Production of new neutron-rich isotopes in transfer-type reactions

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   with Z=64-80 at low energies

Binary multinucleon transfer reactions have been known for producing exotic nuclei for many years.
V.V. Volkov, Phys. Rep. 44 (1978) 93

Possibility have been shown to produce the neutron-rich nuclei close to drip-line in the transfer reactions **^{48}Ca+^{232}Th,^{238}U, ^{248}Cm** at incident energies close to the Coulomb barrier.
PL B621 (2005) 119; EPJ A27 (2006) 187

^{238}U(5.5MeV/n)+**^{48}Ca** reaction has been used to produce the **odd and even neutron-rich Ca isotopes** and study their low-lying states.
PR C76 (2007) 021304(R)

Neutron-rich nuclei with **A=50 - 80** have been studied through multinucleon transfer reactions by bombarding **^{208}Pb** & **^{238}U** targets with beams **^{48}Ca, ^{58,64}Ni, ^{70}Zn, ^{82}Se**.
JP G36 (2009) 113101

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

1) the initial dinuclear system with light or heavy nucleus (Z_i, N_i) is formed in the collision;

2) the dinuclear system with light or heavy exotic nucleus (Z, N) is produced by nucleon transfers;

3) this dinuclear system separates into two fragments;

4) neutron emission from these fragments.

Transfer cross sections to more asymmetric or symmetric systems

Cross section of the production of primary exotic nucleus:

$$\sigma_{Z,N} = \sigma_{cap} Y_{Z,N}$$

Cross section with evaporation of x neutrons:

$$\sigma_{ER}(Z, N - x) = \sigma_{Z,N} W_{sur}(xn)$$

Here: ^{48}Ca + ^{238}U, ^{244}Pu, ^{248}Cm

The primary charge and mass yields of fragments can be expressed

$$Y_{Z,N}(t_0)=\Lambda_{Z,N}^{qf}\int_0^{t_0} P_{Z,N}(t)\,dt$$

The time t_0 of reaction is determined by solving the normalization condition

$$\sum_{Z,N} Y_{Z,N}(t_0)+P_{CN}\approx 1$$

$$P_{CN}=\sum_{Z<Z_{BG},\,N<N_{BG}} P_{Z,N}(t_0)$$

Z_{BG}=8-16 in the reactions considered

Microscopical method to find the formation-decay probability

a) Master equation for mass and charge transfer

Probability $P_{ZN}(t)$ to find the dinuclear system (DNS) in fragmentation:

$Z_1=Z$, $N_1=N$, $Z_2=Z_{tot}-Z_1$, $N_2=N_{tot}-N_1$

$Z_1+N_1=A$, $Z_1+Z_2+N_1+N_2=A_{tot}$

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

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

In order to test our method of calculation:

In **^{58}Ni(Ecm=257 MeV) + ^{208}Pb** reaction **^{50}Ti** and **^{52}Ti** are produced with the cross sections **1** and **0.2 mb**, respectively, which are consistent with our calculated cross sections **0.6** and **0.35 mb**, respectively.

In **^{64}Ni(Ecm=307 MeV) + ^{238}U** reaction the experimental and theoretical production cross sections for **^{52}Ti** are **0.5** and **1.6 mb**, respectively.

In **^{48}Ca(Ecm=204 MeV+^{248}Cm->^{40}S + (^{254}Fm+2n)**, the calculated cross sections for **^{254}Fm** is about **0.5 microbarn**, which is close to the experimental result.

In **^{48}Ca(Ecm=275 MeV) + ^{238}U** reaction the experimental and calculated ratios of secondary yields **Y(^{62}Fe)/Y(^{58}Cr)** for the neutron-rich **^{62}Fe** and **^{58}Cr** isotopes are about **0.2** and **0.3**, respectively.

The multinucleon transfer products of the quasifission reactions

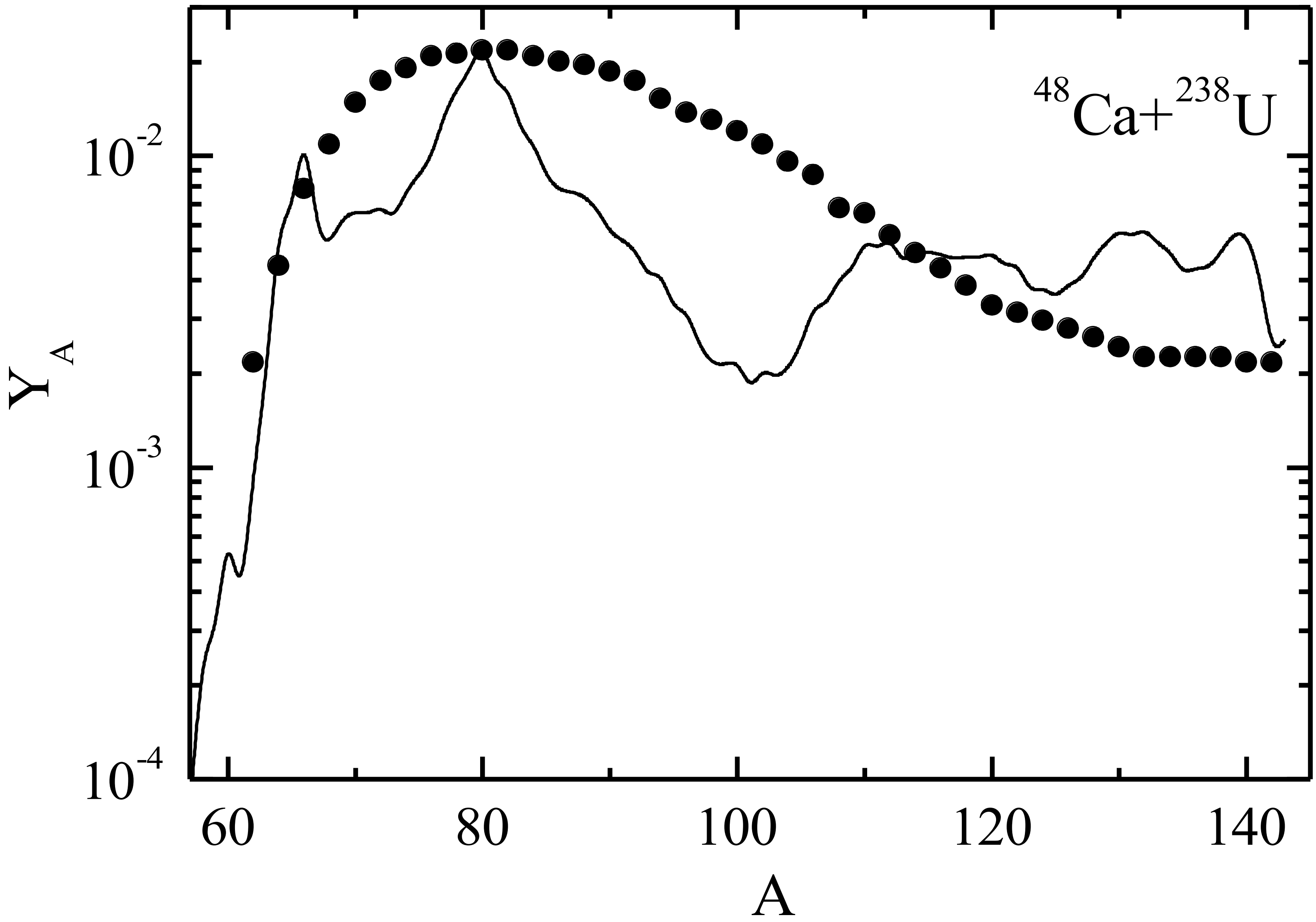
^{48}Ca(Ecm=190 MeV) + ^{238}U ,

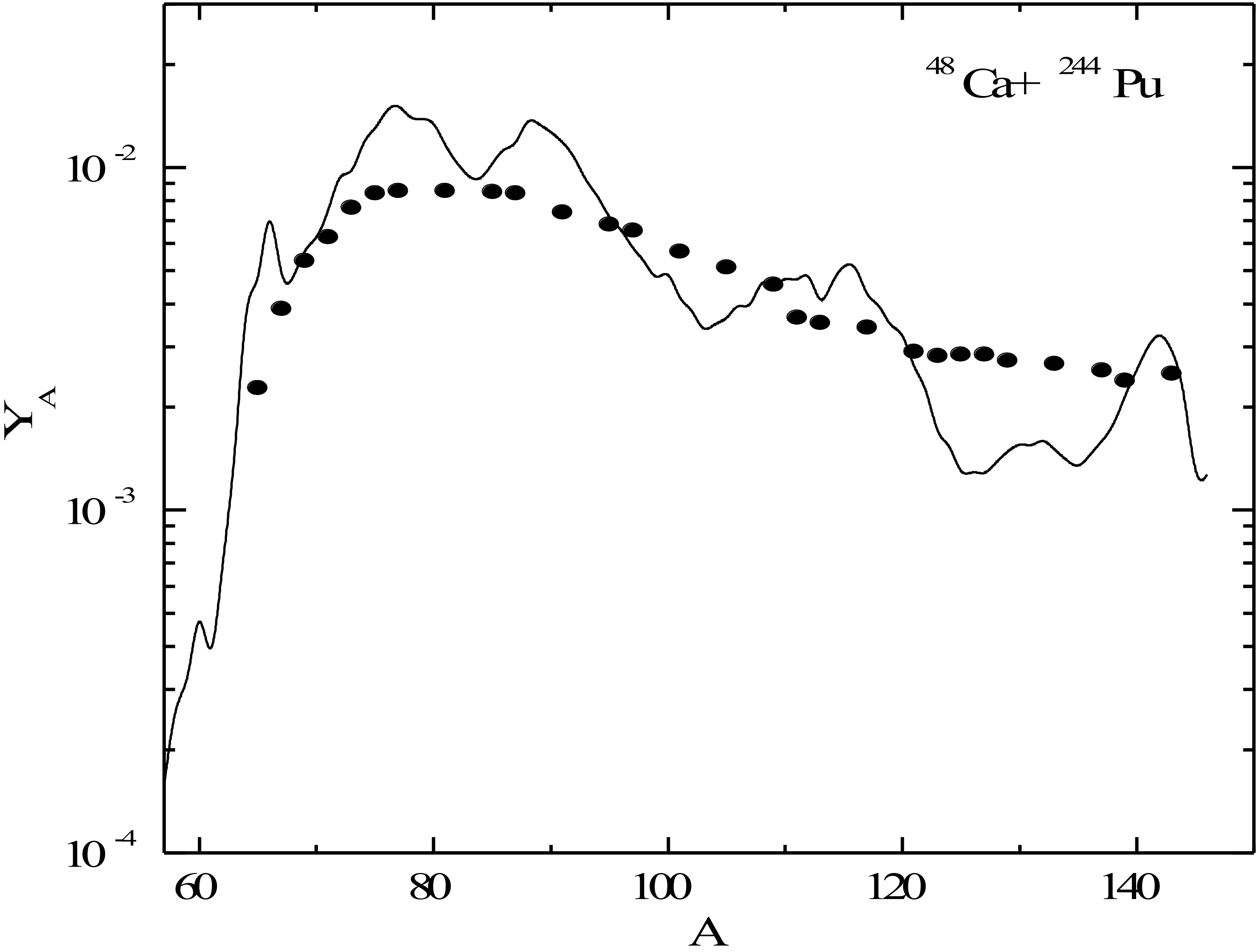
^{48}Ca(Ecm=201 MeV) + ^{244}Pu ,

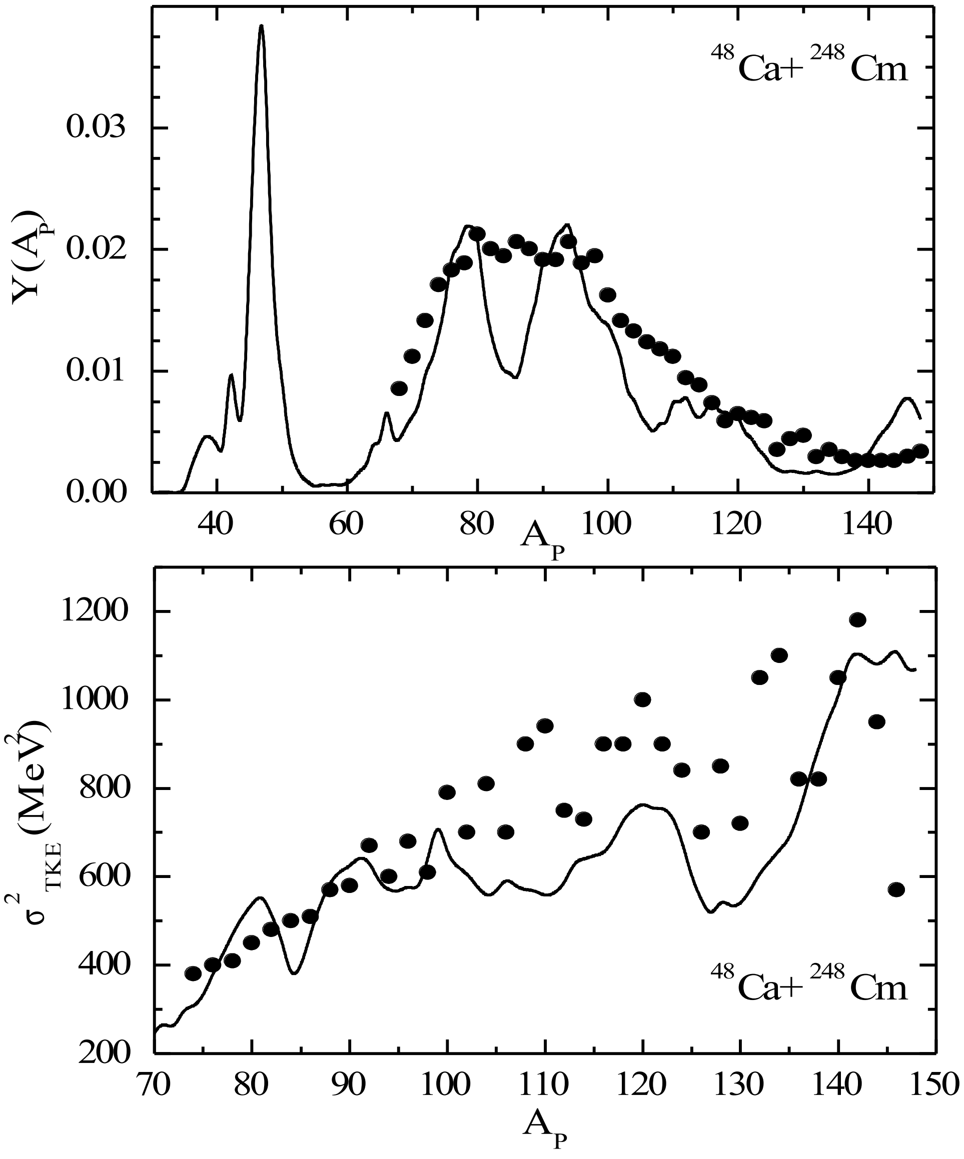
^{48}Ca(Ecm=205 MeV) + ^{248}Cm

at incident energies close to the Coulomb barrier are correctly described within our model.

In accordance with our model, the quasifission products are identical to the multinucleon transfer products at these energies. **[PRC 68 (2003) 034601]**


^{48}Ca+^{238}U
Y_A
10^{-2}
10^{-3}
10^{-4}
60
80
100
120
140
A


^{48}Ca+ ^{244}Pu
10^{-2}
10^{-3}
10^{-4}
Y_A
60
80
100
120
140
A


^{48}Ca+^{248}Cm
$Y(A_P)$
0.00
0.01
0.02
0.03
40
60
80
100
120
140
A_P
^{48}Ca+^{248}Cm
σ^2_{TKE} (MeV^2)
200
400
600
800
1000
1200
70
80
90
100
110
120
130
140
150
A_P

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

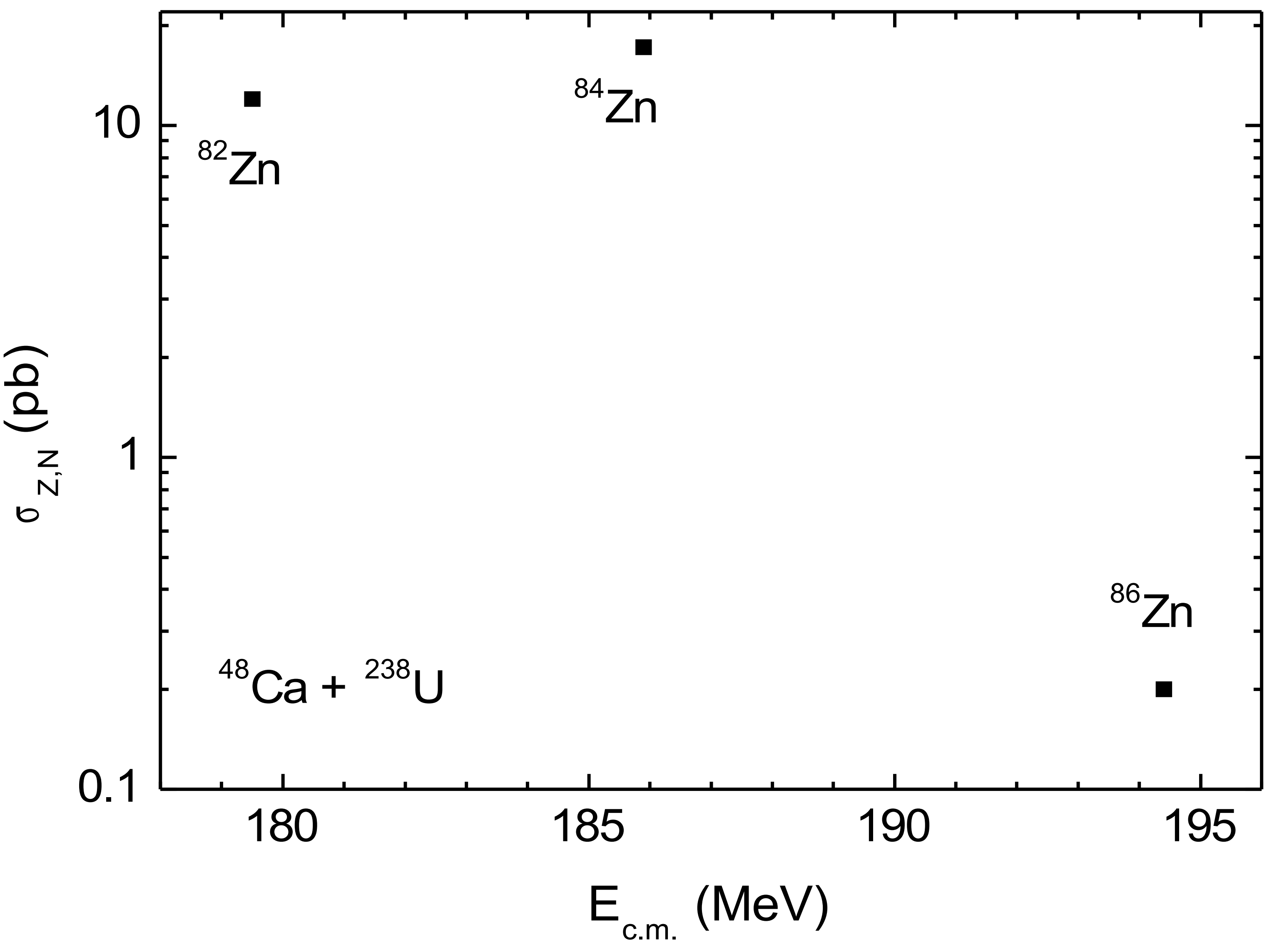
^{48}Ca(Ecm=190 MeV) + ^{238}U

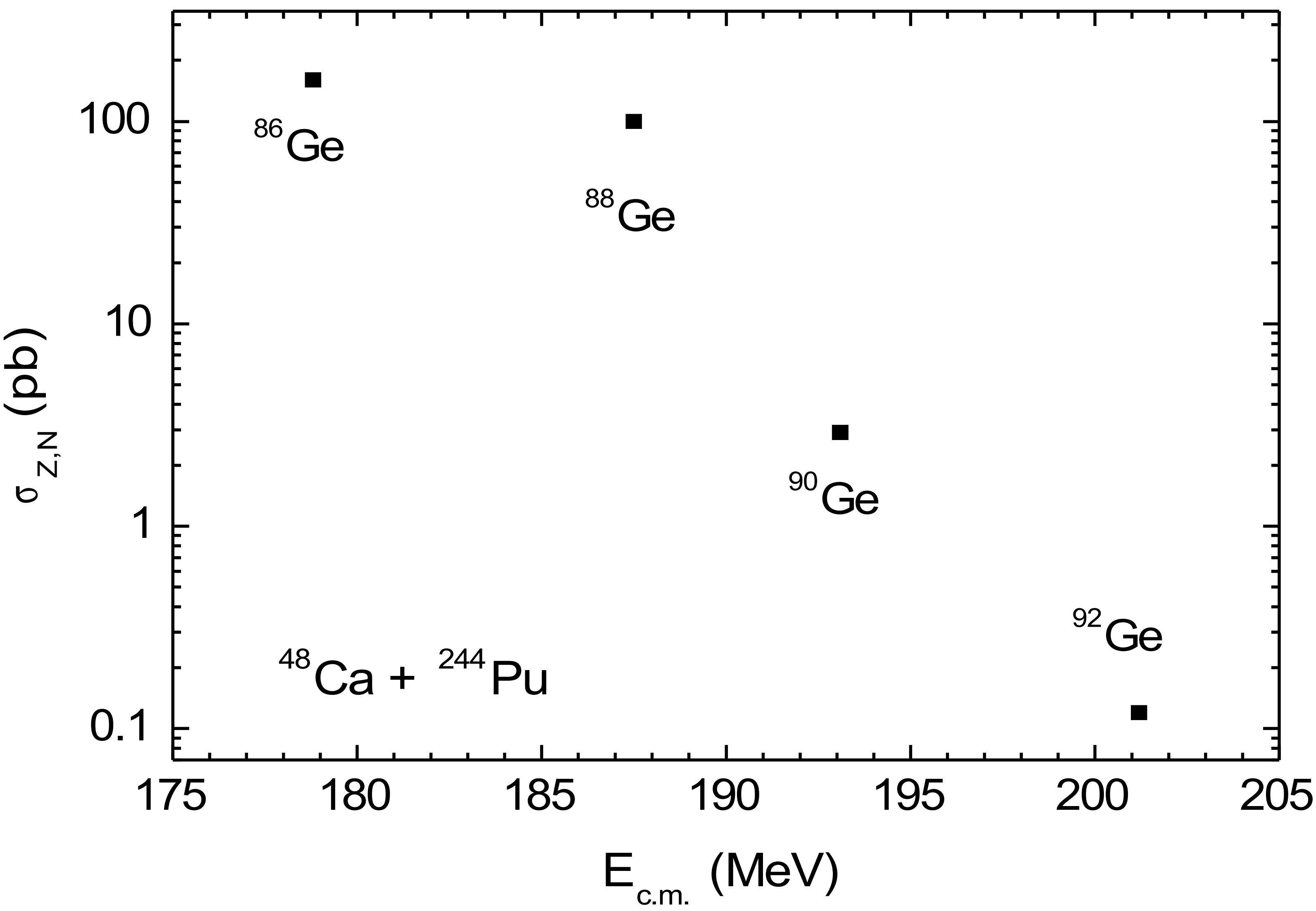
and

^{48}Ca(Ecm=201 MeV) + ^{244}Pu at low energies

[PR C81 (2010) 024604]

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


$\sigma_{Z,N}$ (pb)
$E_{c.m.}$ (MeV)
0.1
1
10
180
185
190
195
^{82}Zn
^{84}Zn
^{86}Zn
^{48}Ca + ^{238}U


$\sigma_{Z,N}$ (pb)
$E_{c.m.}$ (MeV)
175
180
185
190
195
200
205
0.1
1
10
100
^{86}Ge
^{88}Ge
^{90}Ge
^{92}Ge
^{48}Ca + ^{244}Pu

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

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

and

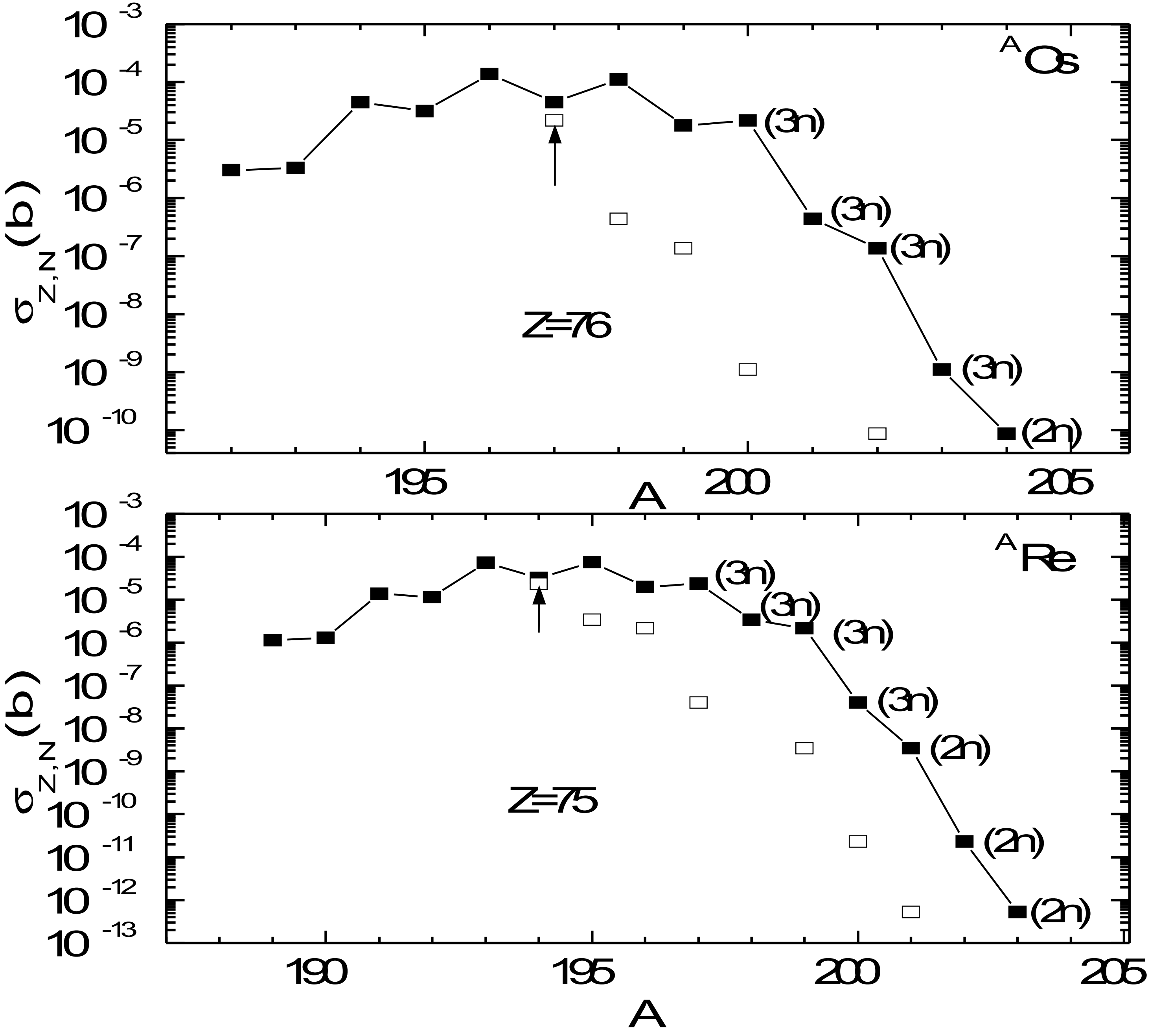
$$^{48}\mathrm{Ca} + {}^{244}\mathrm{Pu} \longrightarrow {}^{84,82}\mathrm{Ge} + {}^{208,210}\mathrm{Pb} \longrightarrow {}^{88,90,92}\mathrm{Ge} + {}^{204,202,200}\mathrm{Pb}$$

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.

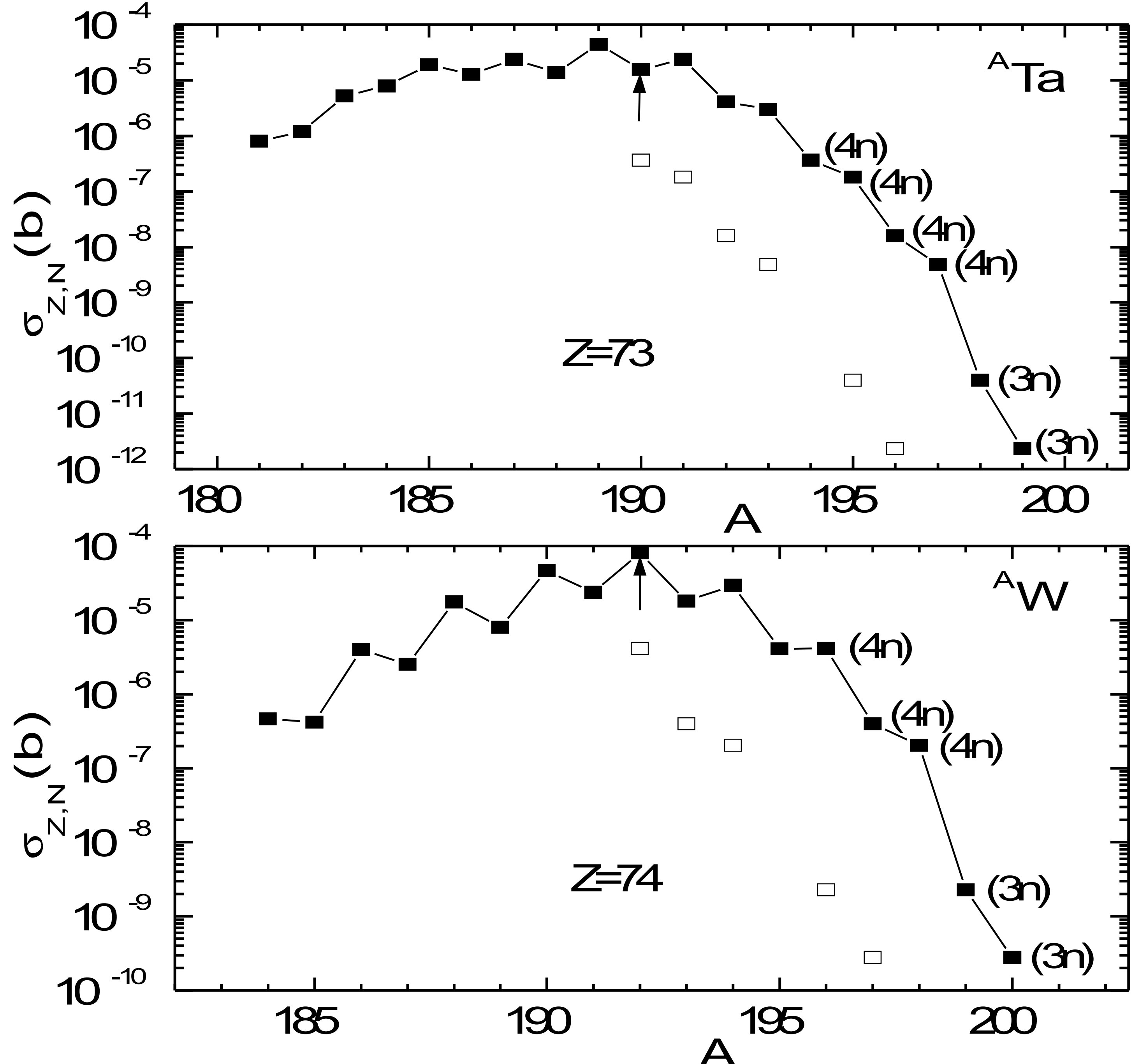
3. Possibility of production of neutron-rich isotopes of nuclei with Z=64-80 as complementary to light fragments in transfer reaction ^{48}Ca(Ecm=189 MeV)+ ^{238}U at low energies

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!

[PR C81 (2010) 057602]



^{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



$\sigma_{Z,N}$(b)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
^{A}Ta
Z=73
(4n)
(4n)
(4n)
(4n)
(3n)
(3n)
180
185
190
195
200
A
$\sigma_{Z,N}$(b)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
^{A}W
Z=74
(4n)
(4n)
(4n)
(3n)
(3n)
185
190
195
200
A

Since the predicted production cross sections for new exotic isotopes **^{193}W**, **^{195,196}Re**, **^{198}Os** & **^{200}Ir** are at the **microbarn level**, they can be easily identified.

For these nuclei, the known heaviest isotopes are in the vicinities of maxima of the primary isotopic distributions.

The calculated production cross sections for new exotic isotopes **^{178}Er, ^{180,181}Tm, $^{182-184}$Yb, $^{185-187}$Lu, $^{191-193}$Ta, ^{194,196}W, ^{197,199}Re, ^{199,200}Os, ^{201,202}Ir, ^{203}Pt** are between **microbarn** and **nanobarn levels**.

They can be also detected with the present experimental setups.

Conclusions

1) The possibility of production of the nuclei near the drip line (f.e., $^{82-86}Zn$, $^{86-92}Ge$) in multinucleon transfer reactions $^{48}Ca + ^{238}U$, ^{244}Pu at incident energies close to the Coulomb barrier was shown. Predicted cross sections are on the level (0.1-160)pb.

Note that $^{84,86}Zn$ and $^{90,92}Ge$ isotopes were not observed yet in the experiments!

The maximal expected cross sections are predicted (>0.1pb). The production cross section increases with the charge number of target.

Qgg-values influence the production cross sections because of binary character of reaction.

2) One can also produce new heavy neutron-rich isotopes of nuclei with **Z=64-79** in the actinide-based multinucleon transfer reaction **^{48}Ca(Ecm=189 MeV) + ^{238}U** .

One can propose such type of the experiment. Note that in this experiment one can study the odd-even effects which are clearly observed in calculations.

It is apparent that the use of the heavier actinide target, for example, **^{244}Pu** or **^{248}Cm**, with **^{48}Ca** beam at energies near the Coulomb barrier one can reach more neutron-rich region of nuclide.
Irradiating the heavier actinide targets by **^{48}Ca** beam for producing neutron-rich isotopes, we gain in the **Qgg**-value and the known heaviest isotopes are closer to the maxima of isotopic distributions.

The current experimental technology allows us to reach the cross section of 1 pb in about one weak of beam time.

So, the multinucleon transfer reactions at low energies provide an efficient tool for producing nuclei far from stability and may be the fruitful method to reach the neutron drip line.

The production of isotopes treated can be a supplementary information in the experiments on production of superheavy nuclei which run a long time with the same reactions.

4. Production of new superheavies with Z=103-108 in transfer-type reactions ^{48}Ca + ^{244,246,248}Cm

(Asymmetry-exit-channel quasifission)

[PR C71 (2005) 034603]

In the asymmetry-exit-channel quasifission reactions ^{48}Ca+Actinides one can produce new isotopes of superheavies 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\text{-}xn}$115+xn alpha-decay chains end at unknown nuclei ^{267,268}Db (Z=105).

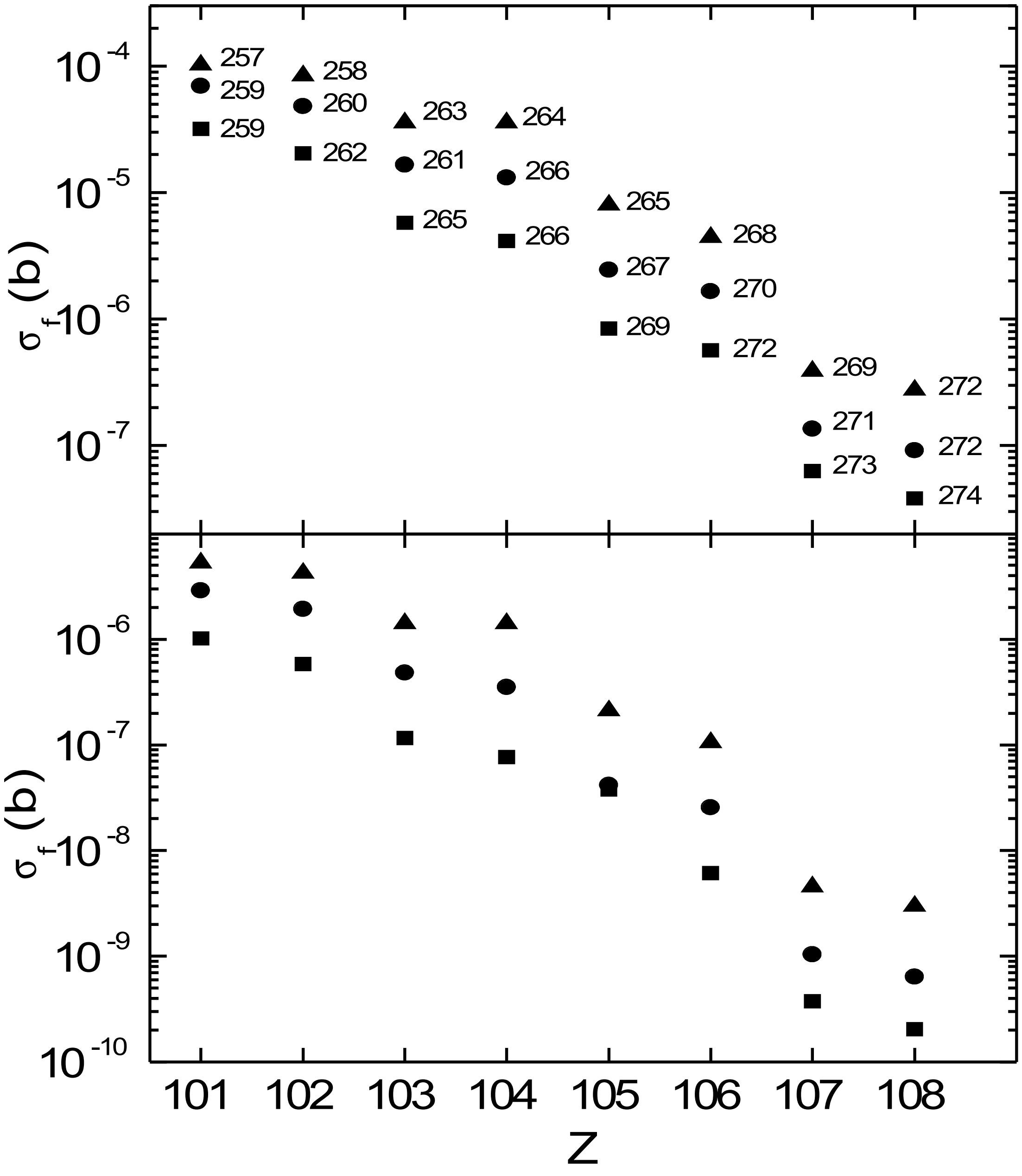
The diract production of ^{268,267}Db:

$$^{48}\mathrm{Ca} + {}^{248}\mathrm{Cm} \rightarrow {}^{27,28,29}\mathrm{Na} + {}^{269,268,267}\mathrm{Db} \rightarrow {}^{269,268,267}\mathrm{Db} \rightarrow$$
$$\rightarrow (\ 0n,\ 1n\ ) \rightarrow {}^{268,267}\mathrm{Db}$$

Production cross sections are about (10 -200)pb
at Ec.m.=202-209 MeV

Possibilities of transfer-induced fission of new isotopes of superheavy nuclei with Z=103 - 108 are studied for the first time in reactions ^{48}Ca + ^{244,246,248}Cm

[PR C68 (2003) 034601;
PR C82 (2010) 017601]



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

The predicted cross sections of the fission following multinucleon transfer are on the level (100 nb – 100 μb) in the reactions ^{48}Ca + ^{244,246,248}Cm at energies which are about 28 MeV above the corresponding Coulomb barriers.

The complementary to the fission fragments of superheavies are the O, F, Ne, Na, Mg, Al, Si, P nuclei (*the quasi-ternary-fission*)**.**

One can propose the experiment in which the fission fragment mass and angular distributions in coincidence with the complementary transfer products ranging from O to P ions can be measured.

Since the fission barrier of the superheavies is mainly determined by the shell correction in the ground state, in these experiments one can study the dependence of the value of shell correction on the average excitation energy, which is easily calculated, and (Z,N) of the fissioning nucleus.

In the complete fusion-fission reactions it is difficult to separate the fission fragments from the quasi-fission fragments.

This problem is absent in the transfer-induced fission reactions!

Comparing mass distributions of fragments of the same fissioning nucleus produced in the complete fusion-fission and transfer-induced fission reactions, one can distinguish the quasifission products.

Thank you for attention.

Note that isotopes of nuclei with Z=103 – 108 were not observed yet in the experiments.

The complementary to the fission fragments of these nuclei are the O, F, Ne, Na, Mg, Al, Si, and P nuclei. Fission of unknown isotopes with Z=103 – 108 can be measured with acceptable cross sections (100 nb – 100μb) in the reactions with ^{244,246,248}Cm targets and ^{48}Ca beam at energies which are about 28 MeV above the corresponding Coulomb barriers.

The transfer-induced fission is called as the quasi-ternary-fission process by analogy to the binary quasifission process. Note that isotopes of nuclei with Z=103 – 108 produced undergo fission with probability of more than 99% at the excitation energies treated.

In the experiment one can observe the light nucleus from O to P in coincidence with two fission fragments resulting from superheavy nucleus.

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

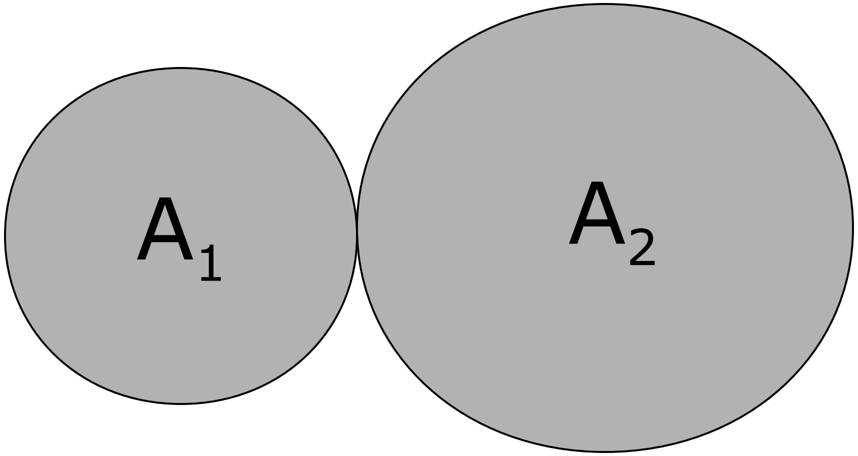
A dinuclear system or a nuclear molecule consists of two touching nuclei (clusters) which both keep their individuality.

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 degree of freedom.

Mass asymmetry coordinate

$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$

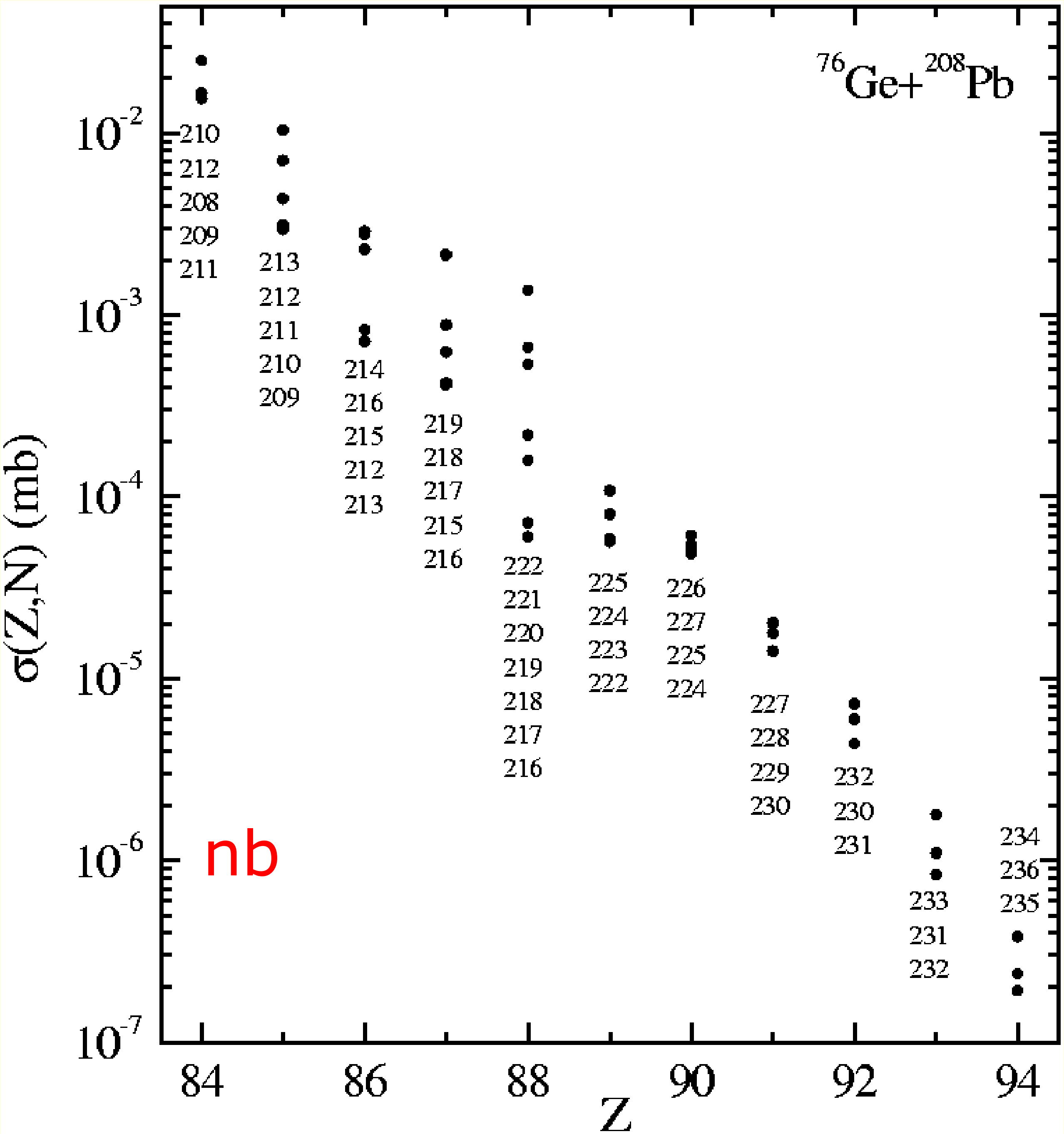


$\eta = 0$ for $A_1 = A_2$, $\eta = \pm 1$ for A_1 or $A_2 = 0$

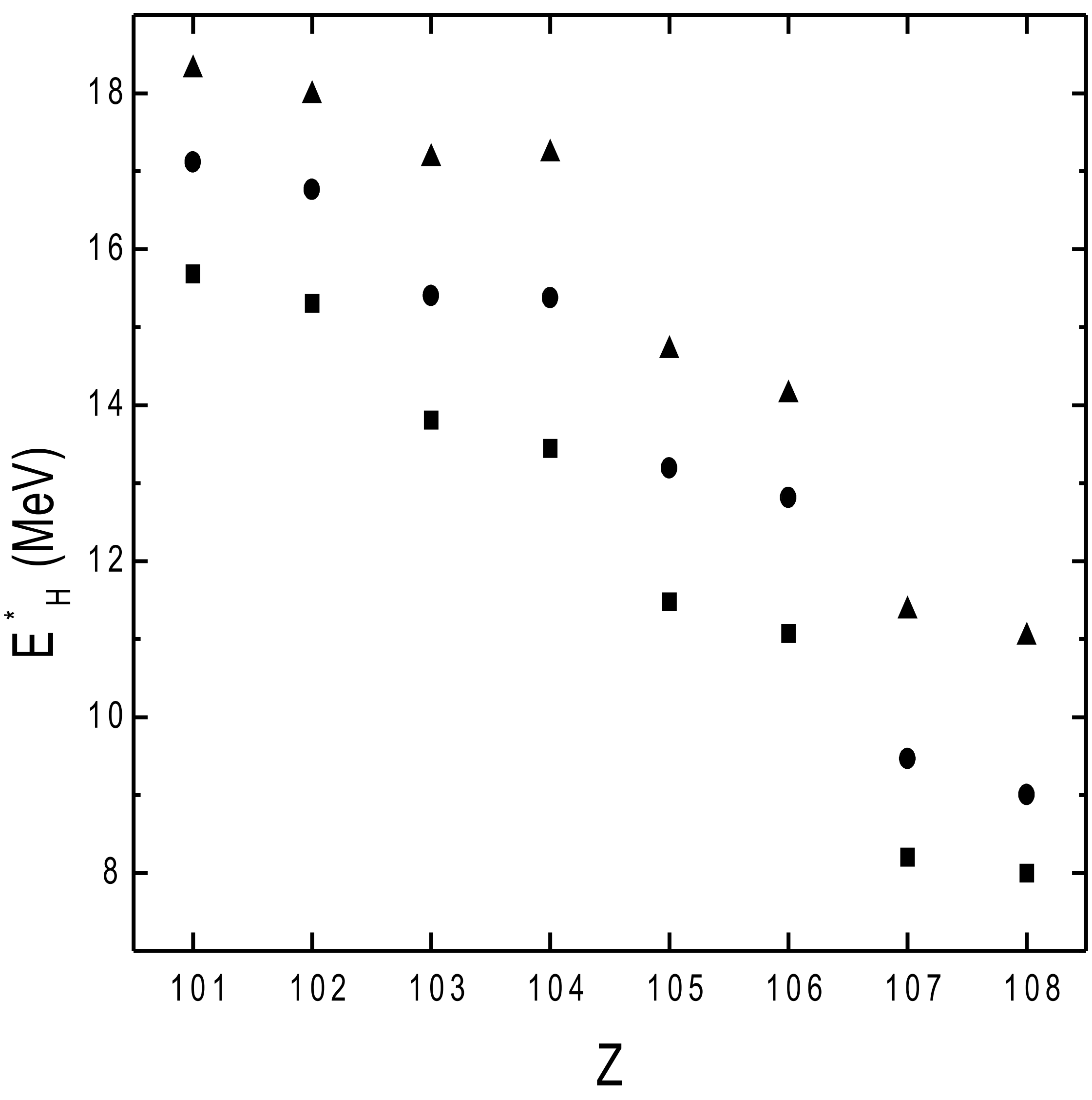
The dinuclear system model uses two main degrees of freedom to describe the fusion and quasifission processes:

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


^{76}Ge+^{208}Pb
σ(Z,N) (mb)
Z
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
84
86
88
90
92
94
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

nb


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