Possibilities of production of new isotopes

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Production of new isotopes

- Fusion reactions, particular with radioactive beams.

- Fission of heavy nuclei.

- Multinucleon transfer reactions (V.V.Volkov et al.). The new neutron-rich nuclei in a wide region of the nuclear chart can be reached by multinucleon transfer reactions with radioactive ion beams at incident energies near the Coulomb barrier. Q_{gg}-systematic

- Quasifission reactions

- Fragmentation reactions.

The cross section of the production of a primary nucleus *(Z,N)* in the diffusive nucleon transfer reaction is written as a sum over all partial waves *J*.

$$\sigma_{Z,N}(E_{\rm c.m.}) = \sum_J \sigma_{Z,N}(E_{\rm c.m.}, J),$$

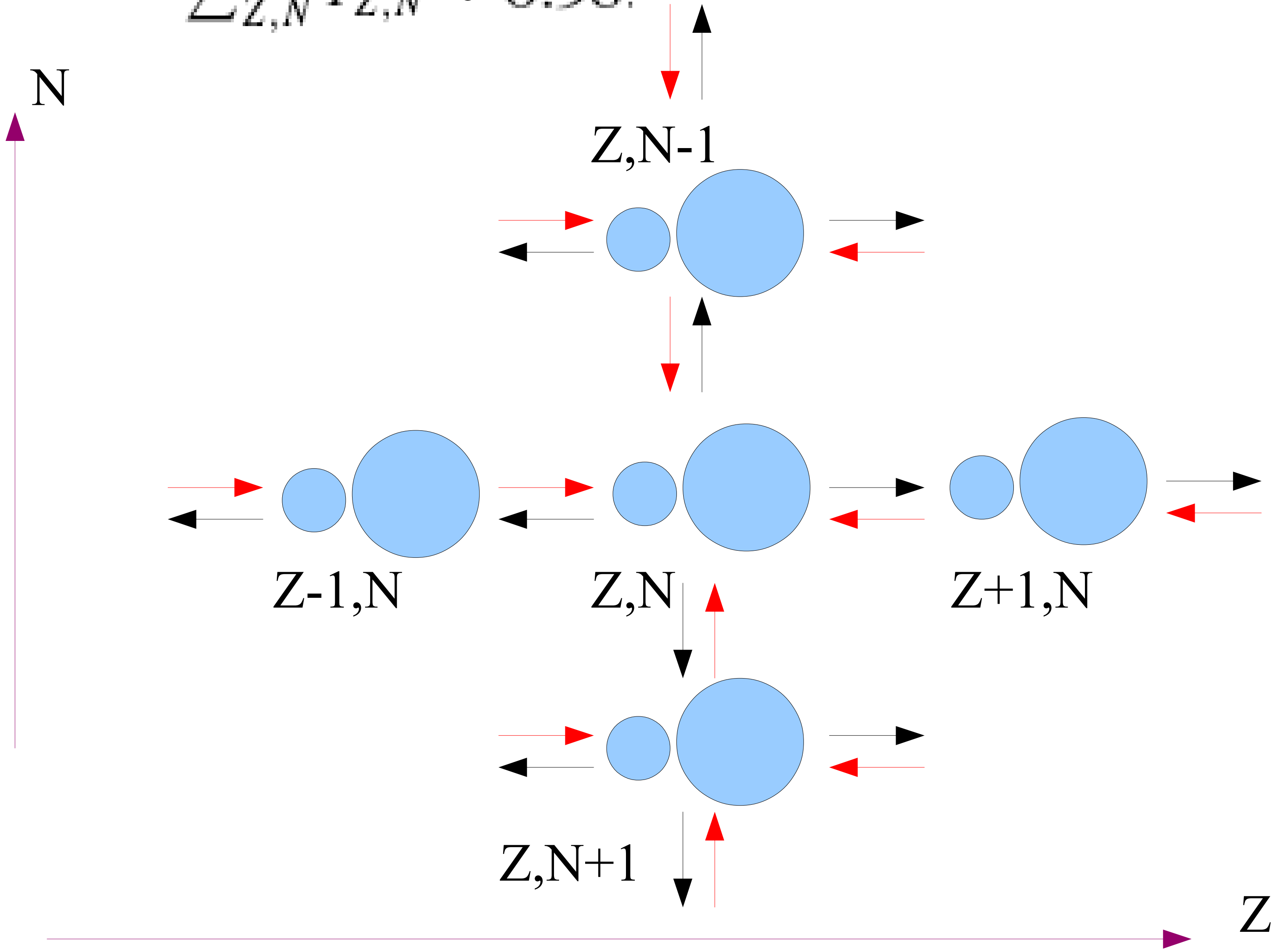
$$\sigma_{Z,N}(E_{\rm c.m.}, J) = \int_0^{\pi/2}\int_0^{\pi/2} d\cos\Theta_1 d\cos\Theta_2 \times \sigma_c(E_{\rm c.m.}, J, \Theta_i) Y_{Z,N}(E_{\rm c.m.}, J, \Theta_i).$$

The primary charge and mass yields of fragments can be expressed by the product of the formation probability $P_{Z,N}(t)$ of the DNS configuration with charge and mass asymmetries given by *Z* and *N* and of the decay probability of this configuration in *R* represented by the rate $\Lambda^{qf}_{Z,N}$

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

t_0 is the time of reaction

$$\sum_{Z,N} Y_{Z,N} \approx 0.98.$$



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

$P_{Z,N}(0) = \delta_{Z,Z_i}\delta_{N,N_i}$ - initial condition

If the primary nucleus is excited, one should take into consideration its survival probability W_{sur} in the deexcitation process to obtain the evaporation residue cross section as follows

$$\sigma^{ER}_{Z,N-x}(E_{\text{c.m.}}) = \sum_J \sigma_{Z,N}(E_{\text{c.m.}}, J) W_{\text{sur}}(E_{\text{c.m.}}, J, x),$$

In the experiments

S.Heinz *et al.* EPJ A **38** (2008) 227;

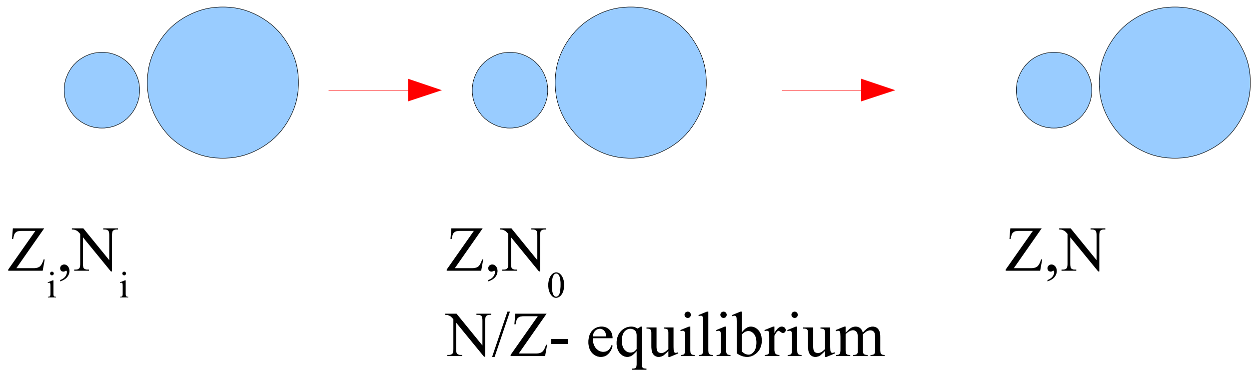
EPJ A **43** (2010) 181;

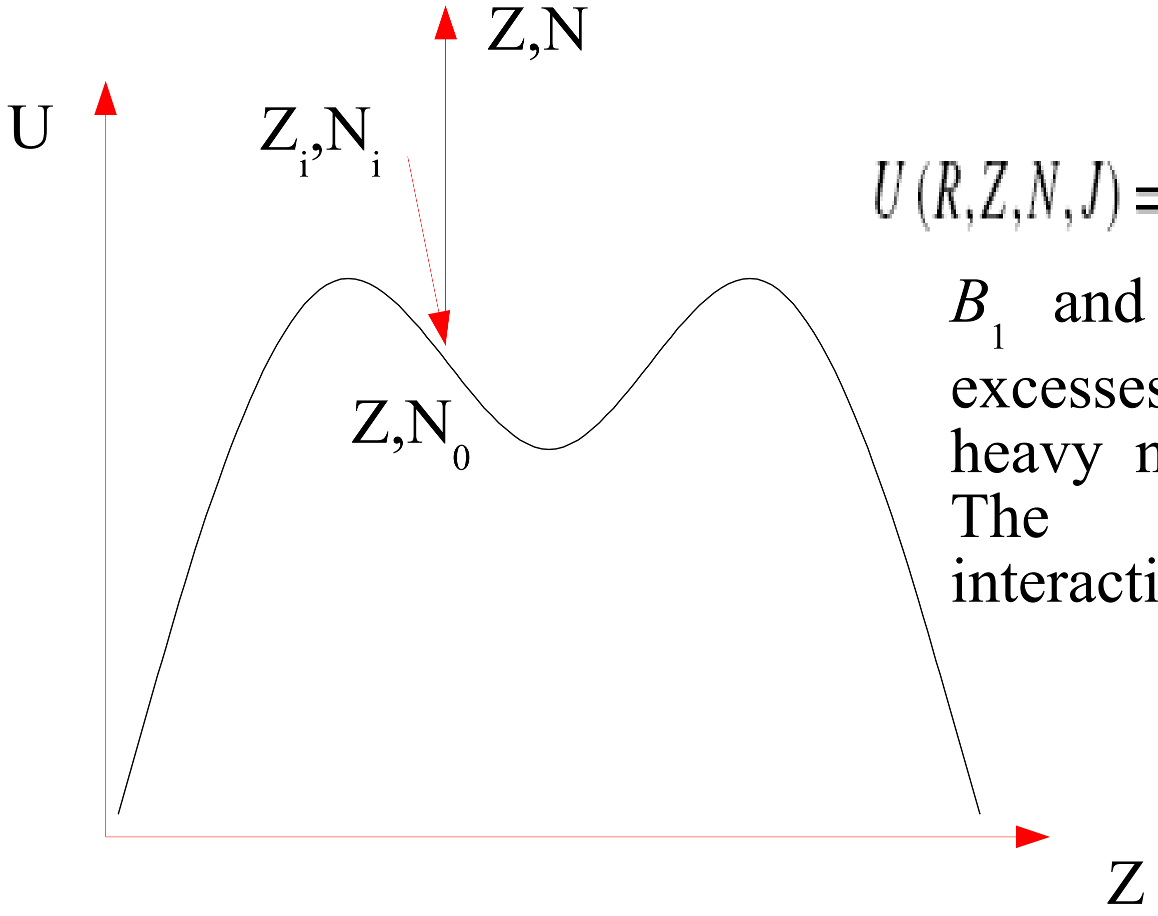
V.Comas *et al.* EPJ A **48** (2012) 48;

EPJ A **38** (2013) 49;

S.Heinz *et al.* EPJ A **51** (2015) 140

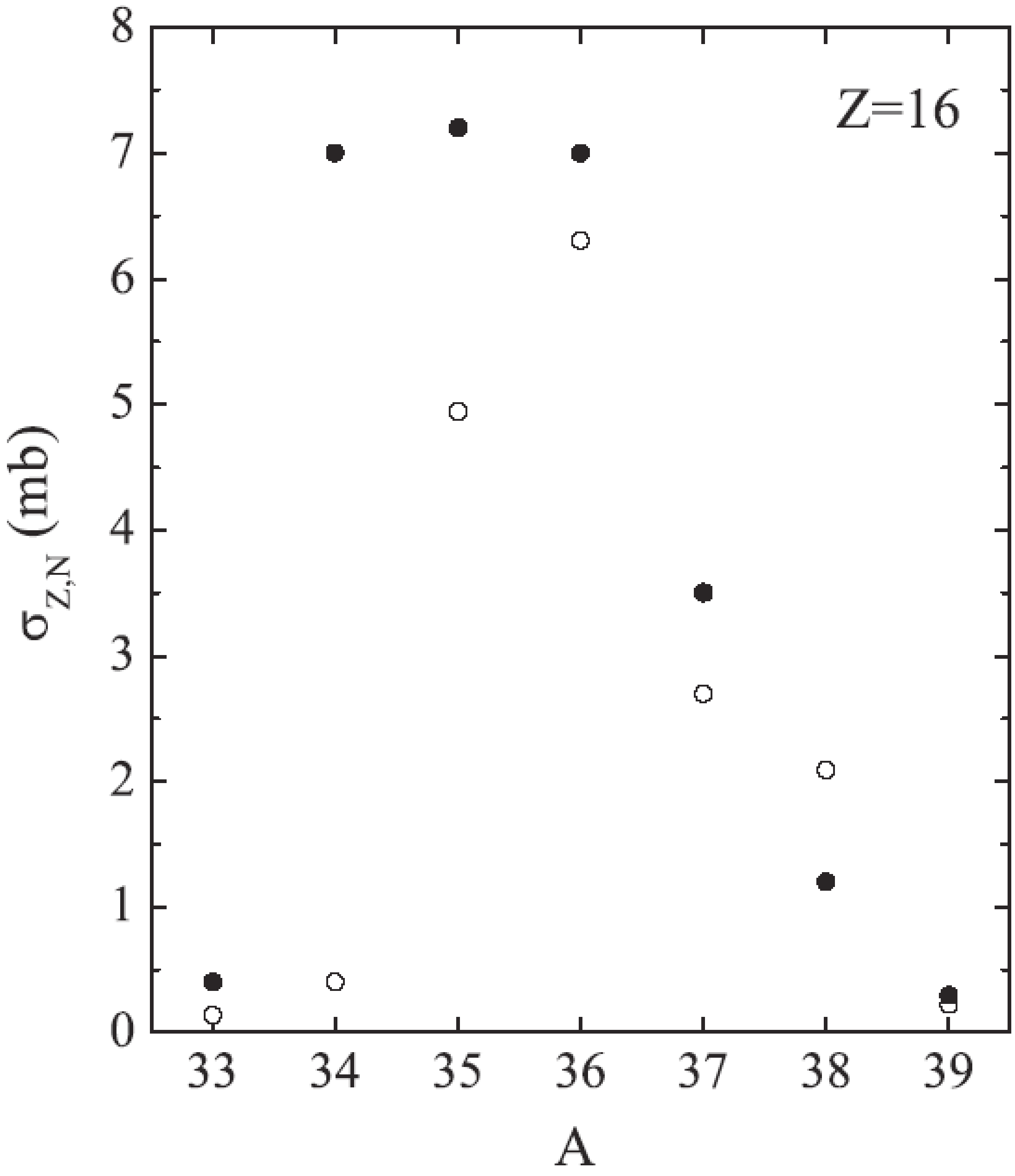
the clear signatures were observed for the formation of long-living DNS which rotates by large angles.





$$U(R,Z,N,J) = B_1 + B_2 + V(R,Z,N,J),$$

B_1 and B_2 are the mass excesses of the light and heavy nuclei, respectively. The nucleus-nucleus interaction potential V.



The calc. (open circles) cross sections of S isotopes are compared with the exp. ones (solid circles) for the ^{40}Ca + ^{208}Pb reaction ($E_{c.m}$=208.8 MeV)
[PRC **71**, 044610 (2005)].

^{58}Ni($E_{\mathrm{c.m.}} = 256.8$ MeV)+^{208}Pb L. Corradi *et al.*, Phys. Rev. C **66**, 024606 (2002); J. Phys. G **36**, 113101 (2009).

^{64}Ni($E_{\mathrm{c.m.}} = 307.4$ MeV)+^{238}U L. Corradi *et al.*, Phys. Rev. C **59**, 261 (1999).

In the ^{58}Ni+^{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 the ^{64}Ni+^{238}U reaction the experimental and theoretical production cross sections for ^{52}Ti are 0.5 and 1.6 mb, respectively.

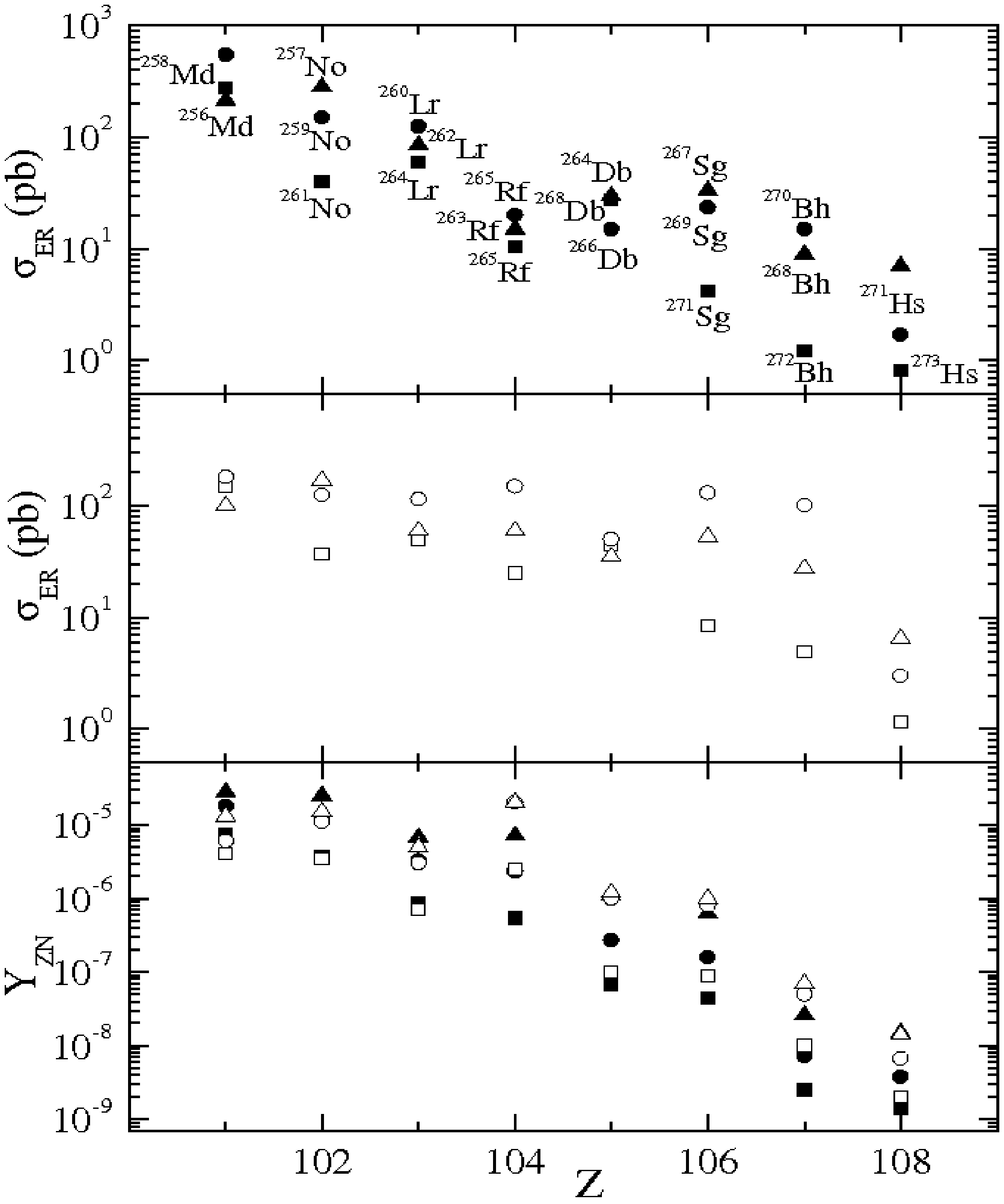
In the ^{48}Ca($E_{\mathrm{c.m.}} = 274.6$ MeV)+ ^{238}U reaction the experimental [S. Lunardi, *AIP Conference Proceedings* **1120**, p. 70.] and calculated ratios of secondary yields Y(^{62}Fe)/Y(^{58}Cr) for the neutron-rich ^{62}Fe and ^{58}Cr isotopes are about 0.2 and 0.3, respectively.

$^{48}Ca+^{244}Cm$ ▲ $E_{cm}=207$ MeV

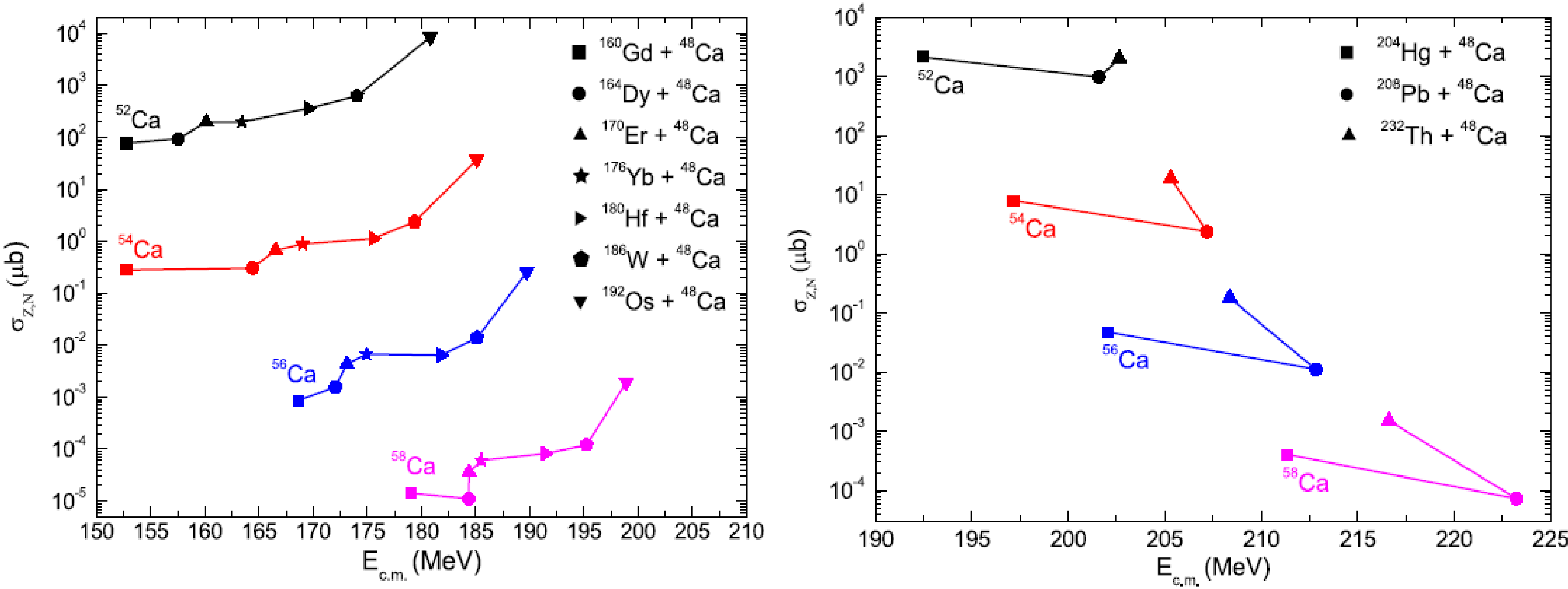
$^{48}Ca+^{246}Cm$ ● $E_{cm}=205.5$ MeV

$^{48}Ca+^{248}Cm$ ■ $E_{cm}=204$ MeV

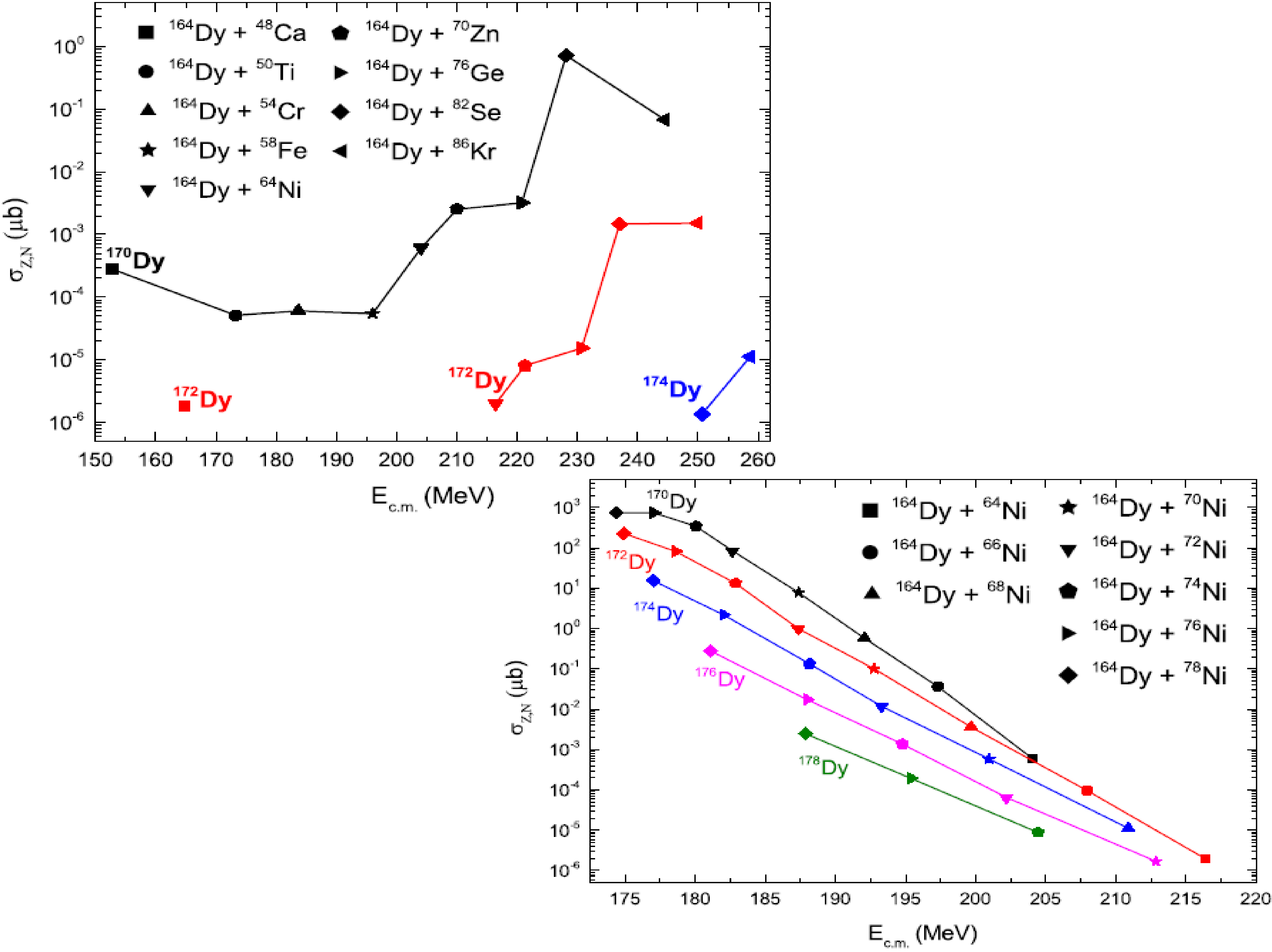
PRC **71** (2005) 034603

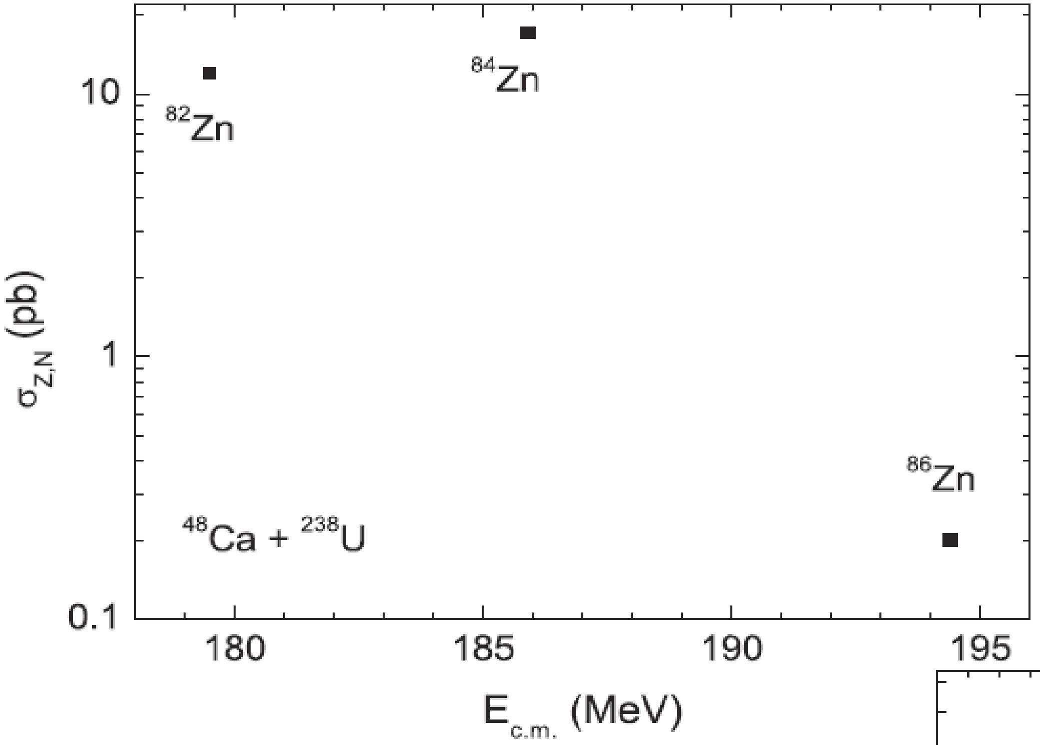


The possibilities for producing neutron-rich isotopes ^{52,54,56,58}Ca in the transfer reactions with rare-earth targets.

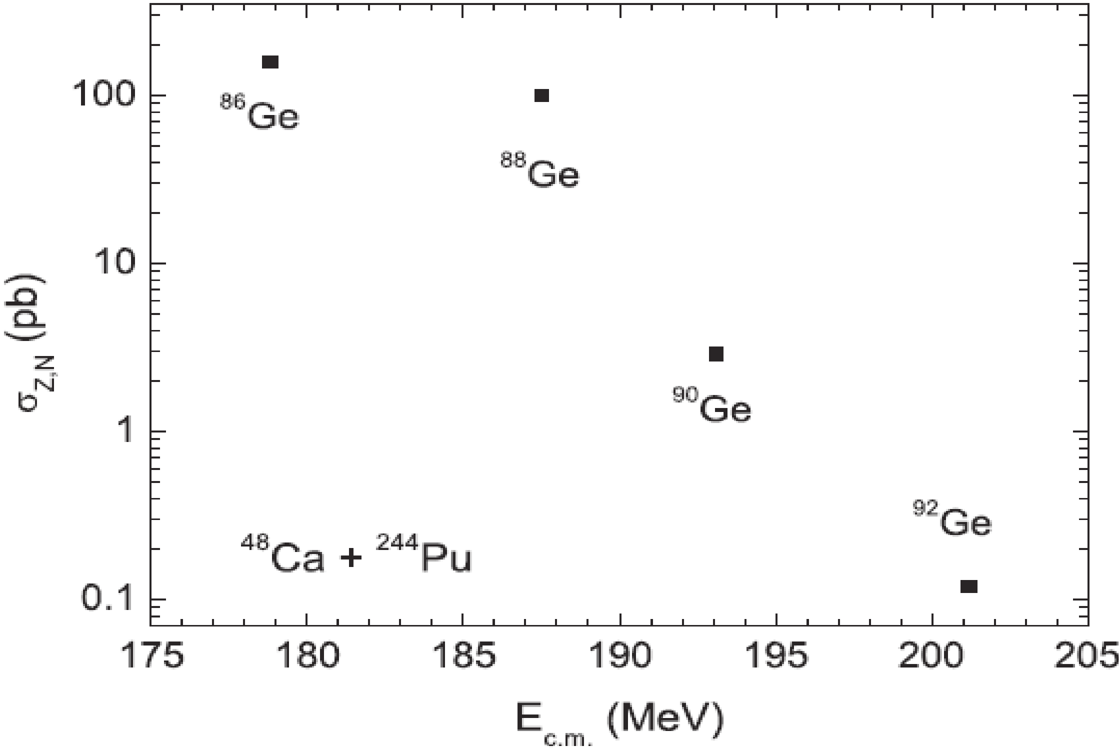


Phys. Rev. C **89** (2014) 034622
Phys. Rev. C **91** (2015) 054610


164Dy + 48Ca
164Dy + 50Ti
164Dy + 54Cr
164Dy + 58Fe
164Dy + 64Ni
164Dy + 70Zn
164Dy + 76Ge
164Dy + 82Se
164Dy + 86Kr
170Dy
172Dy
172Dy
174Dy
σZ,N (μb)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
150
160
170
180
190
200
210
220
230
240
250
260
Ec.m. (MeV)
164Dy + 64Ni
164Dy + 66Ni
164Dy + 68Ni
164Dy + 70Ni
164Dy + 72Ni
164Dy + 74Ni
164Dy + 76Ni
164Dy + 78Ni
170Dy
172Dy
174Dy
176Dy
178Dy
σZ,N (μb)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
175
180
185
190
195
200
205
210
215
220
Ec.m. (MeV)



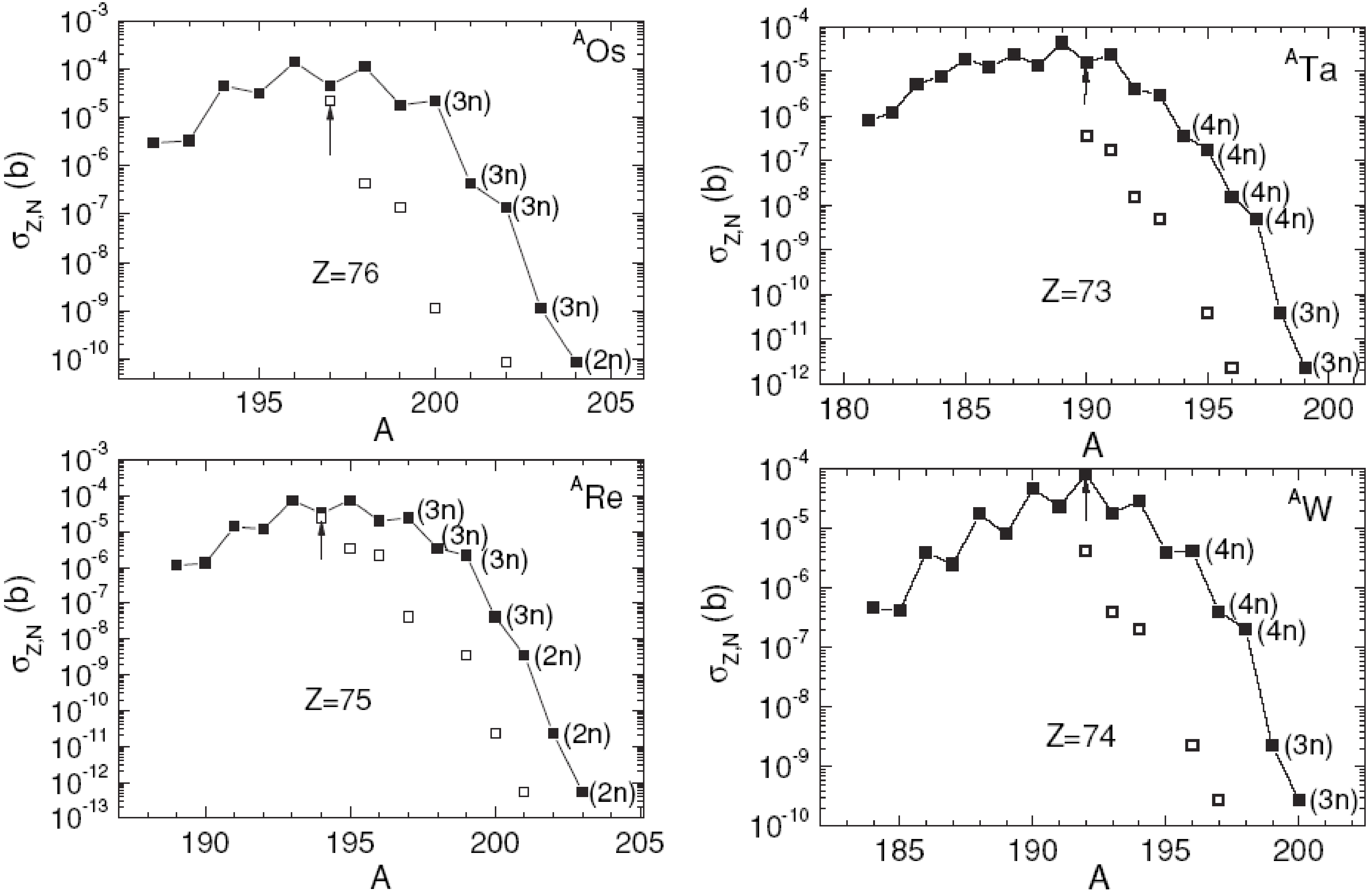
$E_{\text{c.m.}}$ provides the excitations of the isotopes equal to the corresponding threshold for the neutron emission.

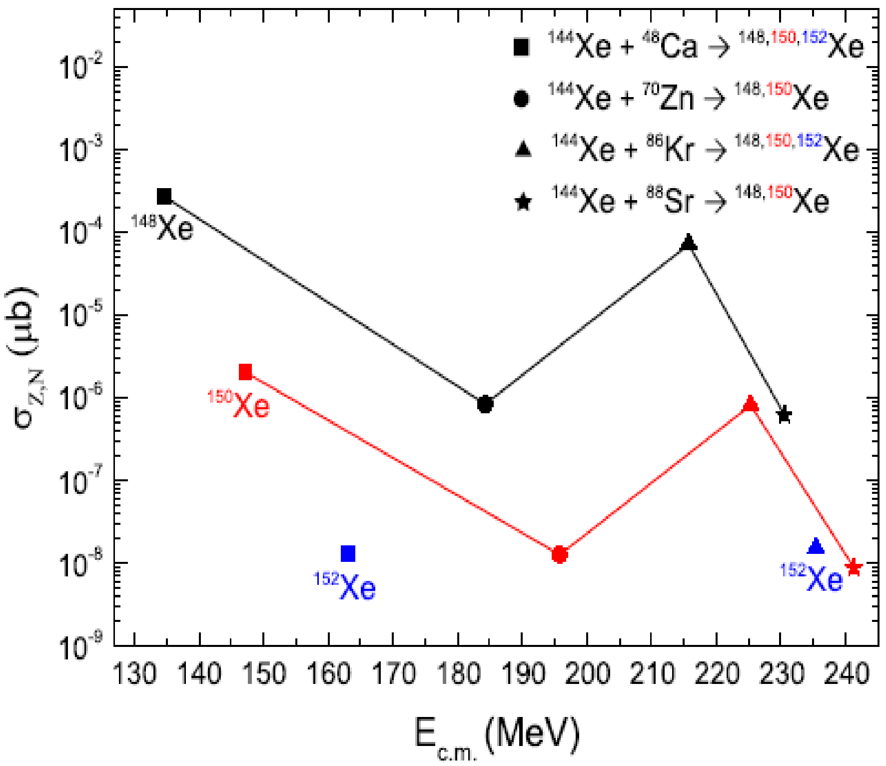


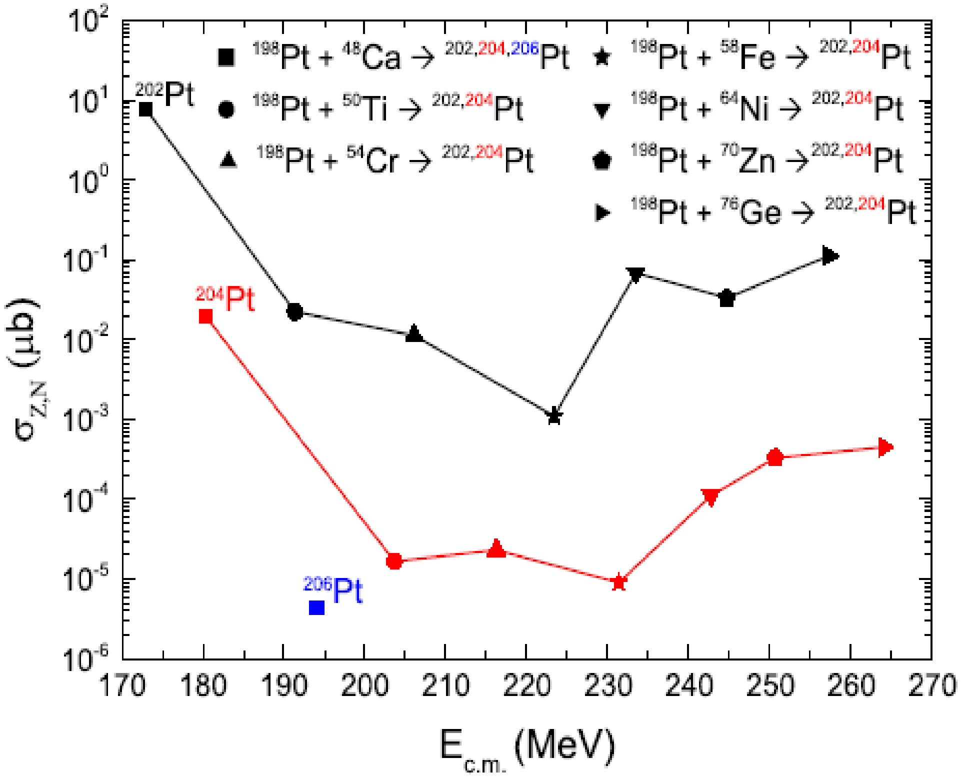
PRC **81**, 024604 (2010)

^{48}Ca + ^{238}U at $E_{\mathrm{c.m.}} = 189$ MeV

PRC **81**, 057602 (2010)



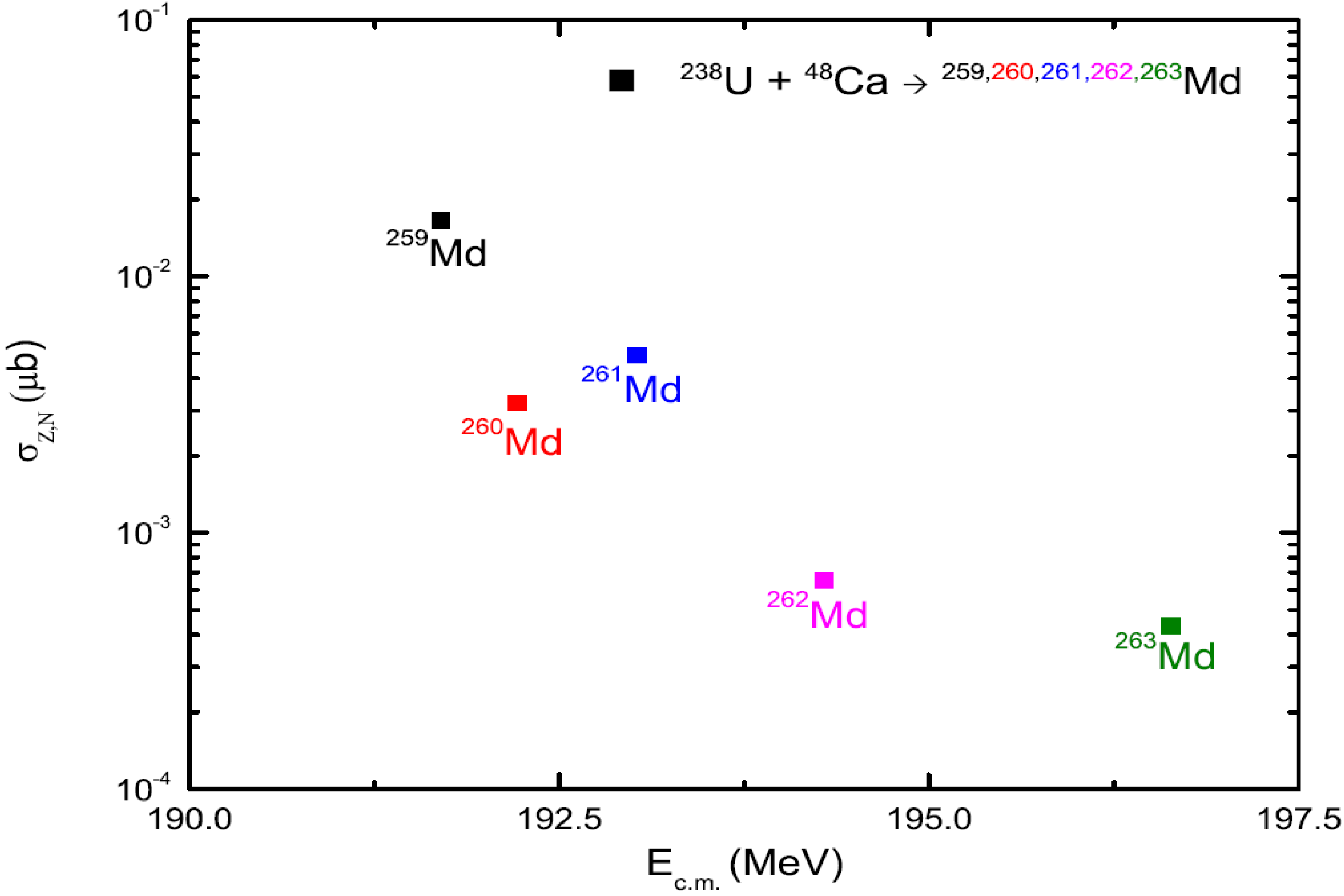


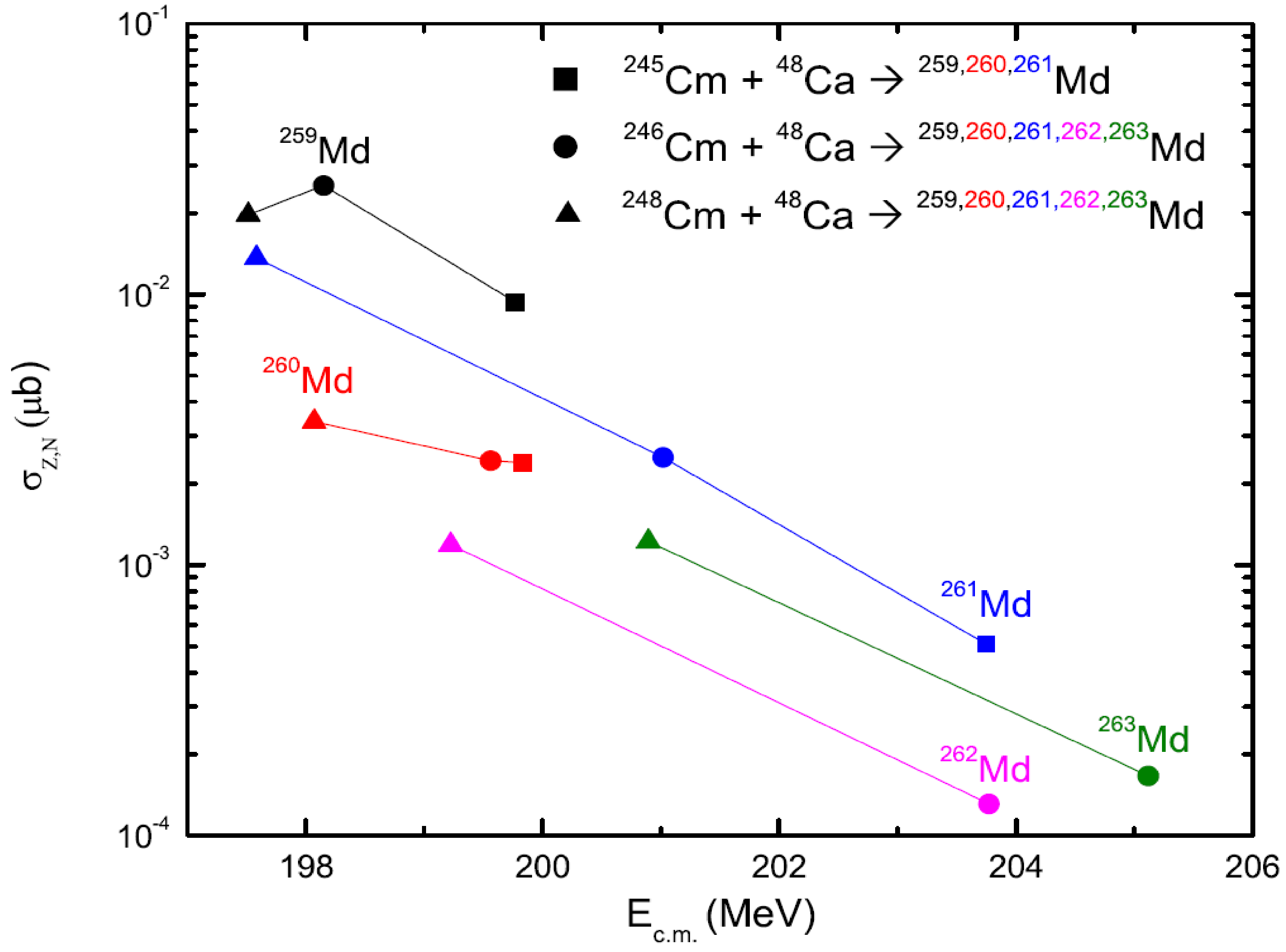


The predicted cross sections of the production of neutron-rich isotopes ^{148,150,152}Xe in the transfer reactions with the radioactive beam of ^{144}Xe. The cross sections correspond to the maxima of 0*n* evaporation channels.

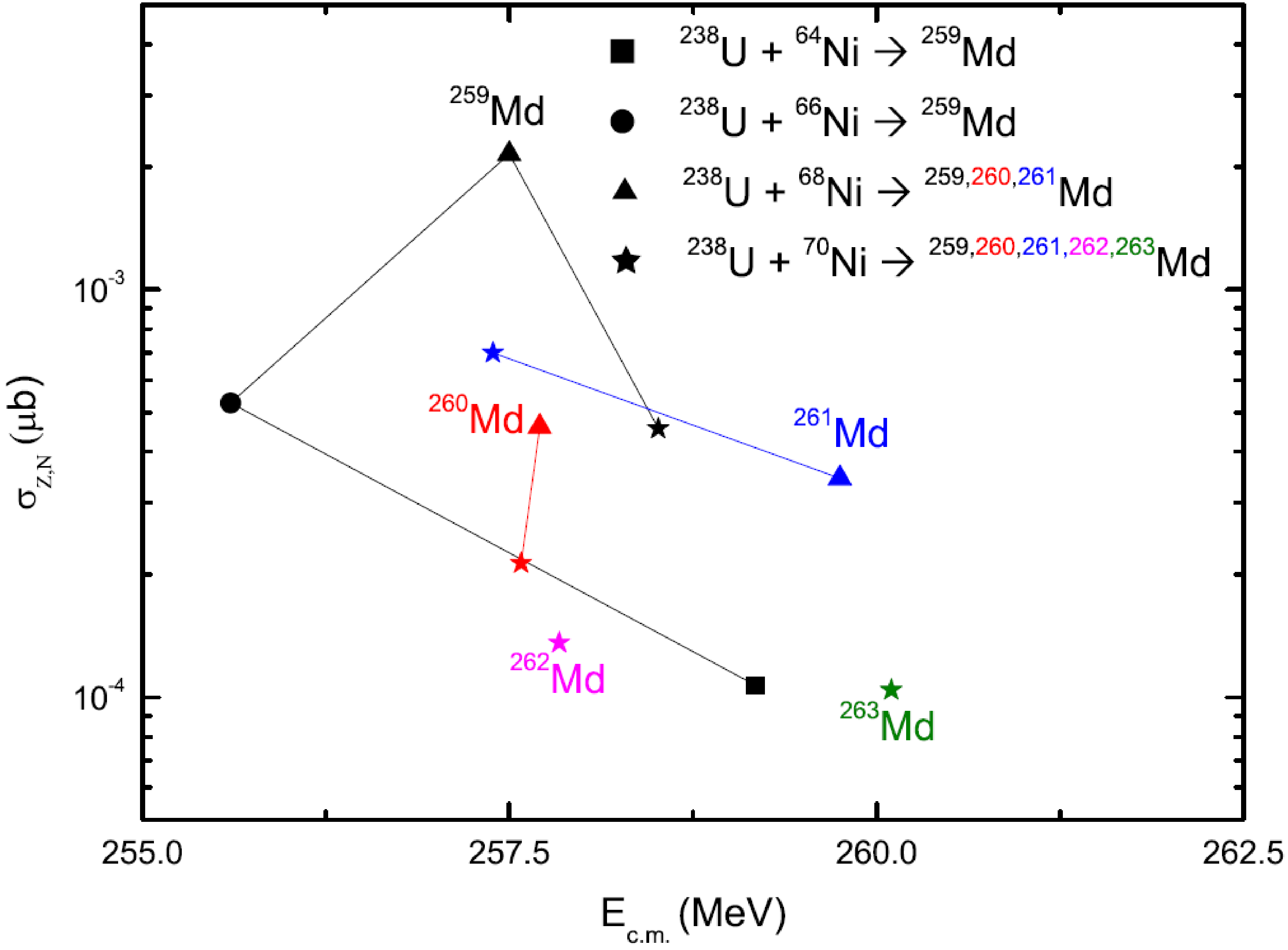
The expected maximal cross sections of the production of neutron-rich isotopes ^{202,204,206}Pt in the 0*n* evaporation channels of the listed transfer reactions.

Possibilities of production of neutron-rich Md isotopes in multi-nucleon transfer reactions (suggested by Yu.Oganessian, G.Ter-Akopian, R.Wolski)





10^-1
10^-2
10^-3
10^-4
198
200
202
204
206
σ_Z,N (μb)
E_c.m. (MeV)
■ 245Cm + 48Ca → 259,260,261Md
● 246Cm + 48Ca → 259,260,261,262,263Md
▲ 248Cm + 48Ca → 259,260,261,262,263Md
259Md
260Md
261Md
262Md
263Md


■ ^{238}U + ^{64}Ni → ^{259}Md
● ^{238}U + ^{66}Ni → ^{259}Md
▲ ^{238}U + ^{68}Ni → ^{259,260,261}Md
★ ^{238}U + ^{70}Ni → ^{259,260,261,262,263}Md
^{259}Md
^{260}Md
^{261}Md
^{262}Md
^{263}Md
10^{-3}
10^{-4}
$\sigma_{Z,N}$ (μb)
255.0
257.5
260.0
262.5
$E_{c.m.}$ (MeV)

Production of unknown neutron-deficient isotopes of U, Np, Pu, Am, Cm, and Cf

N=126

If the lifetimes of these isotopes are larger than 5μ s, the spectroscopic study becomes possible for them.

Evaporation residue cross sections in the reactions

$^{24,25,26}\mathrm{Mg} + {}^{204,206,207,208}\mathrm{Pb} \longrightarrow \mathrm{Pu} + xn$

$^{28,30}\mathrm{Si} + {}^{204,206,207,208}\mathrm{Pb} \longrightarrow \mathrm{Cm} + xn$ and αxn

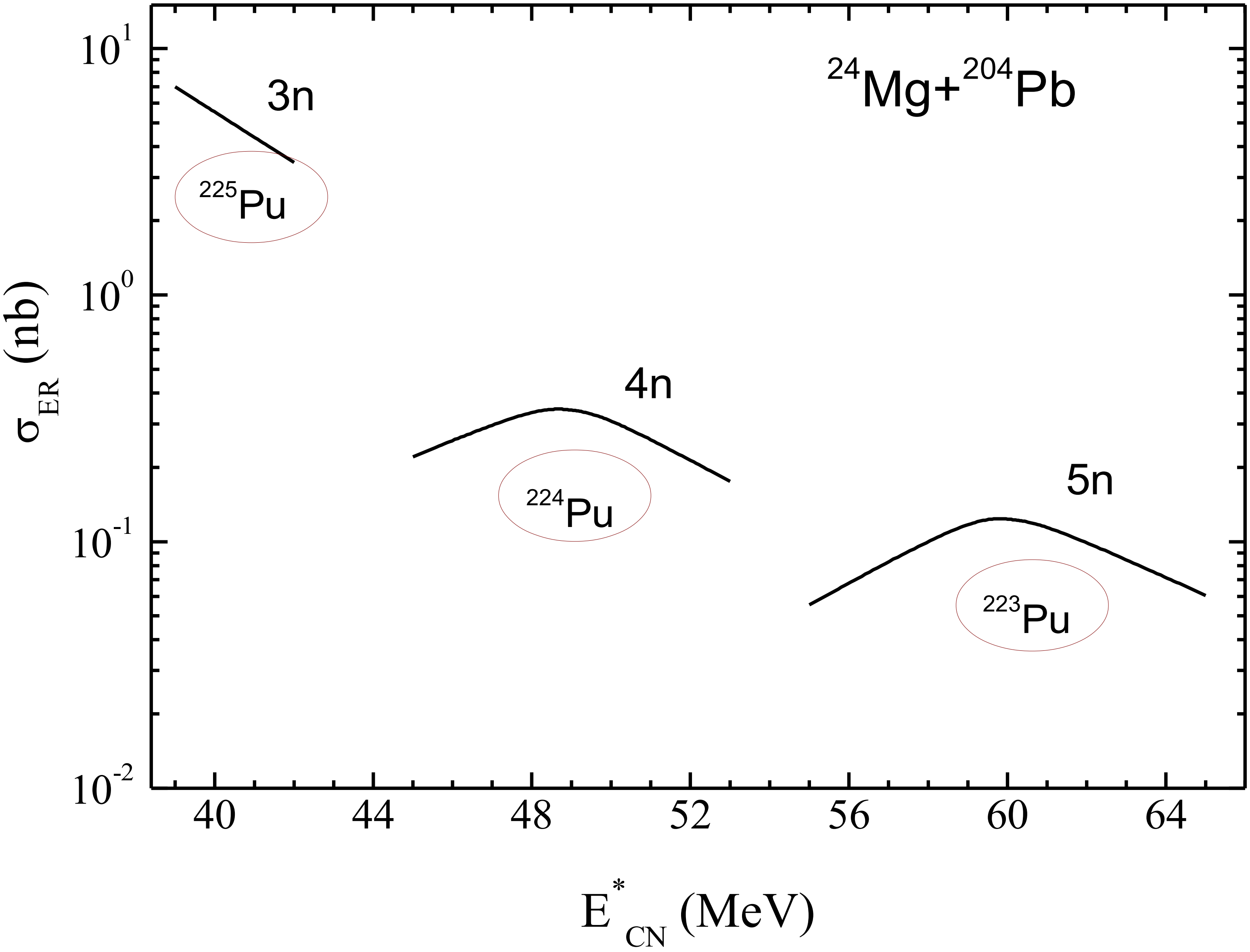
$^{27}\mathrm{Al} + {}^{204,206}\mathrm{Pb} \longrightarrow \mathrm{Am} + xn$

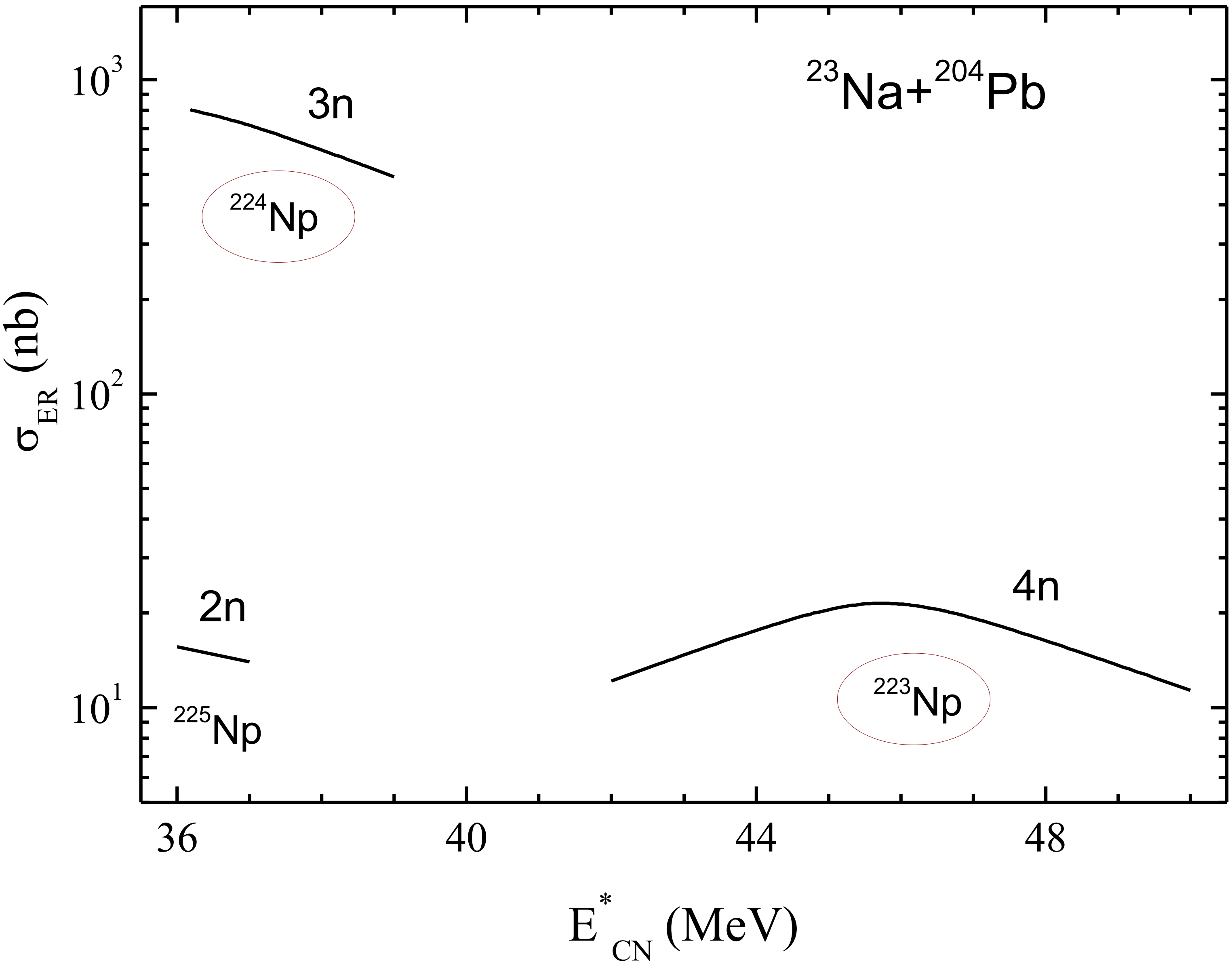
$^{40,44,48}\mathrm{Ca} + {}^{184,186}\mathrm{W} \longrightarrow \mathrm{Pu} + xn$

$^{40,44}\mathrm{Ca} + {}^{190,192}\mathrm{Os} \longrightarrow \mathrm{Cm} + xn$ and αxn

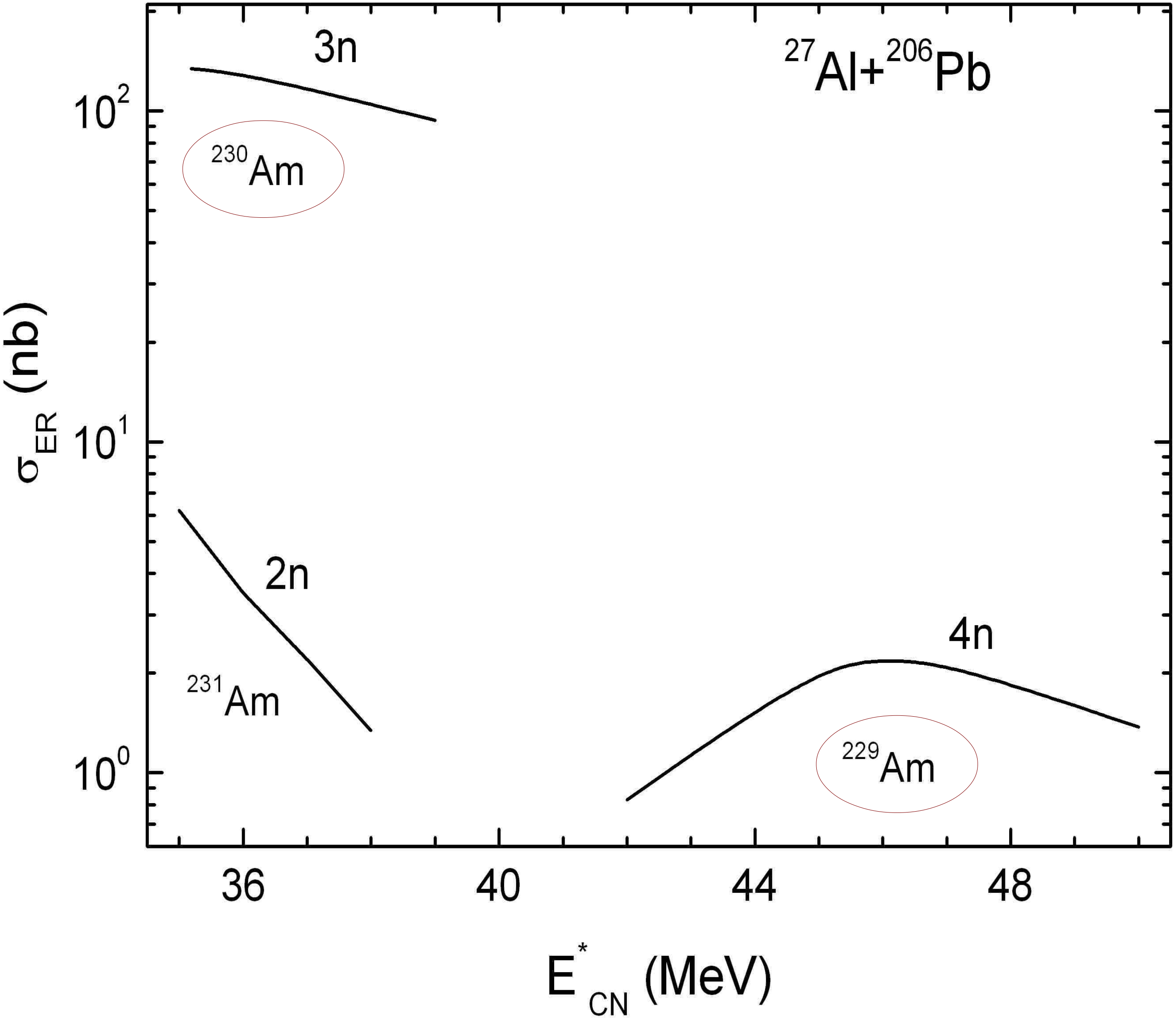
$^{28}\mathrm{Si} + {}^{192}\mathrm{Pt}$, $^{44}\mathrm{Ca} + {}^{176}\mathrm{Hf} \longrightarrow \mathrm{U} + xn$

$^{34}\mathrm{S} + {}^{204,206}\mathrm{Pb} \longrightarrow \mathrm{Cf} + xn$

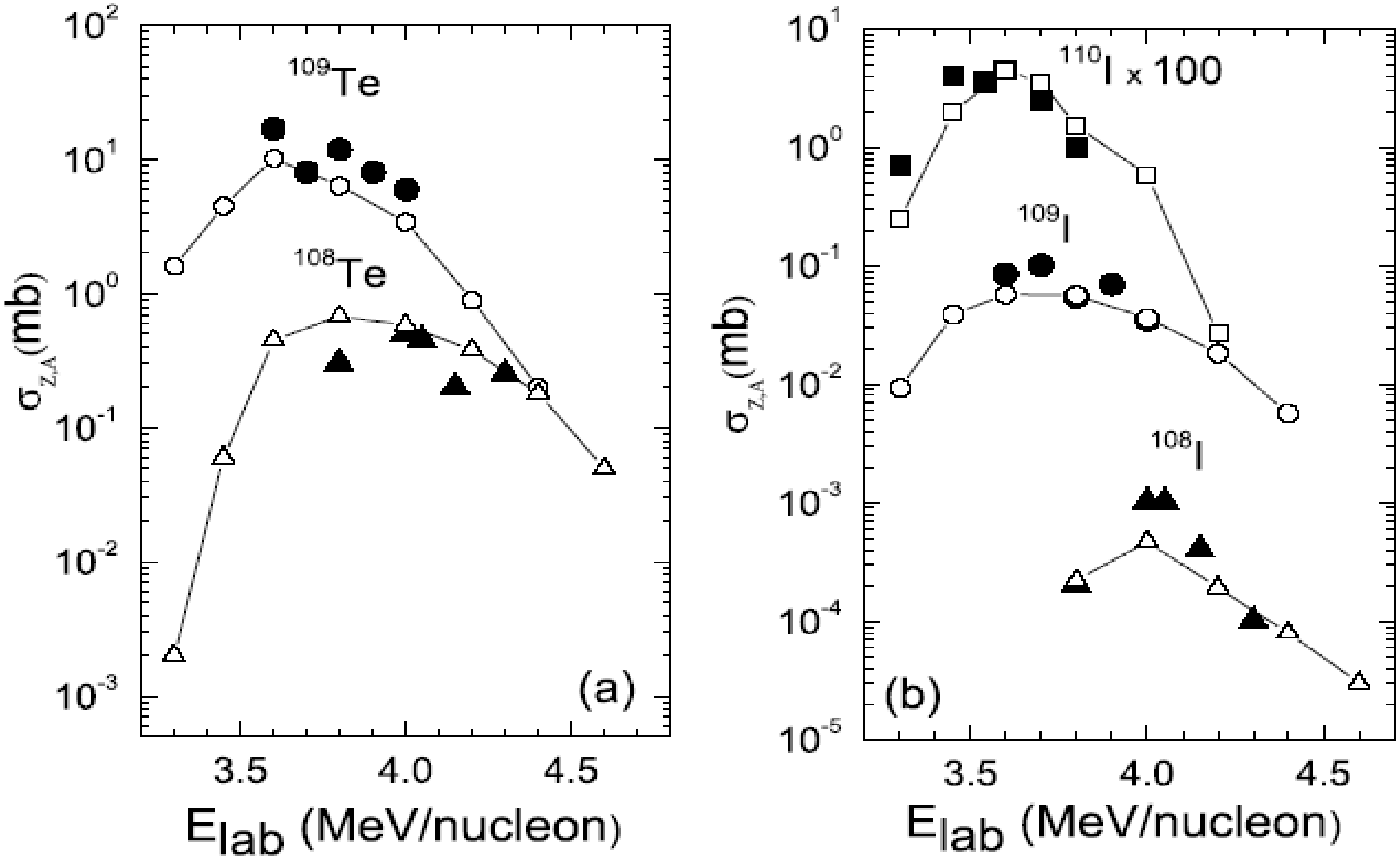

^{24}Mg+^{204}Pb
3n
^{225}Pu
4n
^{224}Pu
5n
^{223}Pu
σ_{ER} (nb)
10^{1}
10^{0}
10^{-1}
10^{-2}
40
44
48
52
56
60
64
E^{*}_{CN} (MeV)



^{23}Na+^{204}Pb
3n
^{224}Np
2n
^{225}Np
4n
^{223}Np
10^3
10^2
10^1
σ_{ER} (nb)
36
40
44
48
E^*_{CN} (MeV)


3n
^{27}Al+^{206}Pb
10^2
^{230}Am
σ_{ER} (nb)
10^1
2n
4n
^{231}Am
10^0
^{229}Am
36
40
44
48
E^*_{CN} (MeV)

Reactions	E_{lab} (MeV)	E^*_{CN} (MeV)	$J_{\max}$	ER	$\sigma^{\text{expt}}_{Z,A}$ (μb)	$\sigma_{Z,A}$ (μb)	Production channels (weights in %)
^{58}Ni + ^{50}Cr	319	102	75	^{100}In	2.6	5.6	$\alpha p3n$
^{58}Ni + ^{58}Ni	325	96	78	^{100}In	0.8	3.1	^{12}C$p3n$ (80%), $3\alpha p3n$ (20%)
^{58}Ni + ^{58}Ni	348	107	78	^{100}In	1.7	5.2	^{12}C$p3n$ (60%), $3\alpha p3n$ (40%)
^{58}Ni + ^{58}Ni	371	119	78	^{100}In	1.7	3.2	^{12}C$p3n$ (40%), $3\alpha p3n$ (60%)
^{58}Ni + ^{58}Ni	394	131	78	^{100}In	1.6	0.86	^{12}C$p3n$ (10%), $3\alpha p3n$ (90%)
^{58}Ni + ^{50}Cr	249	70	64	^{101}Sn	$(1.6 \pm 0.4) \times 10^{-2}$	8.2×10^{-2}	$\alpha 3n$
^{58}Ni + ^{58}Ni	325	96	78	^{101}Sn	$(0.9 \pm 0.4) \times 10^{-2}$	5.0×10^{-2}	^{12}C$3n$ (70%), $3\alpha 3n$ (30%)
^{58}Ni + ^{58}Ni	348	107	78	^{101}Sn	$(1.3 \pm 0.3) \times 10^{-2}$	4.2×10^{-2}	^{12}C$3n$ (50%), $3\alpha 3n$ (50%)
^{58}Ni + ^{58}Ni	371	119	78	^{101}Sn	$(2.8 \pm 1.0) \times 10^{-2}$	3.6×10^{-2}	^{12}C$3n$ (35%), $3\alpha 3n$ (65%)
^{58}Ni + ^{58}Ni	394	131	78	^{101}Sn	$(0.7 \pm 0.4) \times 10^{-2}$	0.6×10^{-2}	^{12}C$3n$ (5%), $3\alpha 3n$ (95%)
^{58}Ni + ^{54}Fe	200	40	27	^{110}Xe	1.0 ± 0.2	0.7	$2n$
^{58}Ni + ^{54}Fe	215	47	40	^{109}Xe	$(1.0 \pm 0.2) \times 10^{-2}$	5.8×10^{-2}	$3n$
^{50}Cr + ^{58}Ni	255	92	75	^{100}In	1.0	0.8	$\alpha p3n$
^{50}Cr + ^{58}Ni	255	92	75	^{100}Sn	4.0×10^{-2}	1.0×10^{-2}	$\alpha 4n$



The comparison of experimental (solid symbols) and calculated (open symbols connected by line) excitation functions for production of indicated isotopes of (a) Te and (b) I in the ^{58}Ni+^{54}Fe reaction. The experimental data are from [A. Korgul *et al.*, Phys. Rev. C **77**, 034301 (2008).].

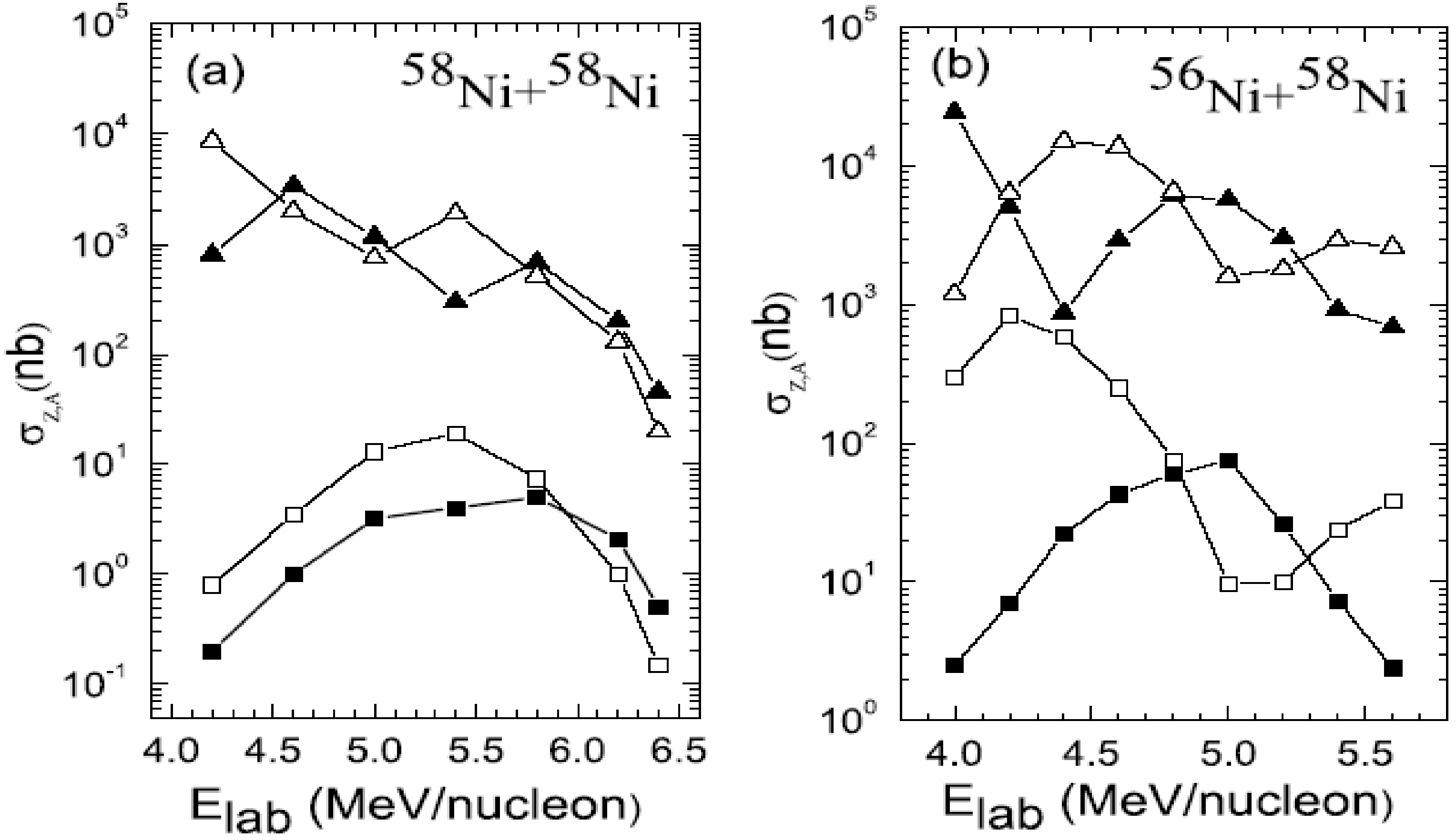


FIG. 5. The calculated excitation functions for the production of ^{100}Sn (■), ^{101}Sn (□), ^{102}Sn (▲), and ^{103}Sn (△) in cluster emission channels of the reactions (a) ^{58}Ni + ^{58}Ni and (b) ^{56}Ni + ^{58}Ni.

Summary

1) The production of neutron-rich nuclei in multinucleon transfer reactions is possible at incident energies close to the Coulomb barrier.

2) Multinucleon transfer reactions could be the only way to produce some unknown isotopes of actinides and transactinides.

3) Complete fusion reactions allow us to produce many neutron-deficient isotopes with N close to 126.

Thank you.