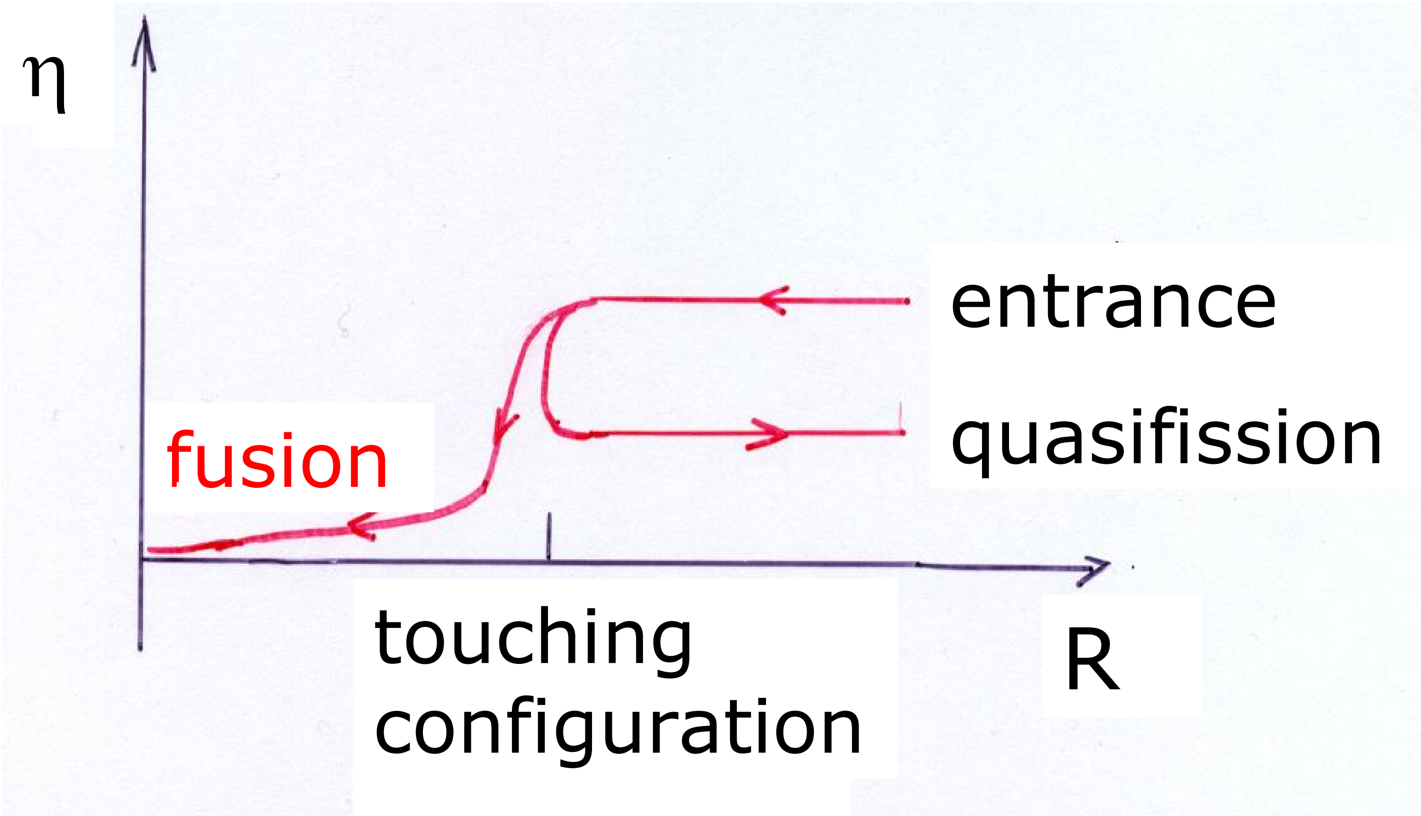
1. Relative internuclear distance R
2. Mass (charge) asymmetry coordinate η
3. Neck parameter
4. Nuclear deformations

a) Models using adiabatic potentials

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

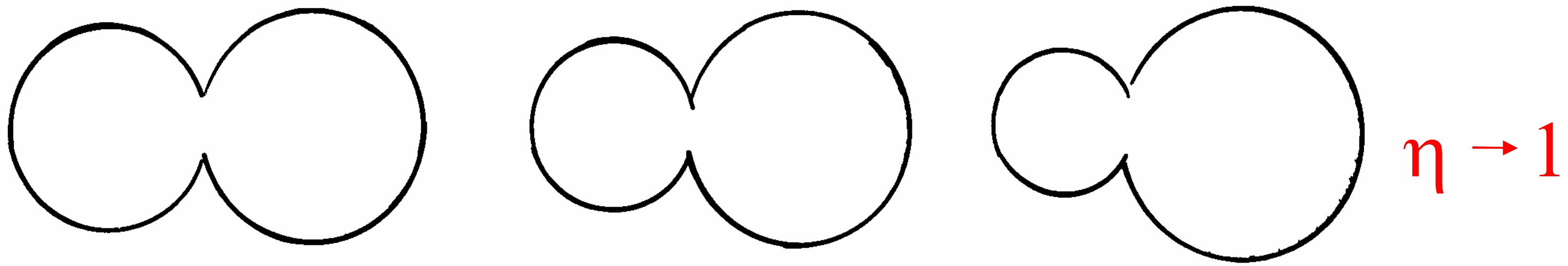


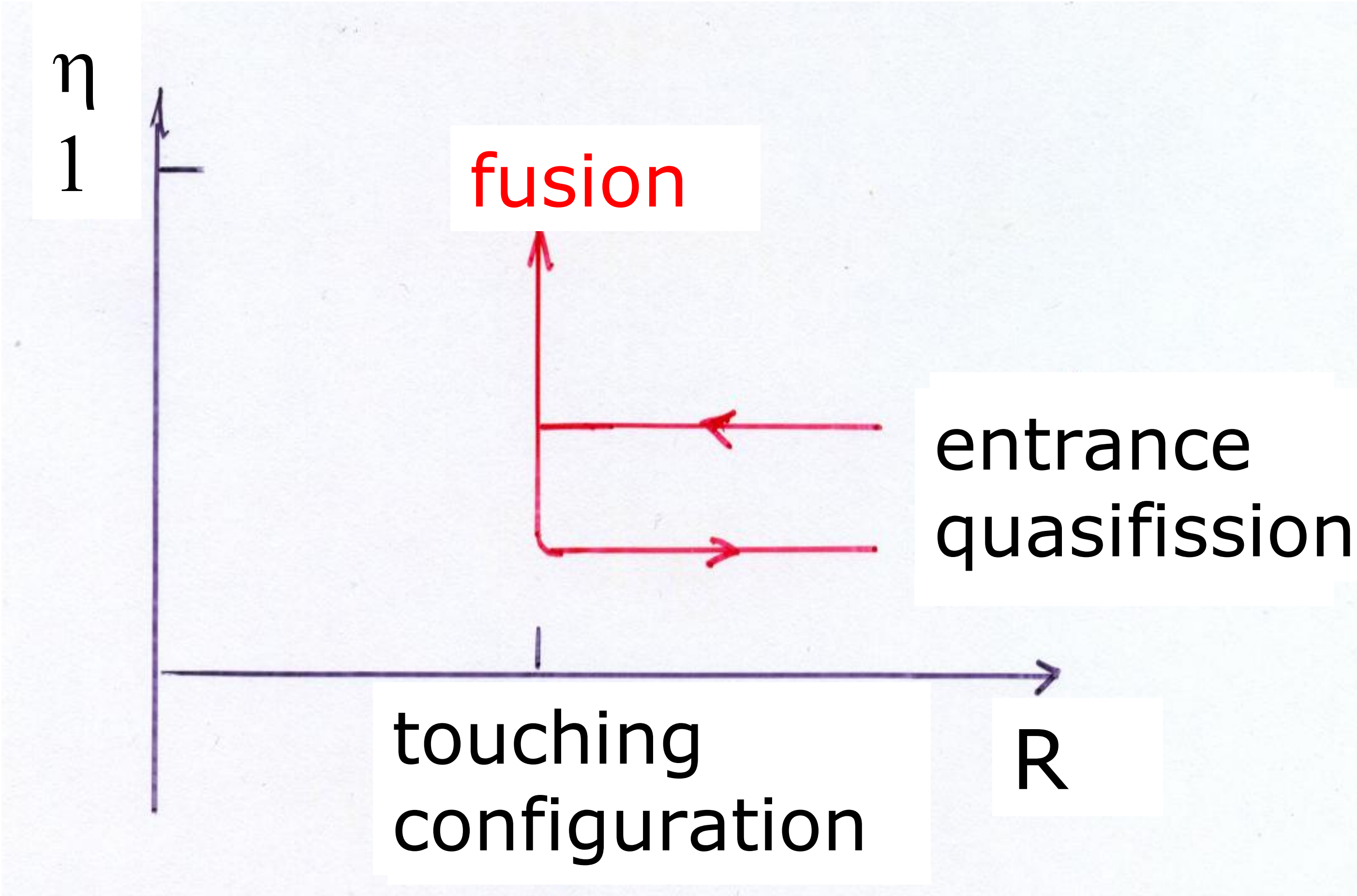
Large probabilities of fusion for producing nuclei with similar projectile and target nuclei.


η
entrance
quasifission
fusion
touching
configuration
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, e.g. calculated with the diabatic two-center shell model.

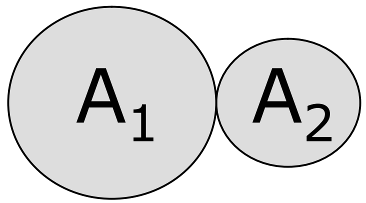



η
1
fusion
entrance
quasifission
touching
configuration
R

Idea of Volkov (Dubna) to describe fusion reactions with the dinuclear system concept:

Fusion is assumed as a transfer of nucleons (or clusters) from the lighter nucleus to the heavier one in a dinuclear configuration.

This process is describable with the mass asymmetry coordinate $\eta=(A_1-A_2)/(A_1+A_2)$.



If A_1 or A_2 get small, then $|\eta|\rightarrow 1$ and the system fuses.

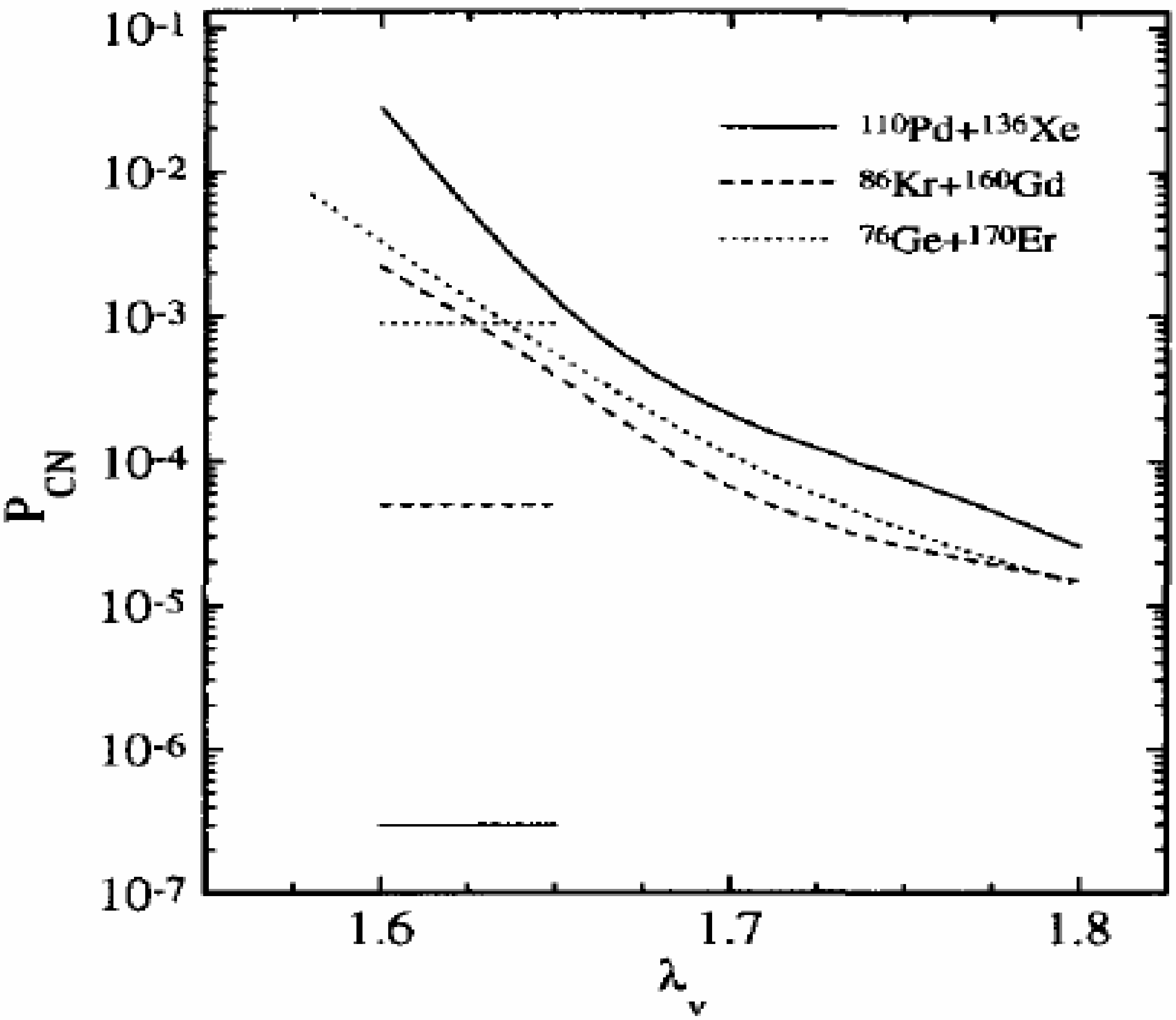
The dinuclear system model uses two main degrees of freedom to describe the fusion and quasifission processes:

1. Relative motion of nuclei,
   capture of target and projectile into dinuclear system,
   decay of the dinuclear system: quasifission
2. Transfer of nucleons between nuclei,
   change of mass and charge asymmetries leading to fusion and quasifission

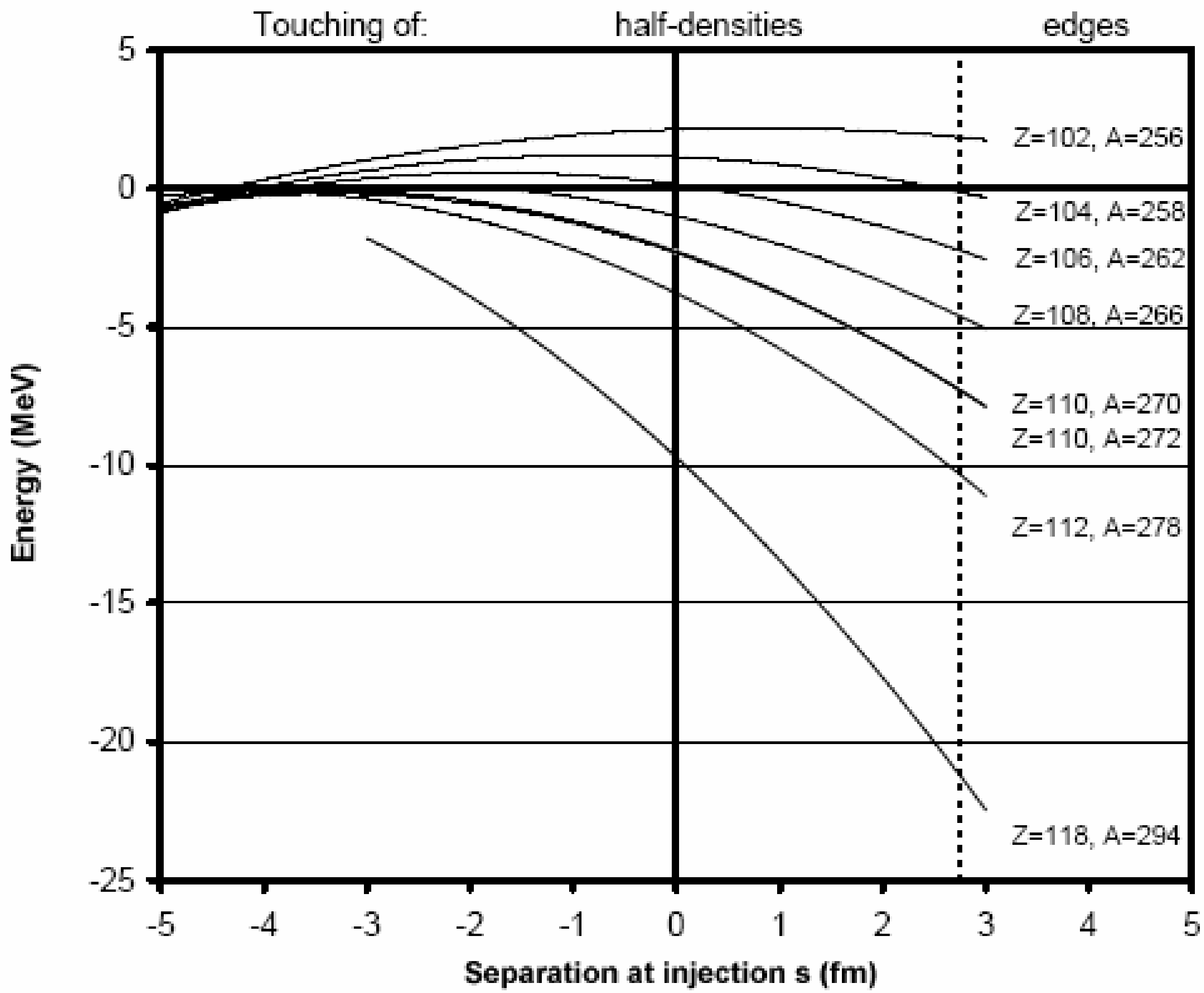
3. Dynamics of fusion in the dinuclear system model

Evaporation residue cross section for the production of superheavy nuclei:

$$\sigma_{ER}(E_{cm}, J) = \sum_{J=0}^{J_{max}} \sigma_{cap}(E_{cm}, J) P_{CN}(E_{cm}, J) W_{sur}(E_{cm}, J)$$



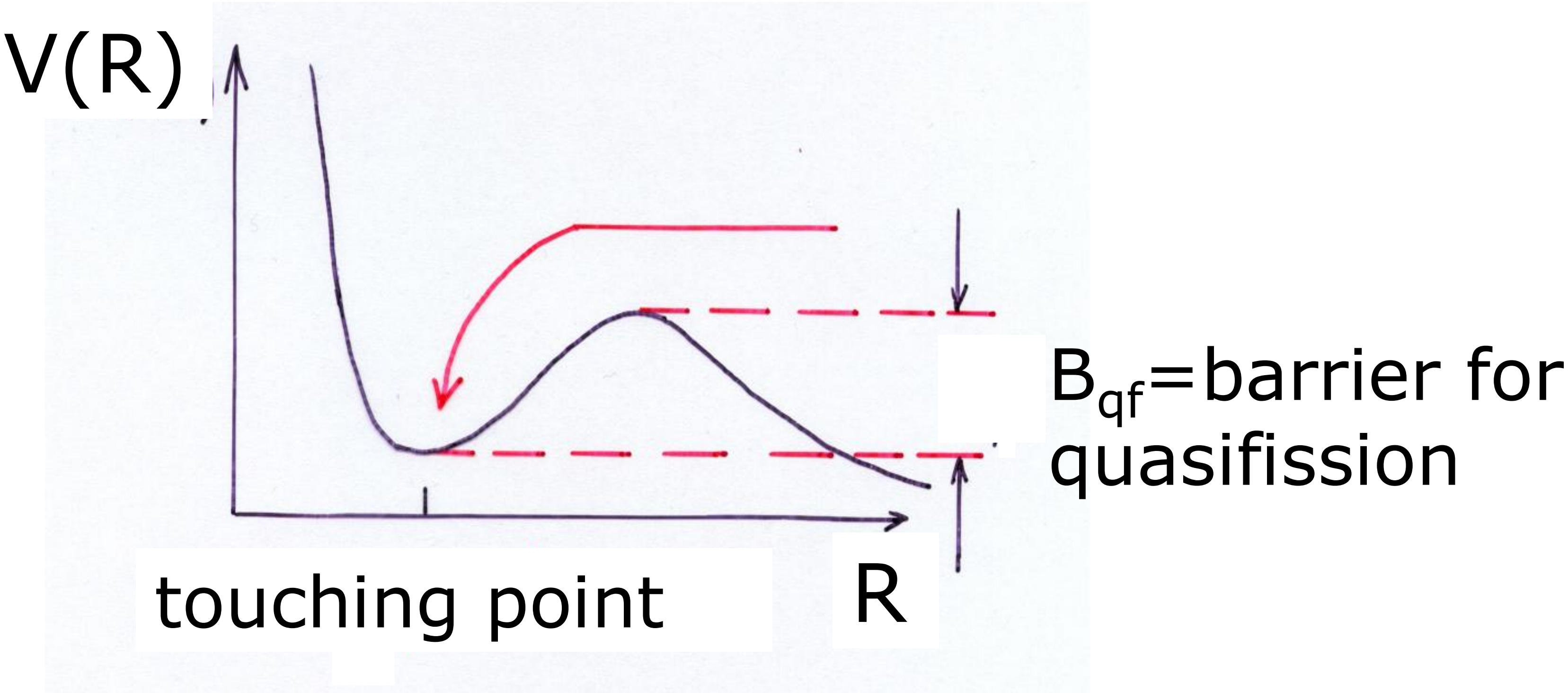
10-1
10-2
10-3
10-4
10-5
10-6
10-7
P_CN
1.6
1.7
1.8
λ_v
110Pd+136Xe
86Kr+160Gd
76Ge+170Er



Touching of:
half-densities
edges
Z=102, A=256
Z=104, A=258
Z=106, A=262
Z=108, A=266
Z=110, A=270
Z=110, A=272
Z=112, A=278
Z=118, A=294
Energy (MeV)
Separation at injection s (fm)
5
0
-5
-10
-15
-20
-25
-5
-4
-3
-2
-1
0
1
2
3
4
5

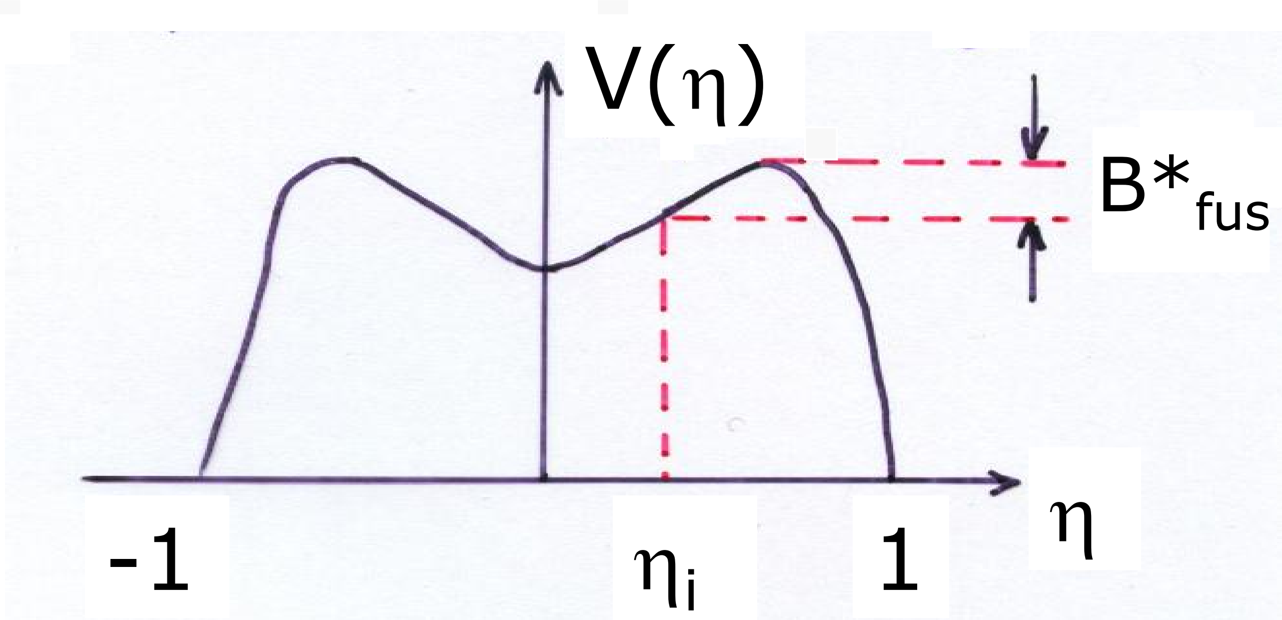
a) Partial capture cross section σ_{cap}

Dinuclear system is formed at the initial stage of the reaction, kinetic energy is transferred into potential and excitation energy.

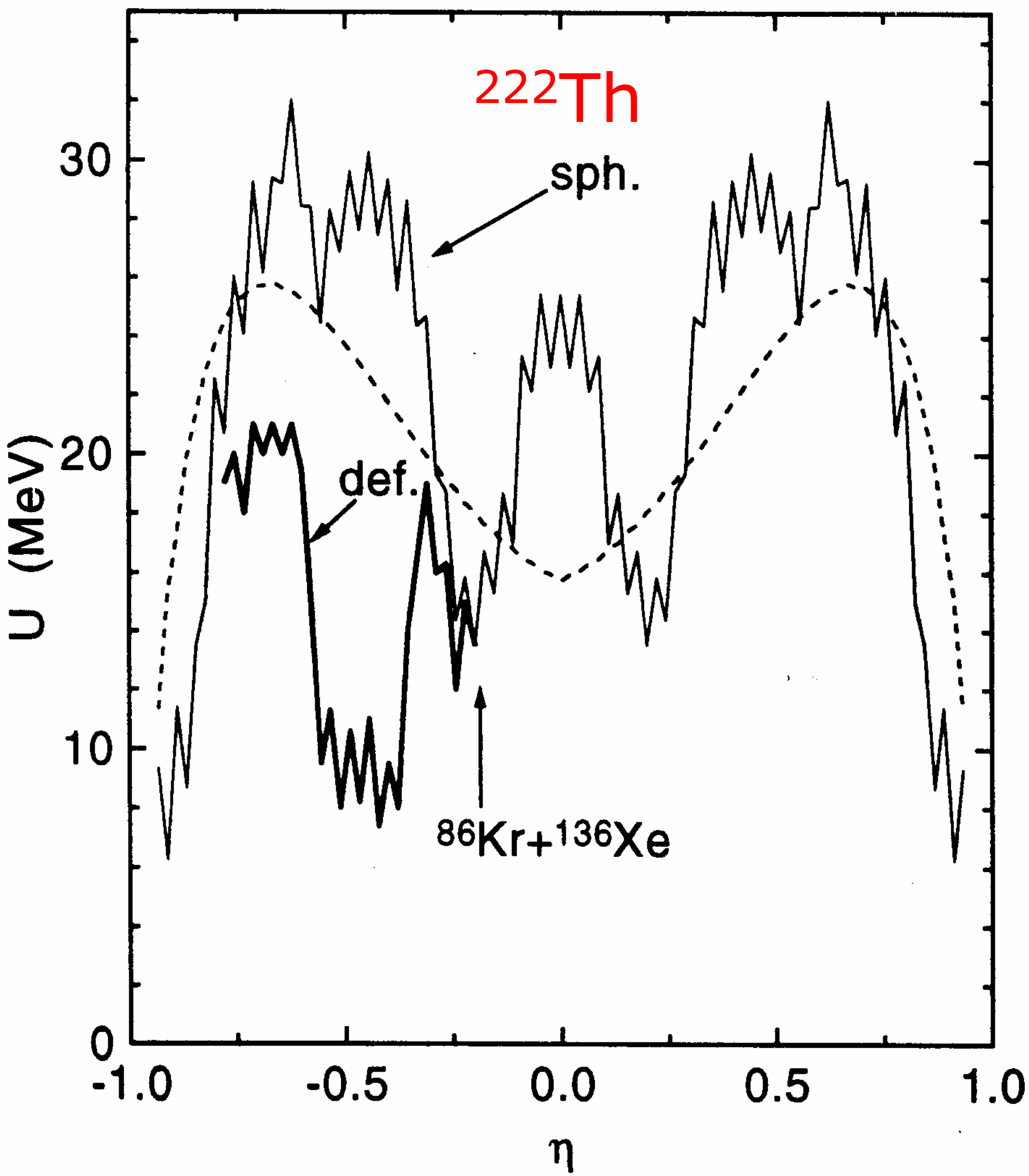


b) Probability for complete fusion P_{CN}

DNS evolves in mass asymmetry coordinate by diffusion processes toward fusion and in the relative coordinate toward the decay of the dinuclear system which is quasifission.



B^*_{fus}=inner fusion barrier


^{222}Th
sph.
def.
^{86}Kr+^{136}Xe
U (MeV)
η
0
10
20
30
-1.0
-0.5
0.0
0.5
1.0

Competition between fusion and quasifission, both processes are treated simultaneously.

Calculation of P_{CN} and mass and charge distributions in η and R:

Fokker-Planck equation, master equations, Kramers approximation

Kramers formula for P_{CN}:

Rate for fusion: $\Lambda_{\eta\ fus}$

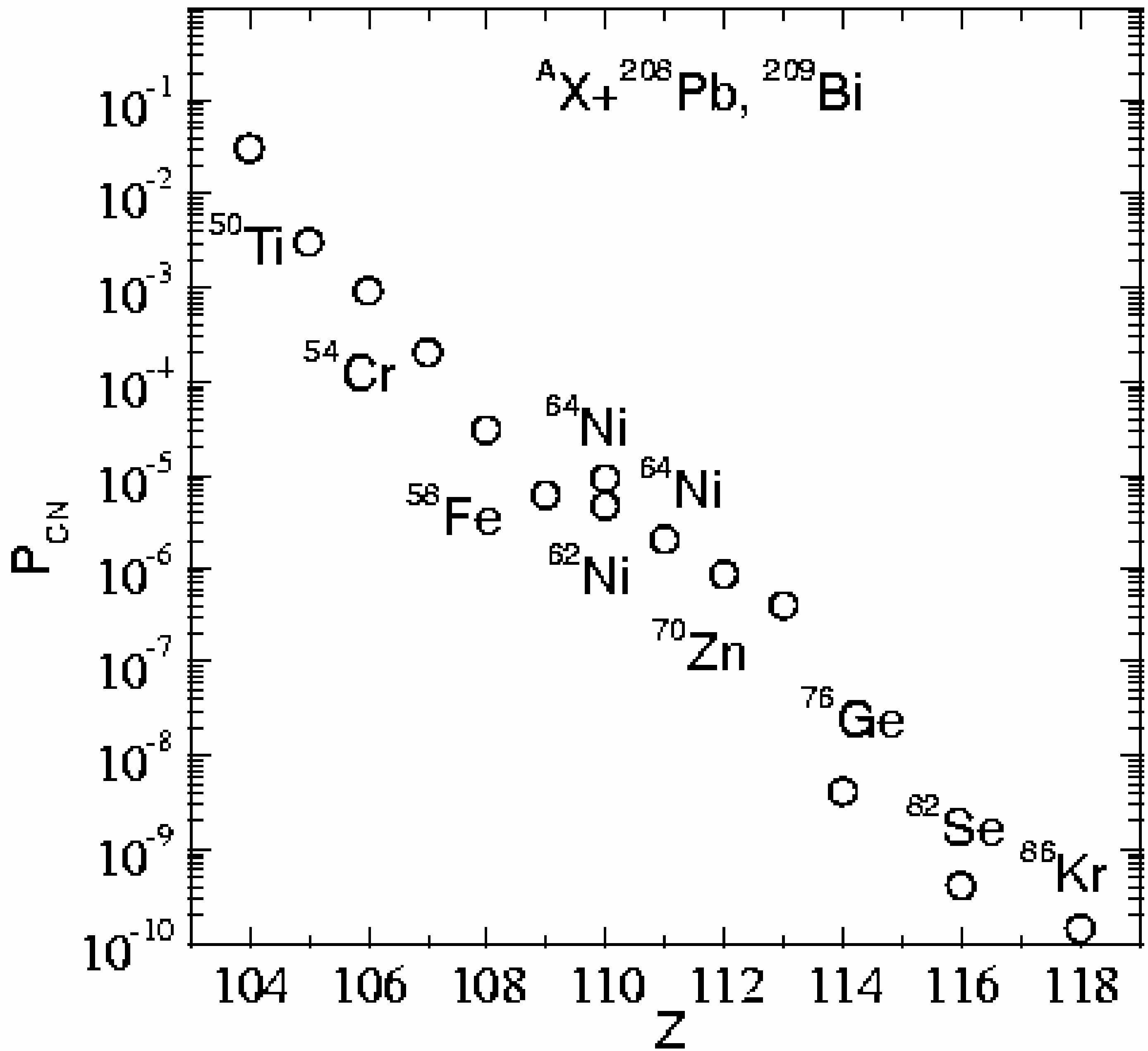
Rate for quasifission: $\Lambda_{qf} = \Lambda_R + \Lambda_{\eta\ sym}$, i.e. decay in R and diffusion in η to more symmetric DNS.

$$P_{CN} = \frac{\Lambda_{\eta fus}}{\Lambda_{\eta fus} + \Lambda_{qf}}$$

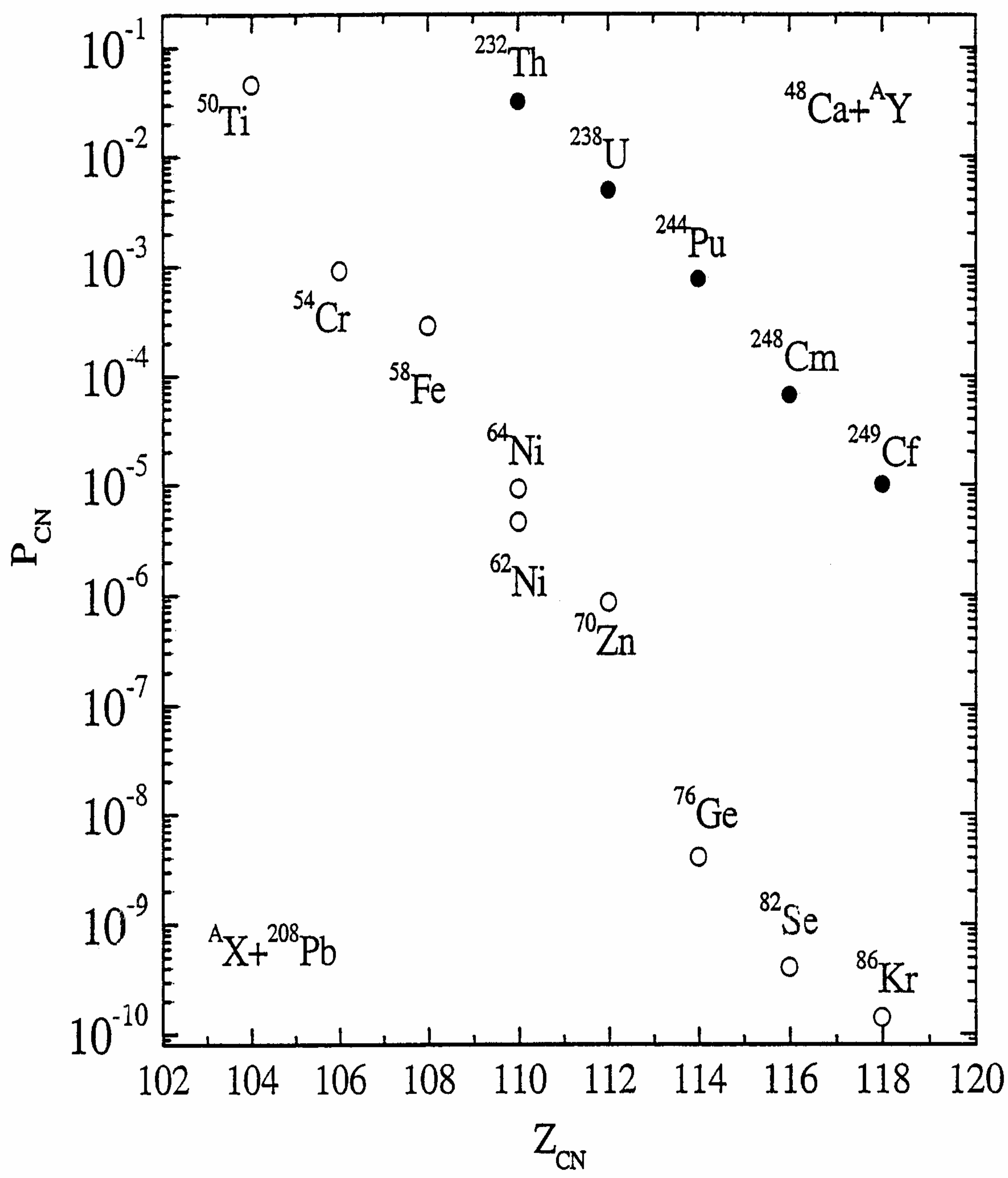
$$P_{CN} \sim \exp(-(B^*_{fus} - B_{qf})/kT)$$

Cold fusion (Pb-based reactions): $\Lambda_R \ll \Lambda_{\eta sym}$

Hot fusion (^{48}Ca projectiles): $\Lambda_R \gg \Lambda_{\eta sym}$



$^{A}X + ^{208}Pb, ^{209}Bi$
P_{CN}
Z
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
104
106
108
110
112
114
116
118
^{50}Ti
^{54}Cr
^{64}Ni
^{58}Fe
^{64}Ni
^{62}Ni
^{70}Zn
^{76}Ge
^{82}Se
^{86}Kr



P_{CN}
Z_{CN}
$^{48}Ca+^{A}Y$
$^{A}X+^{208}Pb$
^{232}Th
^{238}U
^{244}Pu
^{248}Cm
^{249}Cf
^{50}Ti
^{54}Cr
^{58}Fe
^{64}Ni
^{62}Ni
^{70}Zn
^{76}Ge
^{82}Se
^{86}Kr
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
102
104
106
108
110
112
114
116
118
120

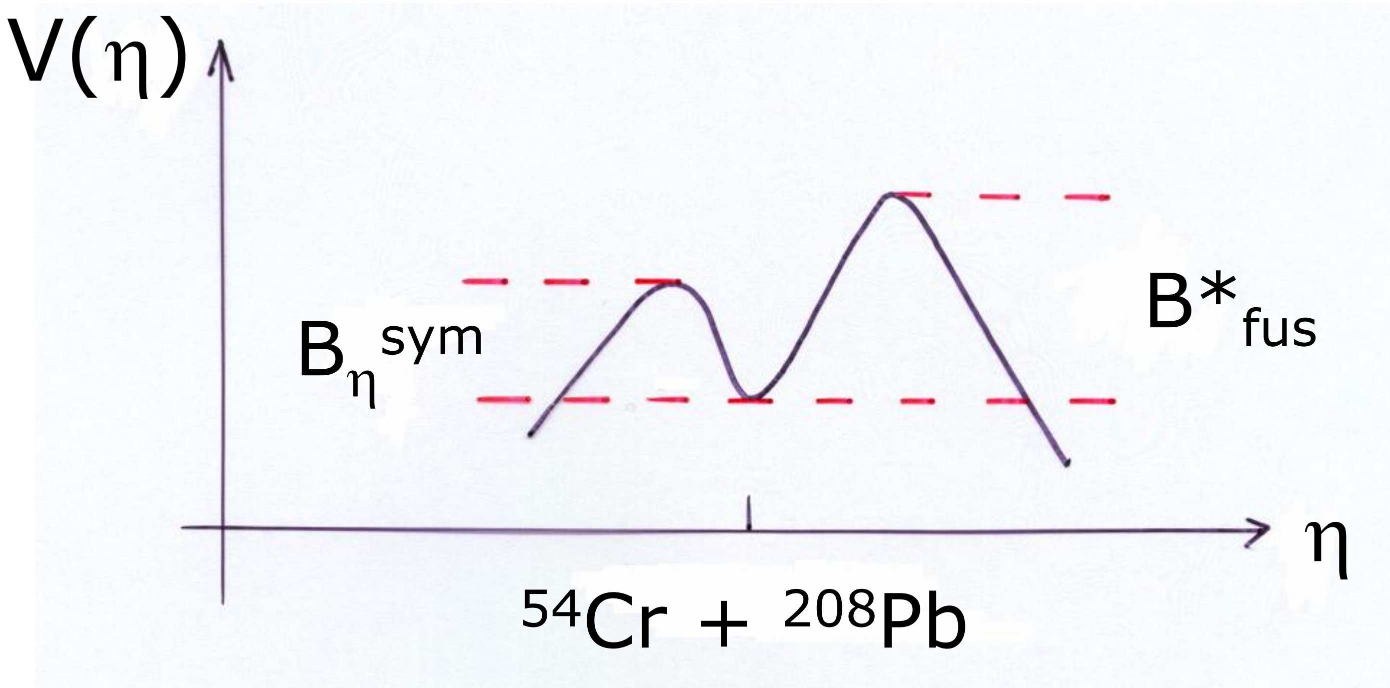
Importance of minima in the driving potential

Shell and deformation effects lead to local minima in $V(\eta)$. In liquid drop model the mean value of η runs to symmetric fragmentation: $\eta \rightarrow 0$, then quasifission.

Minima in $V(\eta)$ hinder motion to $\eta \rightarrow 0$, then larger probability for fusion.

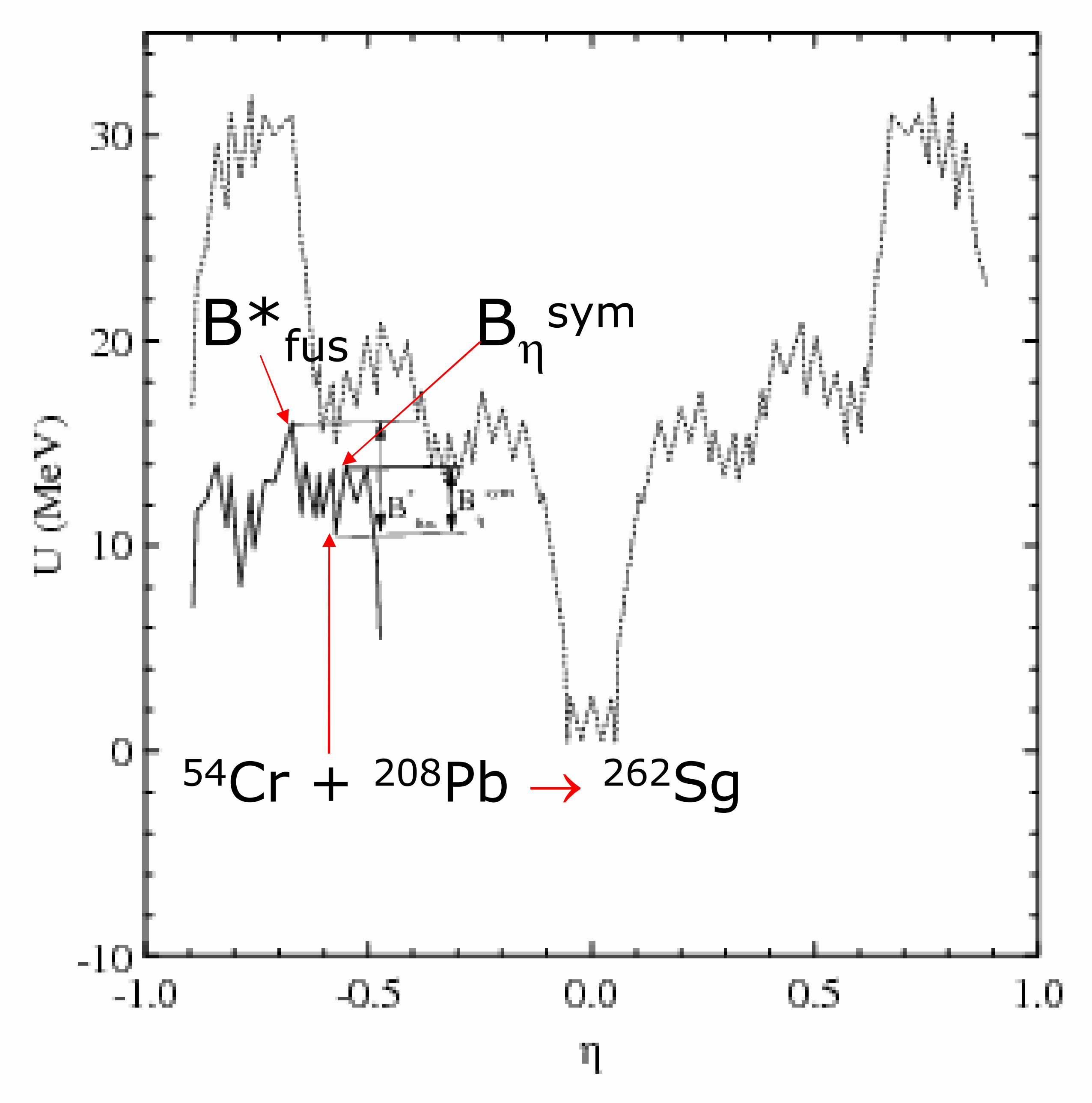
Idea of A. Sandulescu and W. Greiner (1976) for optimum selection of target and projectile: choice of fragmentations in minima of $V(\eta)$.

Example: $^{54}Cr + ^{208}Pb \rightarrow ^{262}Sg$

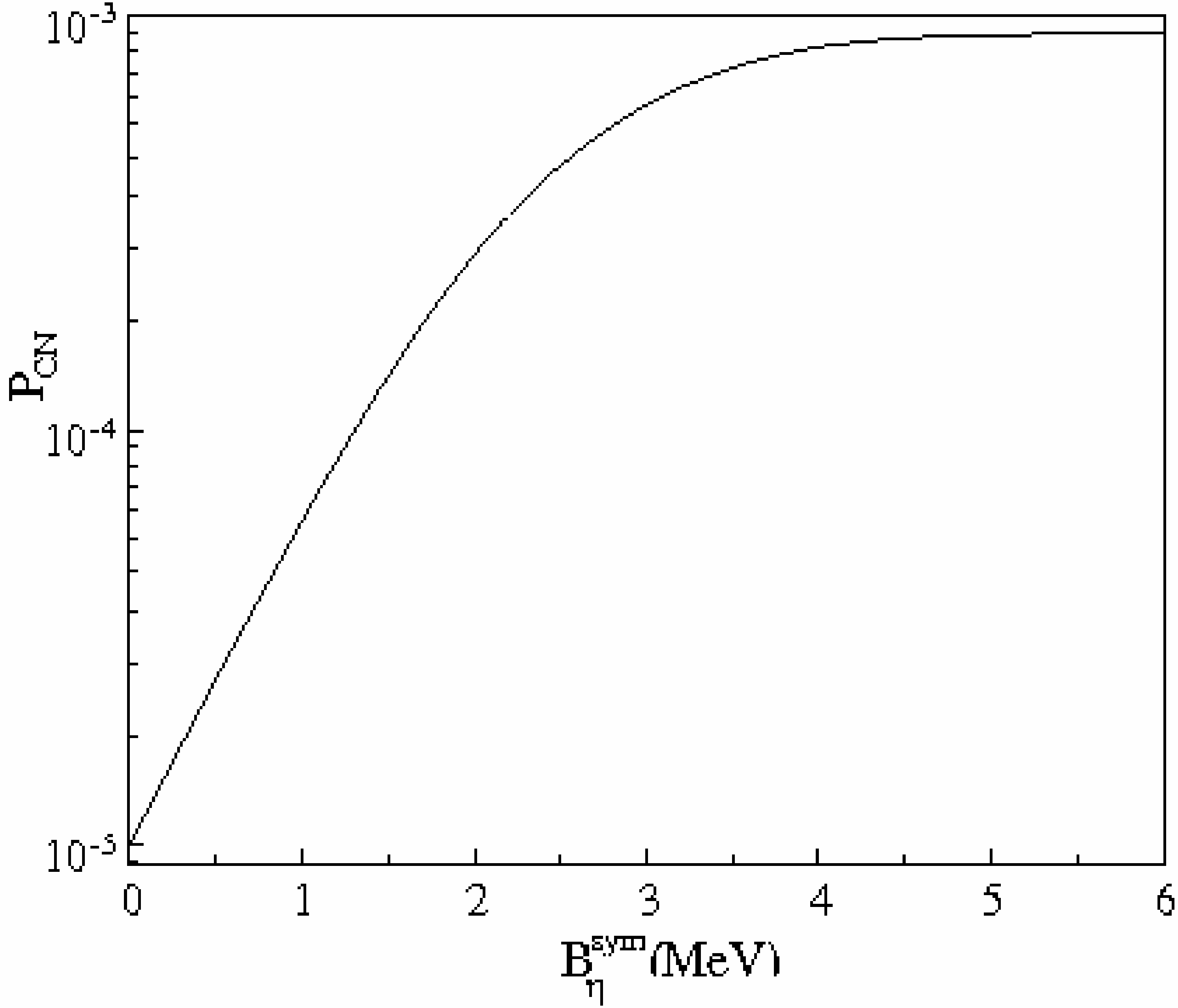


B^*_{fus}=5.7 MeV, B_η^{sym}=3.6 MeV, B_{qf}=2.7 MeV

Dependence of fusion probability P_{CN} on barrier height B_η^{sym}.

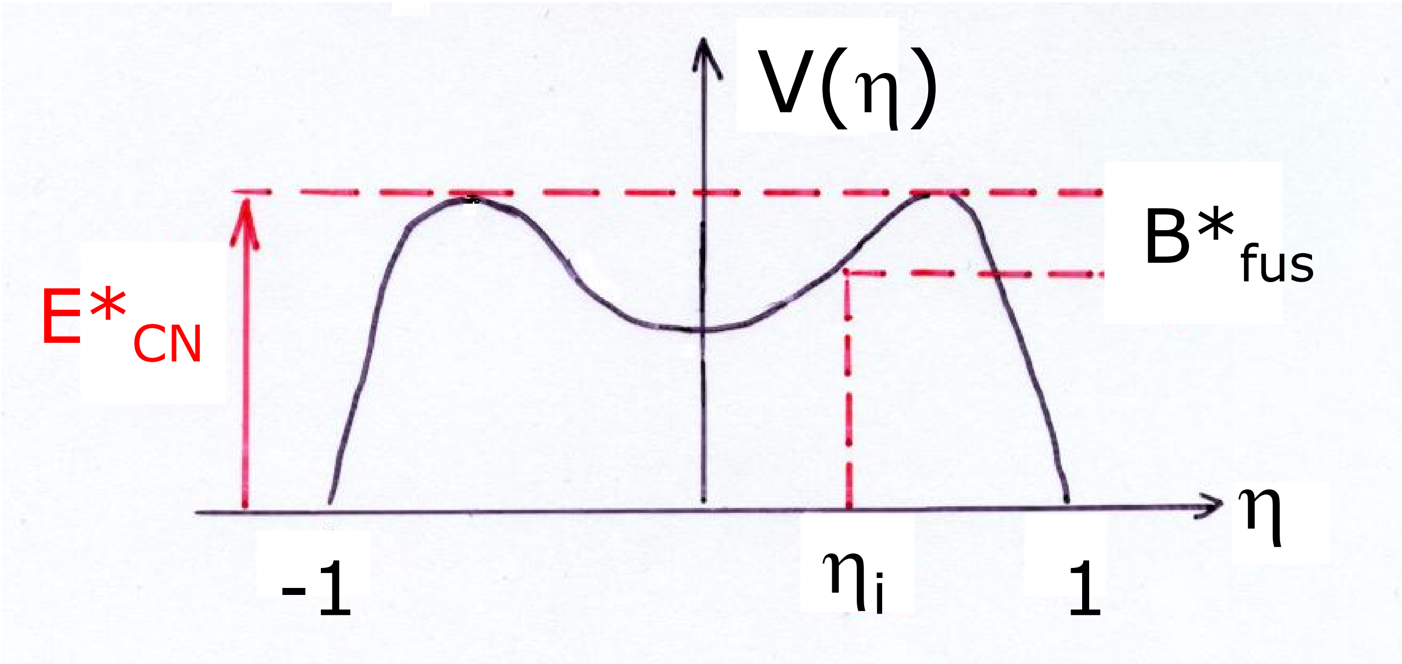


B*fus
Bη sym
54Cr + 208Pb → 262Sg
30
20
10
0
-10
-1.0
-0.5
0.0
0.5
1.0
U (MeV)
η



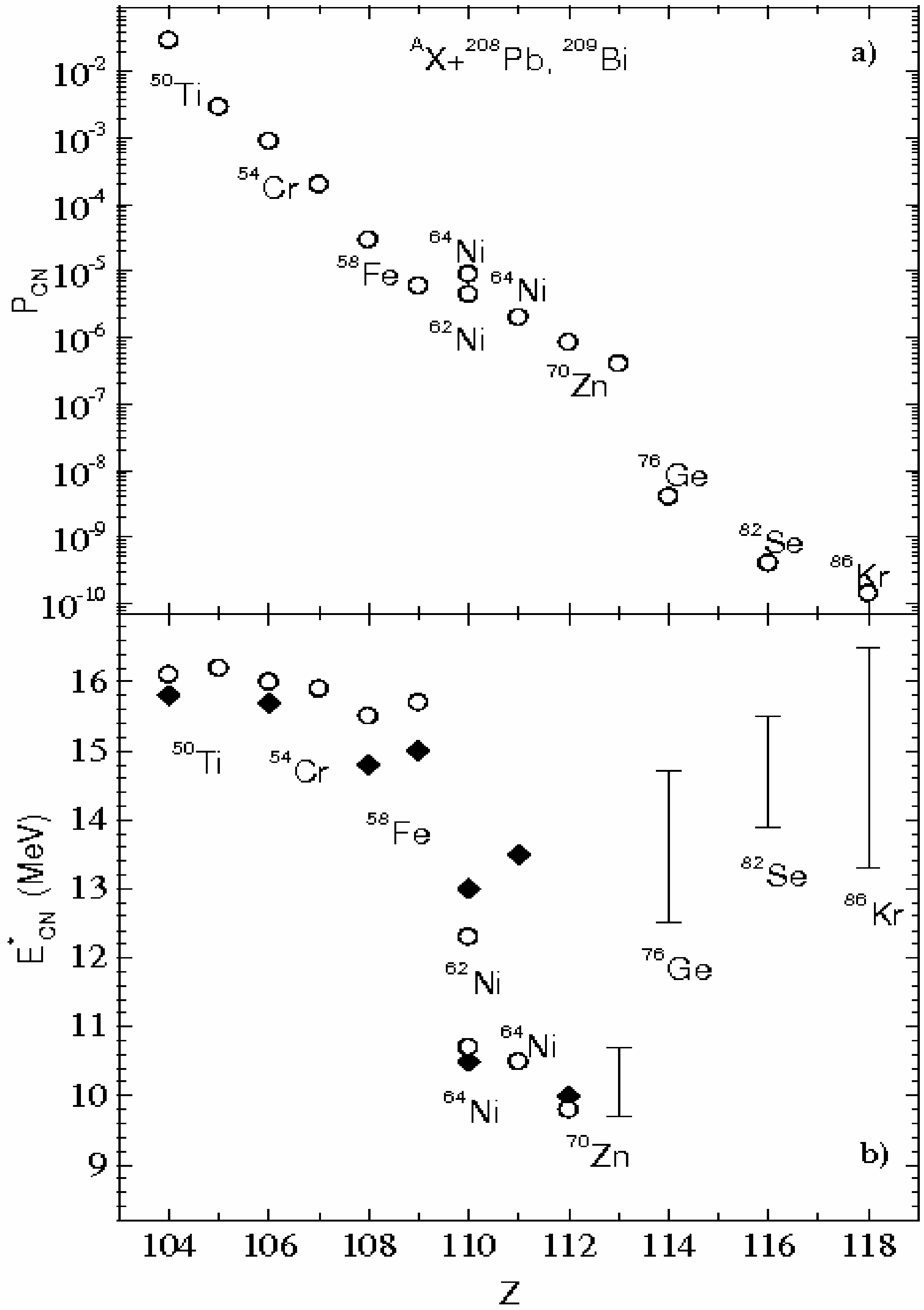
10^{-3}
10^{-4}
10^{-5}
P_{CN}
0
1
2
3
4
5
6
B_η^{sym}(MeV)

Optimum excitation energy for Pb-based fusion reactions



$$E^*_{CN} = E_{cm} + Q$$

$$\approx V(\eta) + B^*_{fus}$$



AX+208Pb, 209Bi
a)
PCN
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
50Ti
54Cr
58Fe
64Ni
64Ni
62Ni
70Zn
76Ge
82Se
86Kr
E*CN (MeV)
16
15
14
13
12
11
10
9
50Ti
54Cr
58Fe
62Ni
64Ni
64Ni
70Zn
76Ge
82Se
86Kr
b)
104
106
108
110
112
114
116
118
Z

c) Survival probability W_{sur}

De-excitation of excited compound nucleus by neutron emission in competition with fission. Other decays (γ–, α–decays) can be neglected.

For Pb-based reactions with emission of one neutron:

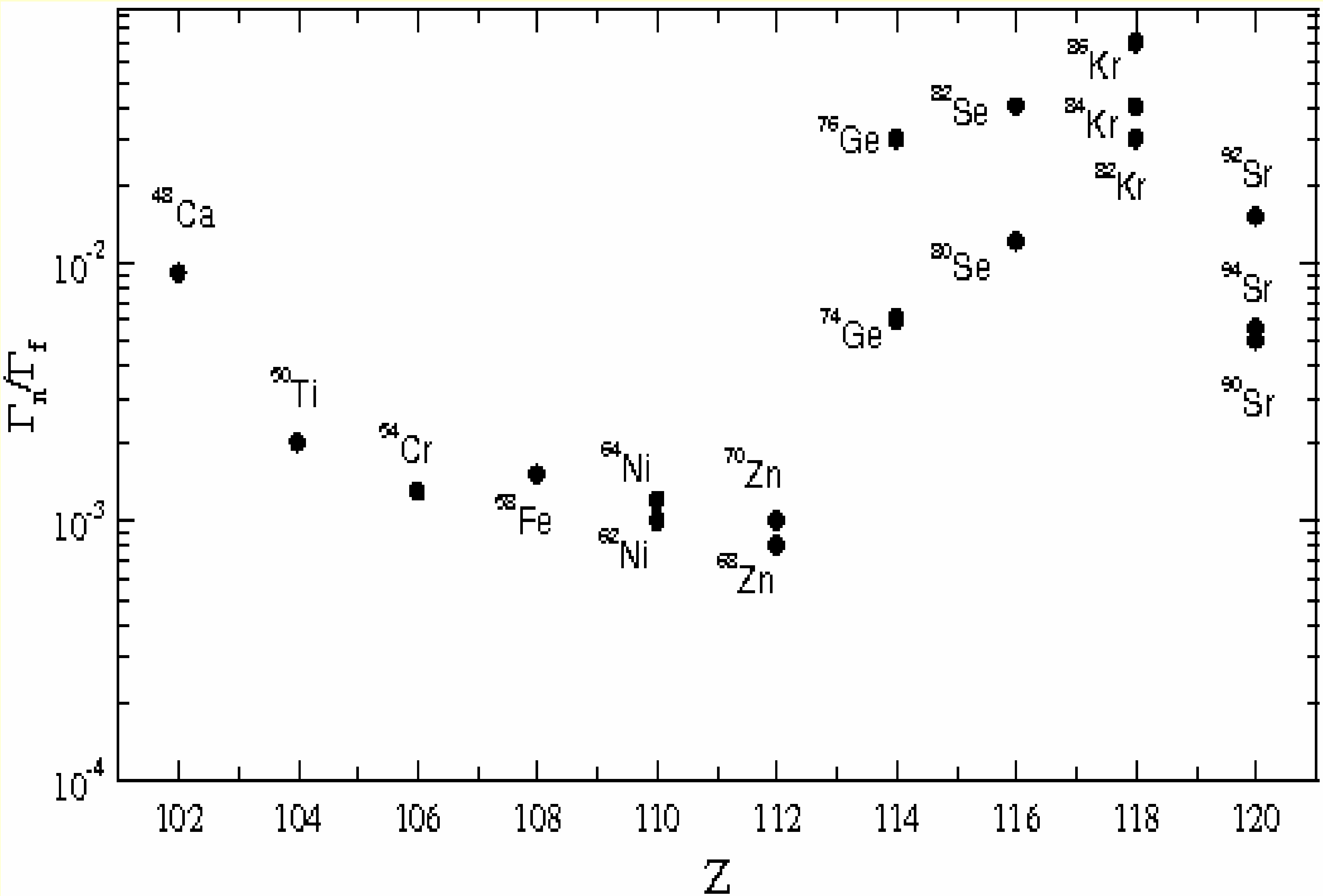
$$W_{sur}(E^*_{CN}, J) = P_{1n}(E^*_{CN}, J)\frac{\Gamma_n(E^*_{CN}, J)}{\Gamma_{tot}(E^*_{CN}, J)}$$

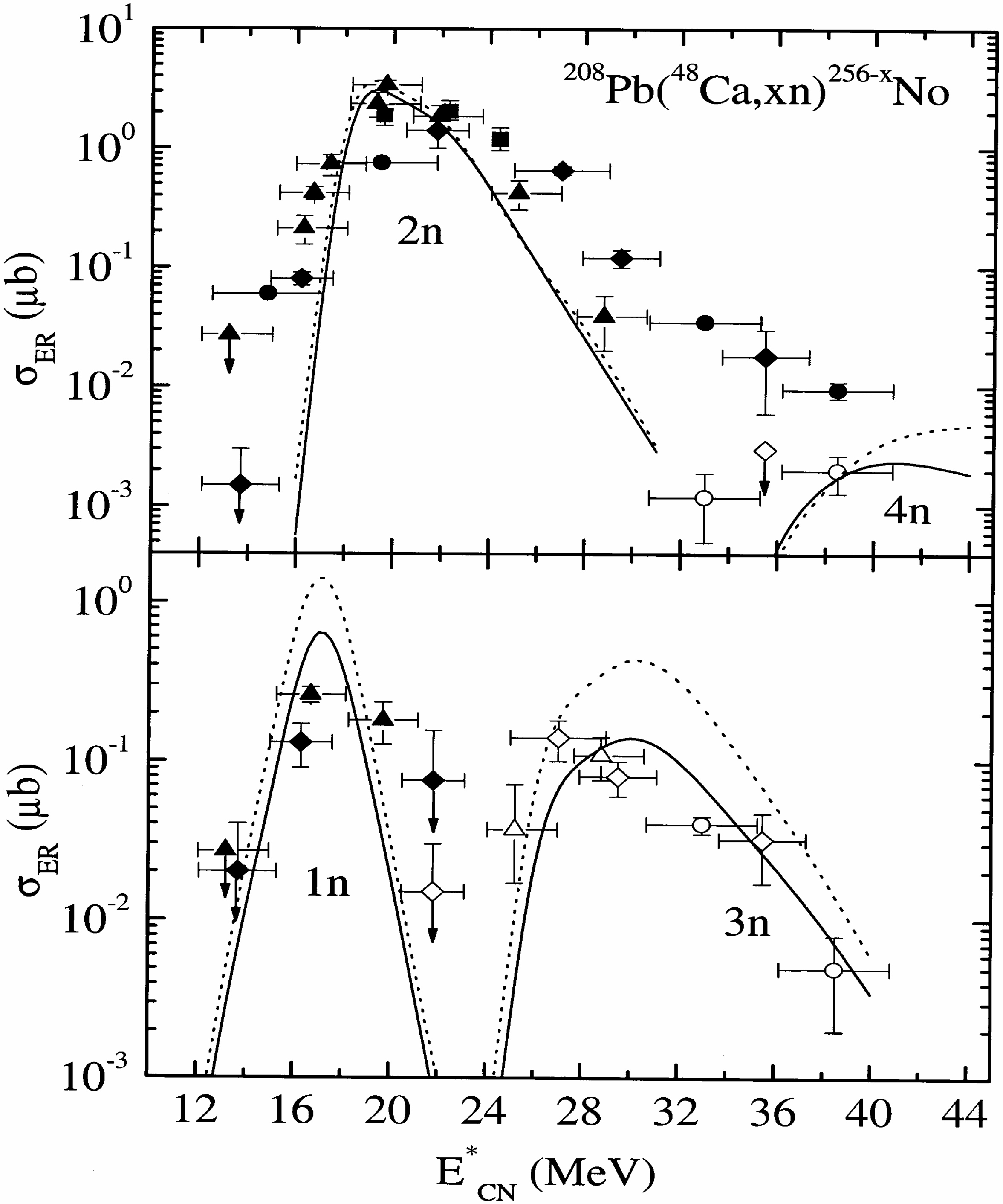
$$\Gamma_{tot} \approx \Gamma_n + \Gamma_f$$

Γ_n =width for neutron emission

Γ_f =fission width, $\Gamma_f >> \Gamma_n$

P_{1n} =probability of realisation of 1n channel


Γ_n/Γ_f
10^{-2}
10^{-3}
10^{-4}
102
104
106
108
110
112
114
116
118
120
Z
^{48}Ca
^{50}Ti
^{54}Cr
^{58}Fe
^{64}Ni
^{62}Ni
^{70}Zn
^{68}Zn
^{76}Ge
^{74}Ge
^{82}Se
^{80}Se
^{86}Kr
^{84}Kr
^{82}Kr
^{92}Sr
^{94}Sr
^{90}Sr

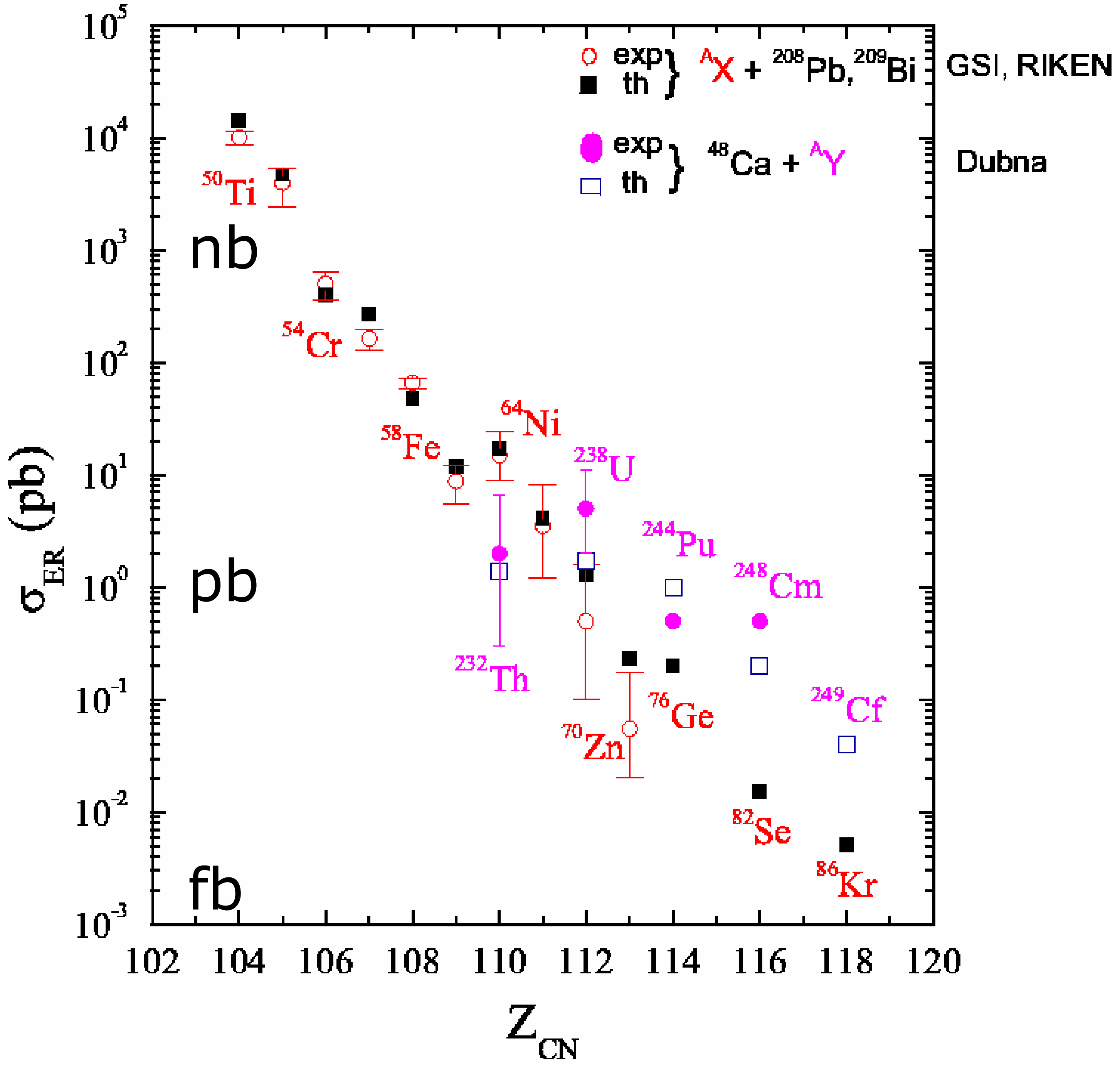


$^{208}Pb(^{48}Ca,xn)^{256-x}No$
2n
4n
1n
3n
σ_{ER} (μb)
E^*_{CN} (MeV)

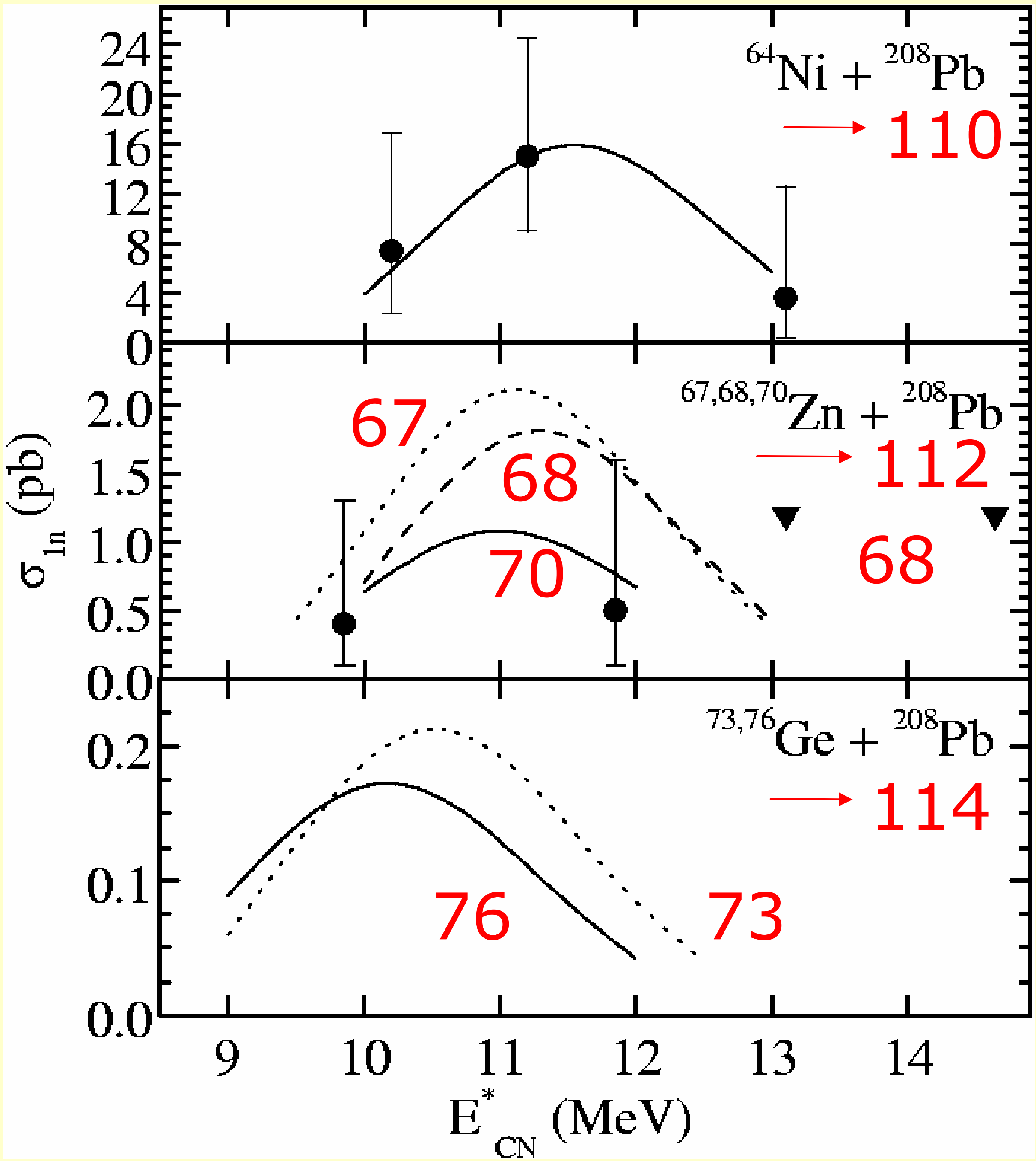
d) Results for cold and hot fusion reactions

Cold reactions: ${}^{A}Z+{}^{208}Pb \rightarrow$ superheavy + n

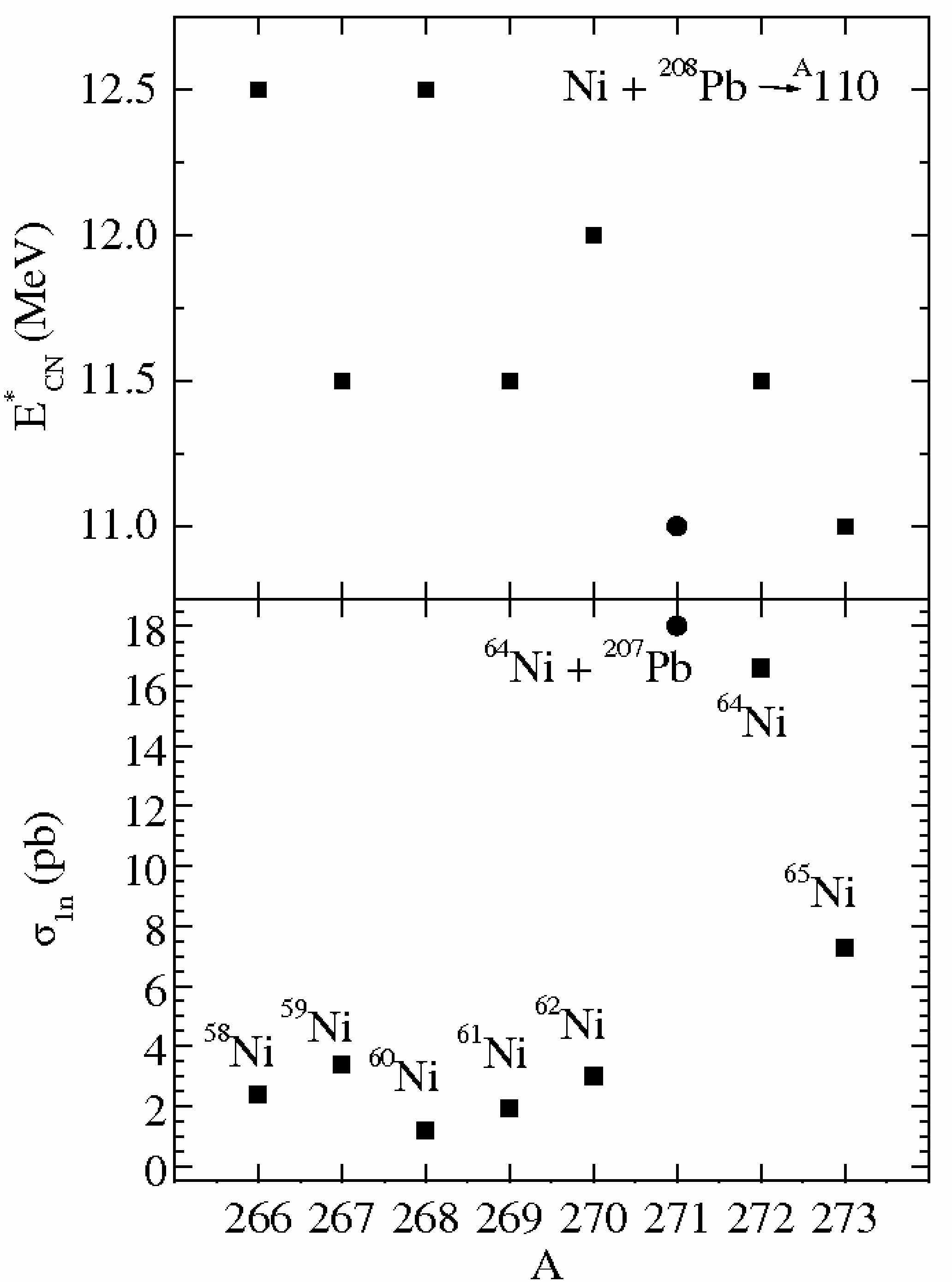
React.	Super-heavy	E^*_{CN} (MeV)	P_{CN}	σ_{cap} (mb)	W_{sur}	σ_{ER}^{th}	σ_{ER}^{ex}
${}^{50}Ti+{}^{208}Pb$	${}^{257}104$ +n	16.1	3×10^{-2}	5.3	9×10^{-5}	14.3 nb	10 nb
${}^{70}Zn+{}^{208}Pb$	${}^{272}112$ +n	9.8	1×10^{-6}	3.0	6×10^{-4}	1.8 pb	0.5 pb
${}^{86}Kr+{}^{208}Pb$	${}^{293}118$ +n	13.3	1.5×10^{-10}	1.7	2×10^{-2}	5.1 fb	< 0.5pb



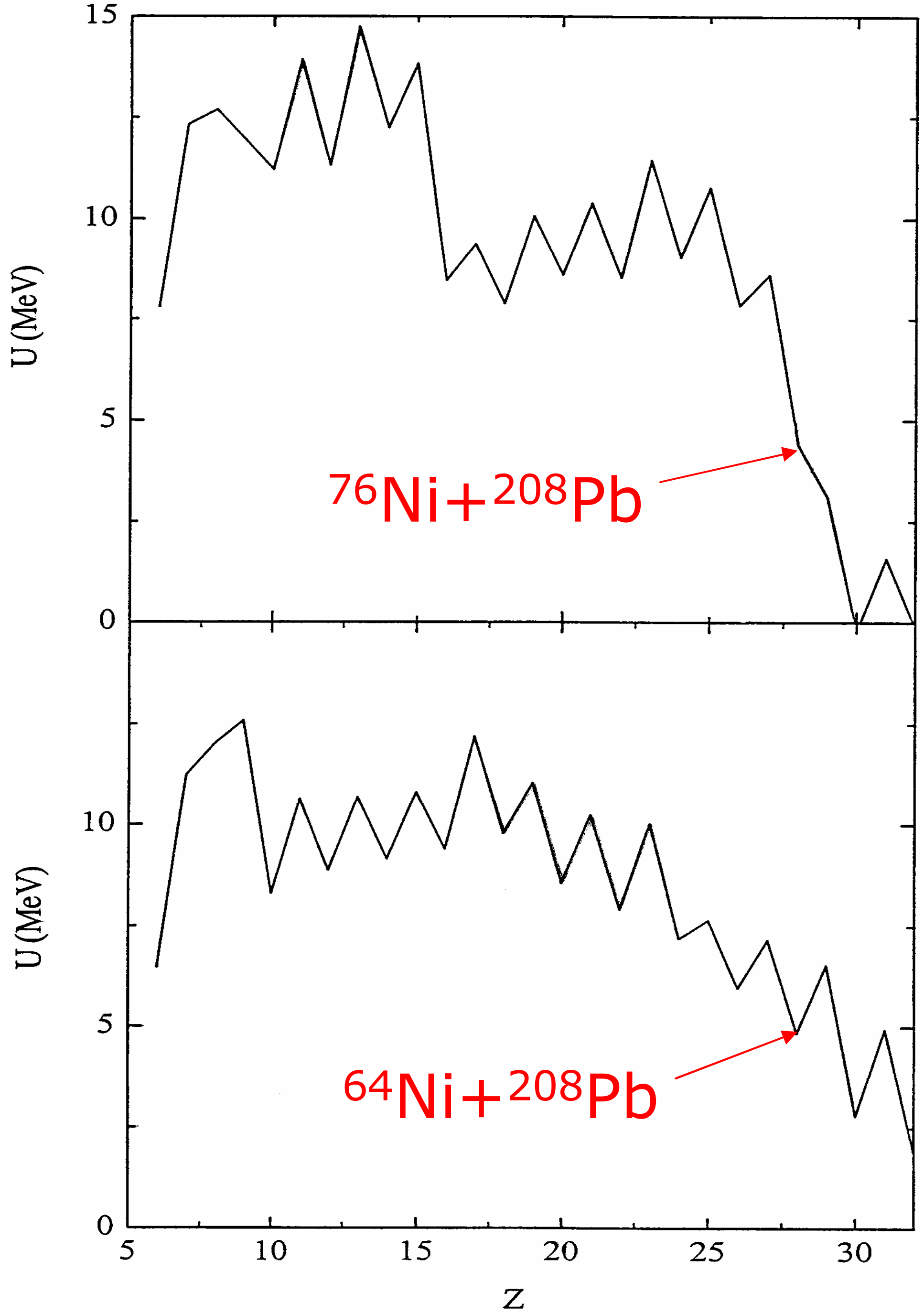
exp
th
$^{A}X + {}^{208}Pb, {}^{209}Bi$
GSI, RIKEN
exp
th
$^{48}Ca + {}^{A}Y$
Dubna
nb
pb
fb
σ_{ER} (pb)
Z_{CN}
^{50}Ti
^{54}Cr
^{58}Fe
^{64}Ni
^{70}Zn
^{76}Ge
^{82}Se
^{86}Kr
^{232}Th
^{238}U
^{244}Pu
^{248}Cm
^{249}Cf
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
102
104
106
108
110
112
114
116
118
120



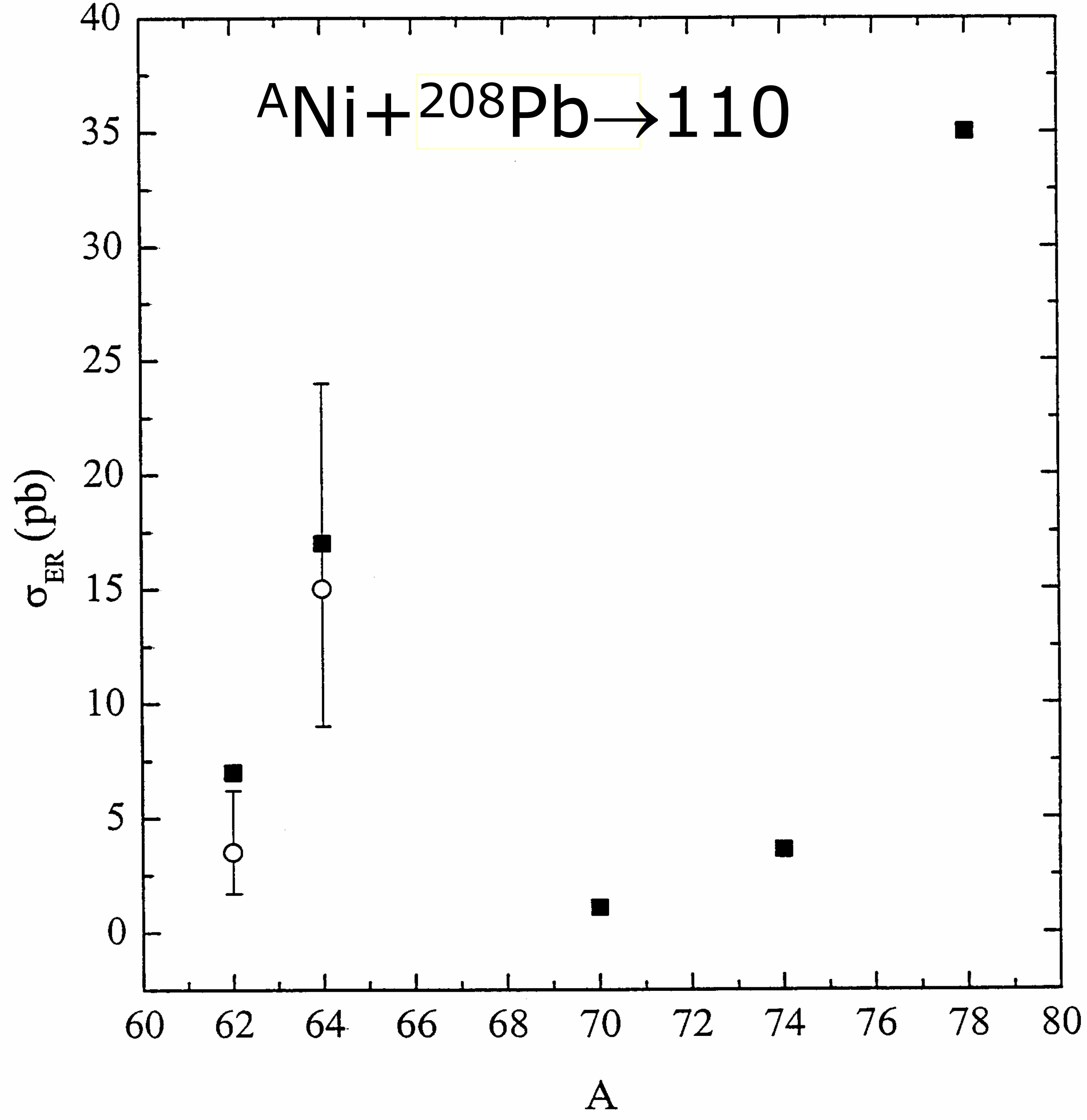
^{64}Ni + ^{208}Pb
→ 110
^{67,68,70}Zn + ^{208}Pb
→ 112
67
68
70
68
^{73,76}Ge + ^{208}Pb
→ 114
76
73
σ_{1n} (pb)
E^*_{CN} (MeV)



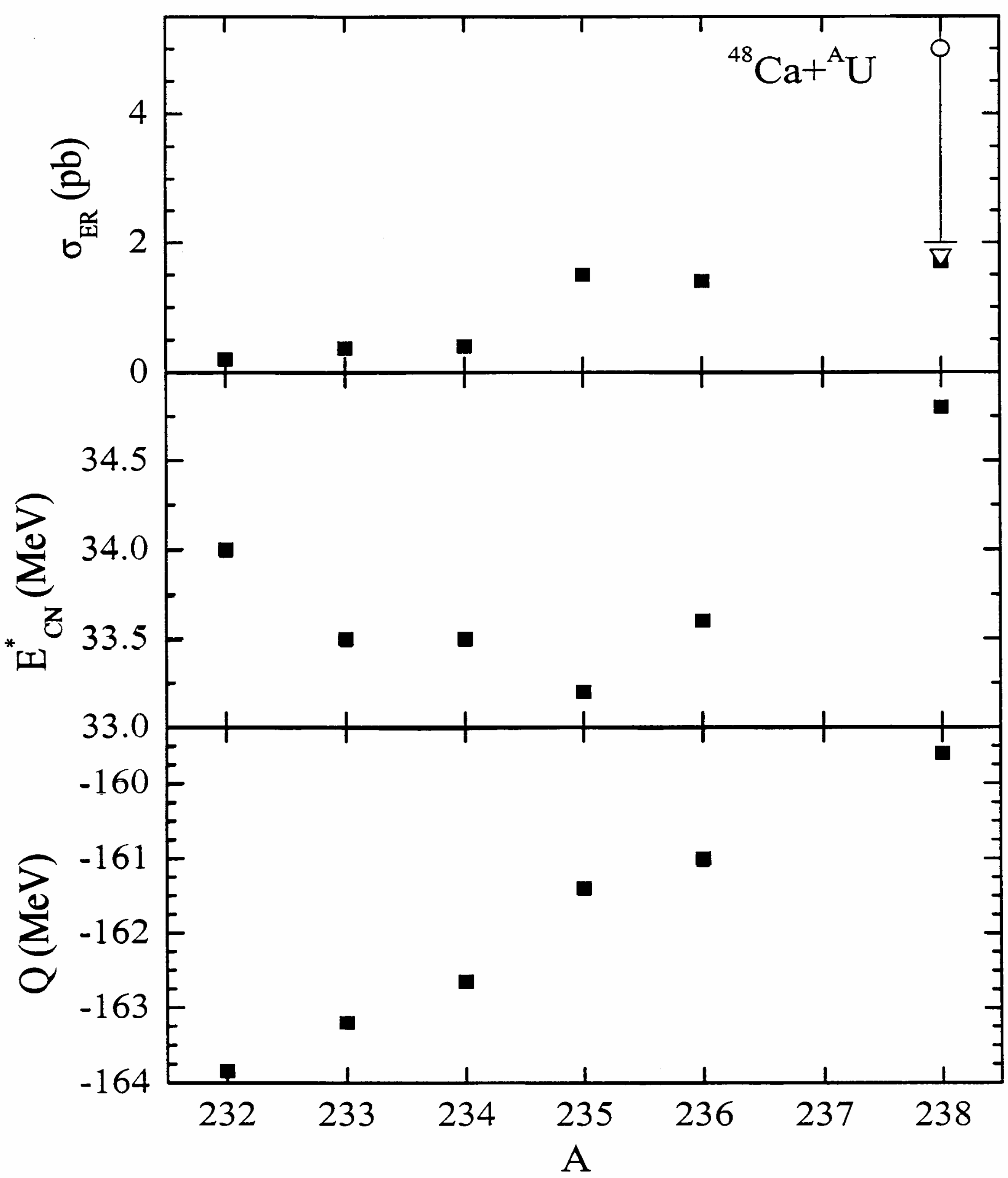
Ni + 208Pb → A110
E*CN (MeV)
12.5
12.0
11.5
11.0
64Ni + 207Pb
64Ni
65Ni
58Ni
59Ni
60Ni
61Ni
62Ni
σ1n (pb)
18
16
14
12
10
8
6
4
2
0
266
267
268
269
270
271
272
273
A



15
10
5
0
U (MeV)
^{76}Ni+^{208}Pb
10
5
0
U (MeV)
^{64}Ni+^{208}Pb
5
10
15
20
25
30
Z

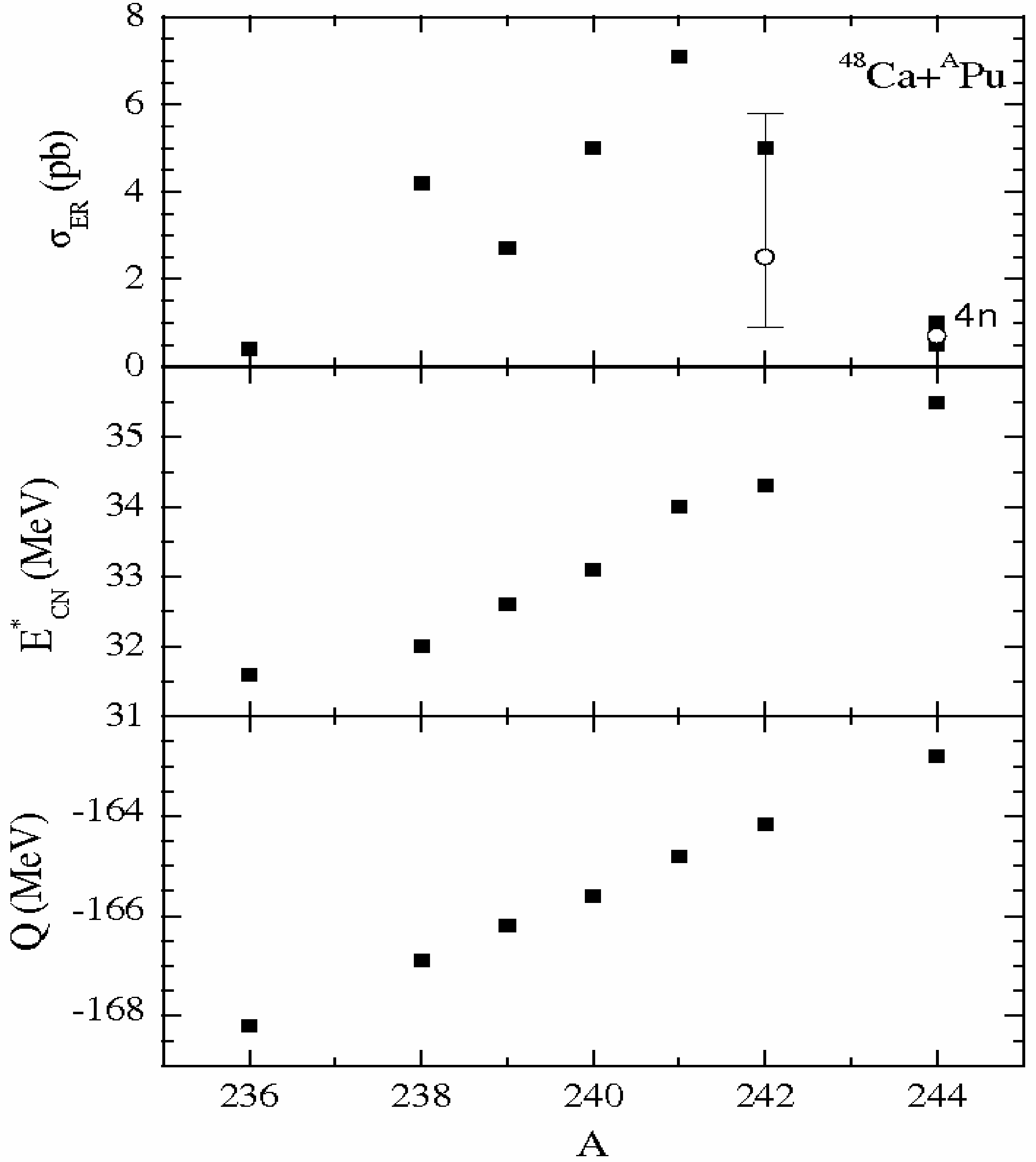


$^{A}Ni+^{208}Pb \rightarrow 110$
40
35
30
25
20
15
10
5
0
σ_{ER} (pb)
60
62
64
66
68
70
72
74
76
78
80
A



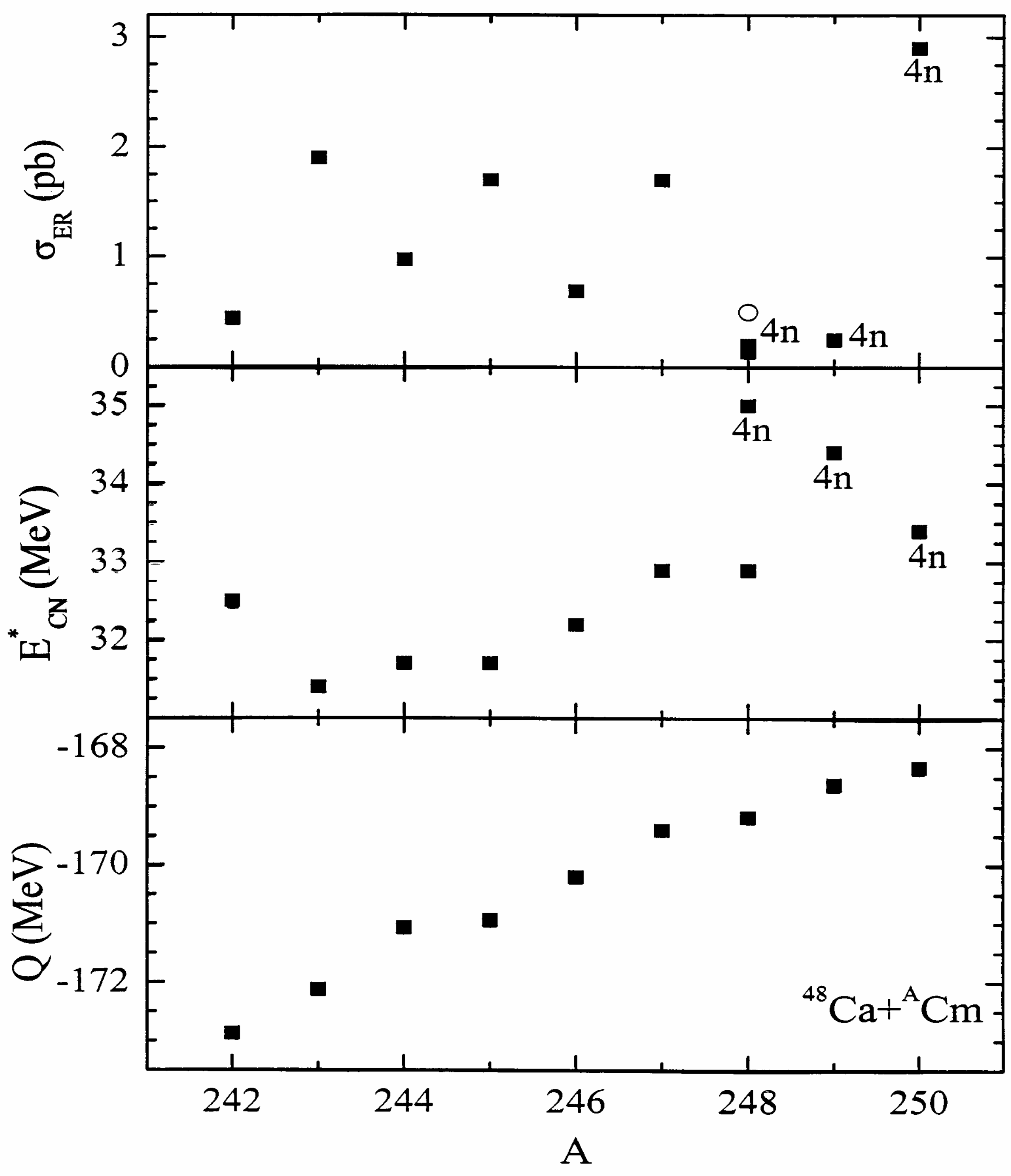
^{48}Ca+^{A}U
σ_{ER} (pb)
4
2
0
E^{*}_{CN} (MeV)
34.5
34.0
33.5
33.0
Q (MeV)
-160
-161
-162
-163
-164
232
233
234
235
236
237
238
A

Z=112



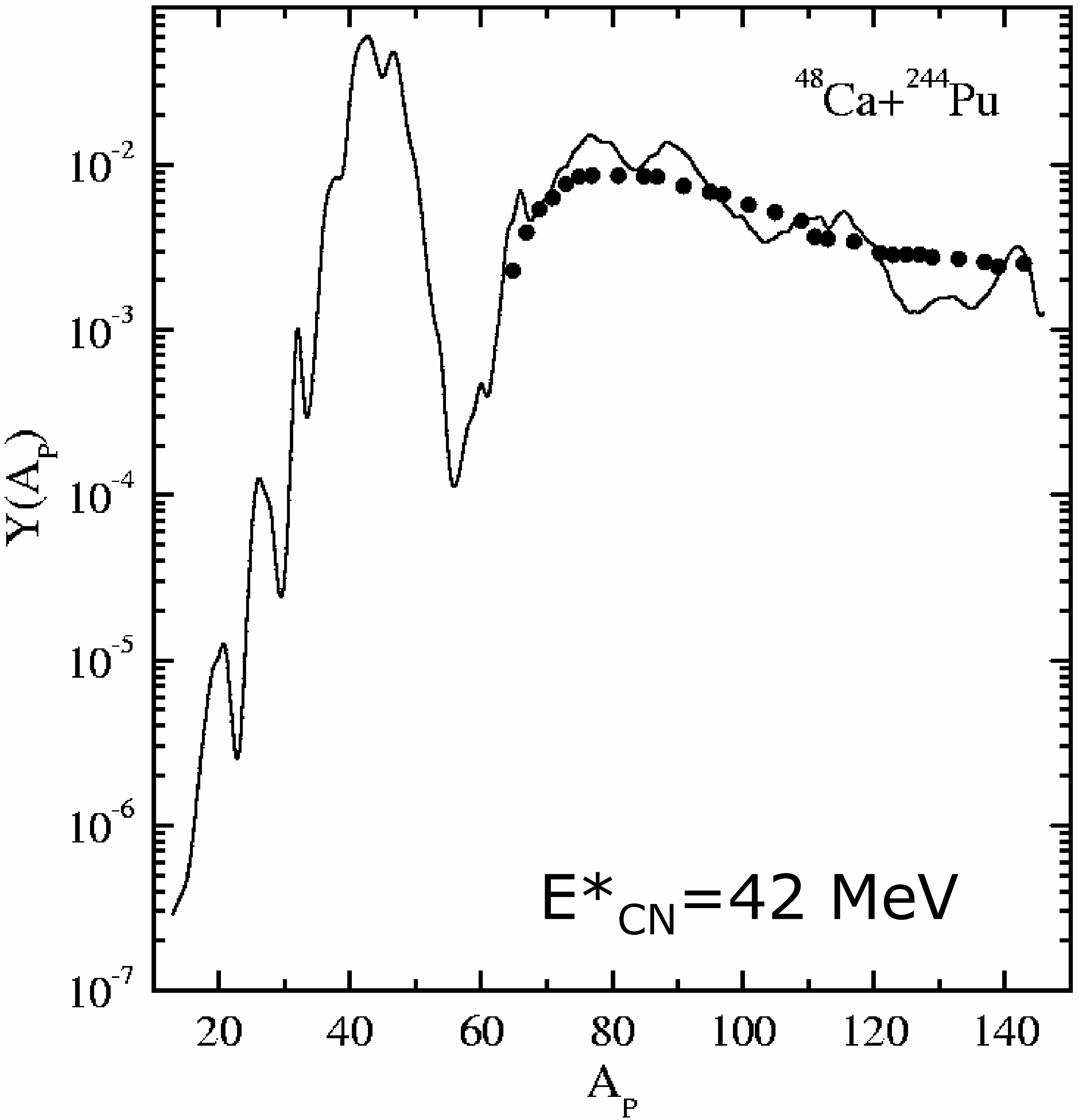
48Ca+APu
4n
σER (pb)
E*CN (MeV)
Q (MeV)
A
0
2
4
6
8
31
32
33
34
35
-164
-166
-168
236
238
240
242
244

Z=114



Z=116

3. Quasifission as a signature for dinuclear systems



$^{48}Ca+^{244}Pu$
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

$^{48}Ca+^{244}Cm$ ▲

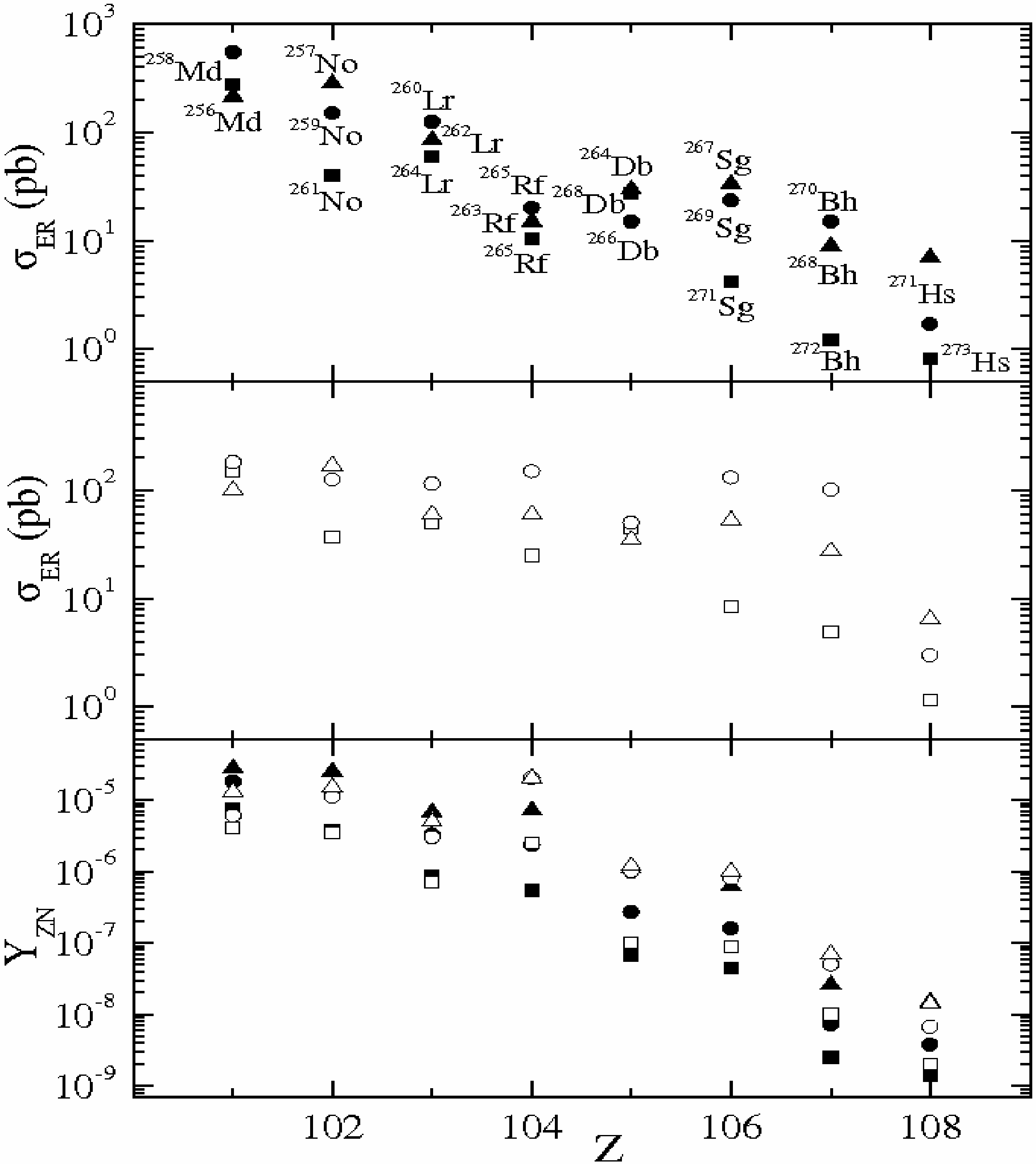
E_{cm}=207 MeV

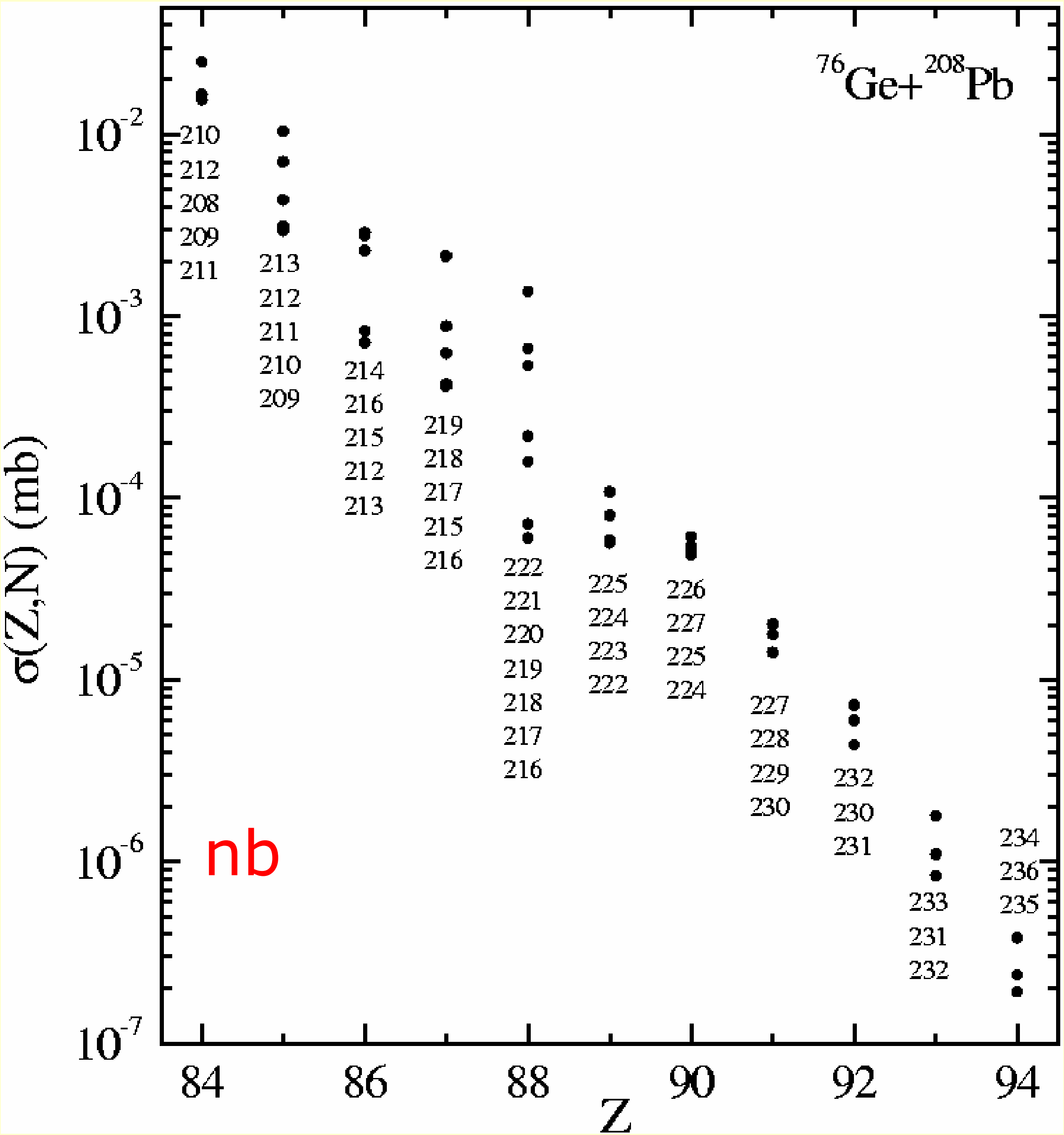
$^{48}Ca+^{246}Cm$ ●

E_{cm}=205.5 MeV

$^{48}Ca+^{248}Cm$ ■

E_{cm}=204 MeV





^{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

4. Summary and conclusions

- The concept of the nuclear molecule or dinuclear system describes nuclear structure phenomena connected with cluster structures, the fusion of heavy nuclei to superheavy nuclei, the competing quasifission and fission.

- The dynamics of the dinuclear system has two main degrees of freedom:
  the relative motion of the nuclei and the mass asymmetry degree of freedom.

- Superheavy nuclei are produced in heavy ion collisons in a process of three stages:
- (1) Capture of nuclei in a dinuclear system,
- (2) Fusion to compound nucleus by nucleon transfer between touching nuclei in competition with quasifission, which is the decay of the dinuclear system,
- (3) De-excitation of compound nucleus by neutron emission into the ground state of superheavy nucleus.

- The dinuclear system has a repulsive, diabatic potential energy surface towards smaller internuclear distances.
  This potential hinders the nuclei to amalgamate directly.

- The transfer of nucleons and the quasifission are statistical diffusion processes in the excited dinuclear system. They are described by Fokker-Planck or master equations or simply by the Kramers approximation. Fusion and quasifission are simultaneously treated.

- A precise prediction of optimum production cross sections for superheavy nuclei can be obtained from the calculation of isotopic series of reactions. The cross sections depend sensitively on the interplay between fusion and survival probabilities.
- For elements $Z > 118$ the production cross sections seem to be lower than 0.1 pb.