Possibilities of production of new isotopes in transfer reactions

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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*.

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

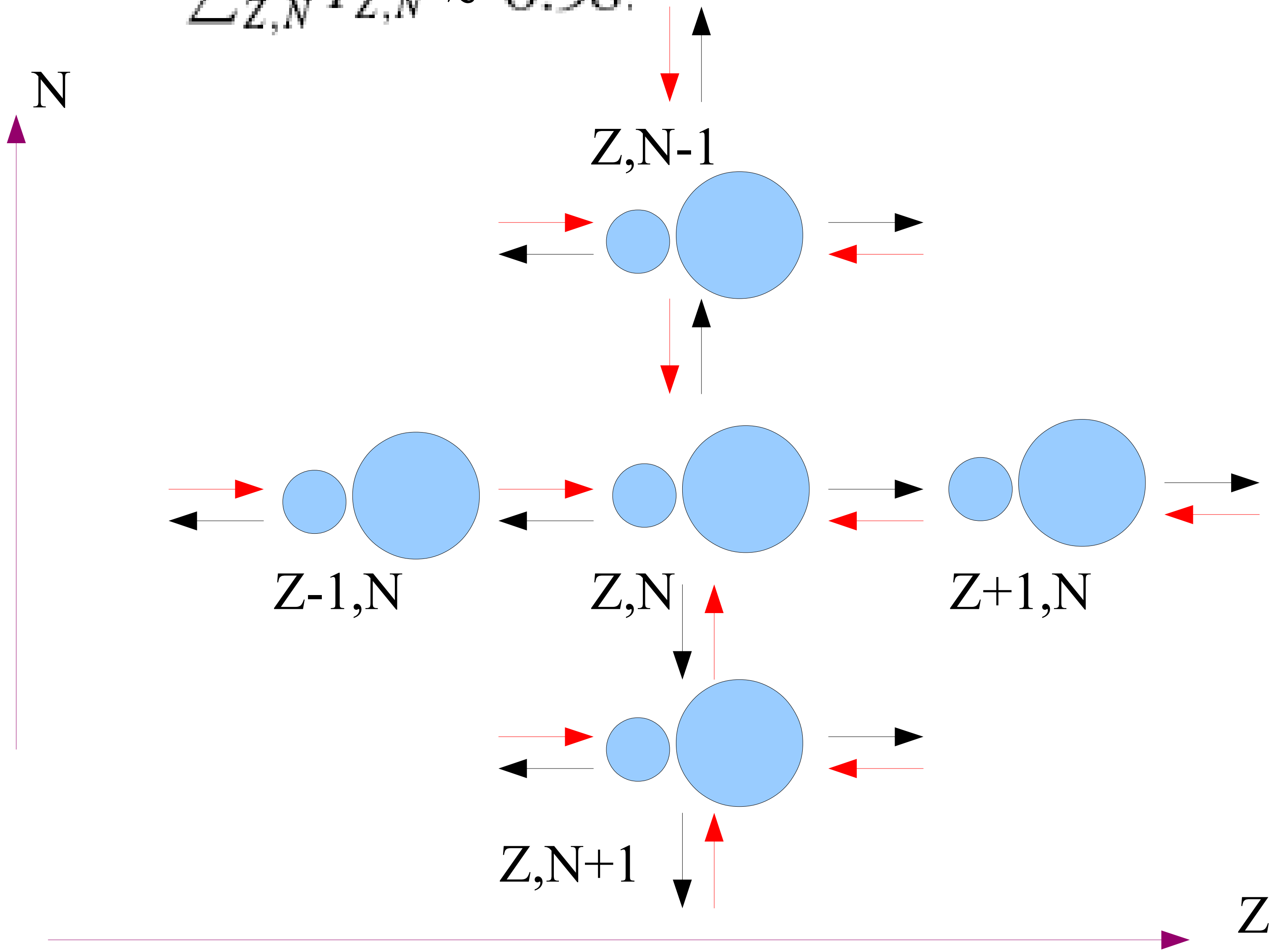
$$\sigma_{Z,N}(E_{\mathrm{c.m.}}, J) = \int_0^{\pi/2} \int_0^{\pi/2} d\cos\Theta_1 d\cos\Theta_2 \times \sigma_c(E_{\mathrm{c.m.}}, J, \Theta_i) Y_{Z,N}(E_{\mathrm{c.m.}}, J, \Theta_i).$$

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;

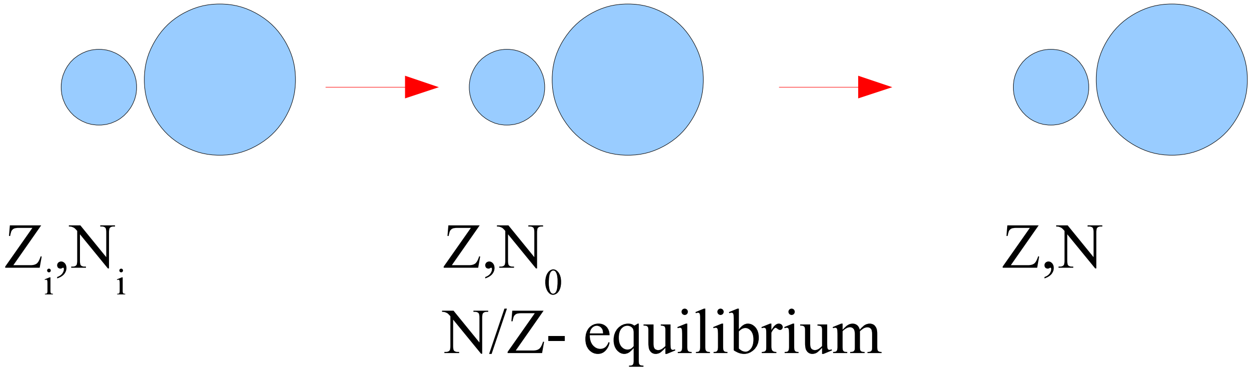
EPJ A **43** (2010) 181;

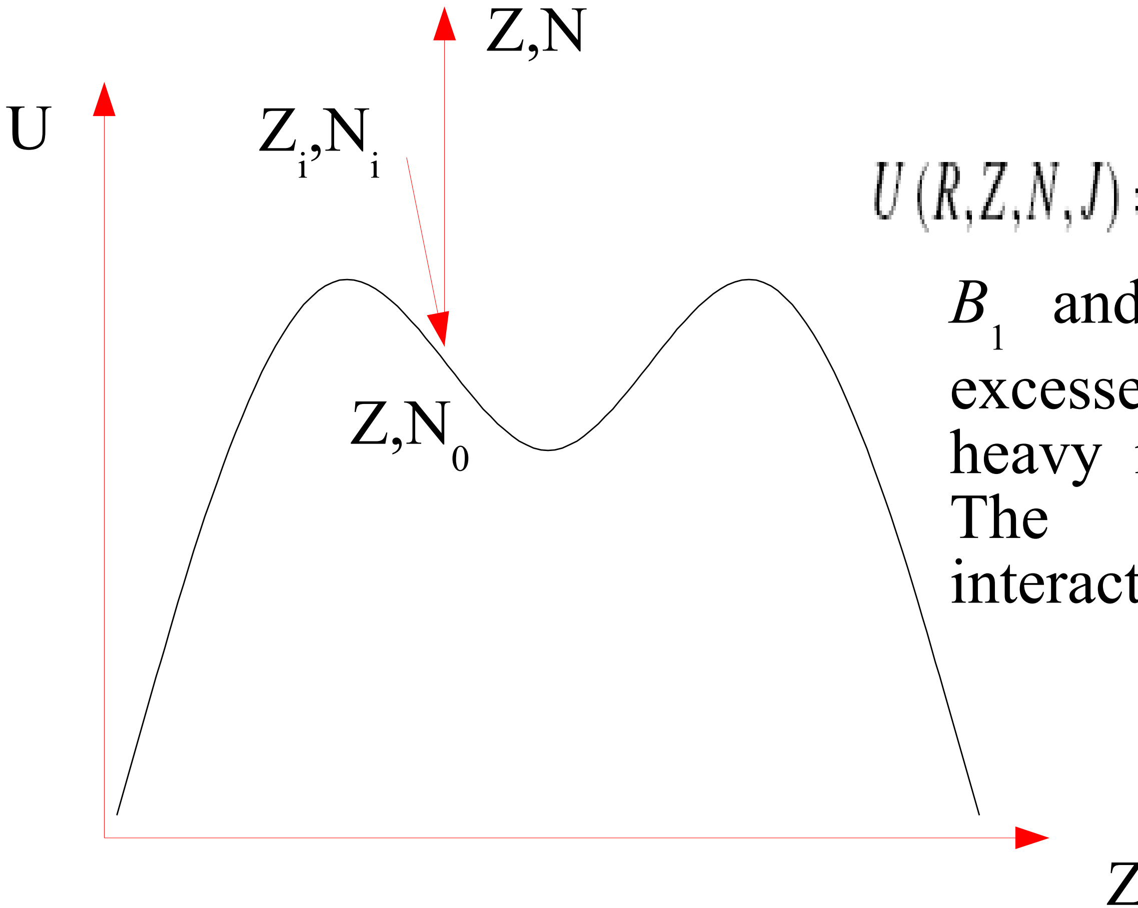
V.Comas *et al.* EPJ A **48** (2012) 48;

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

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

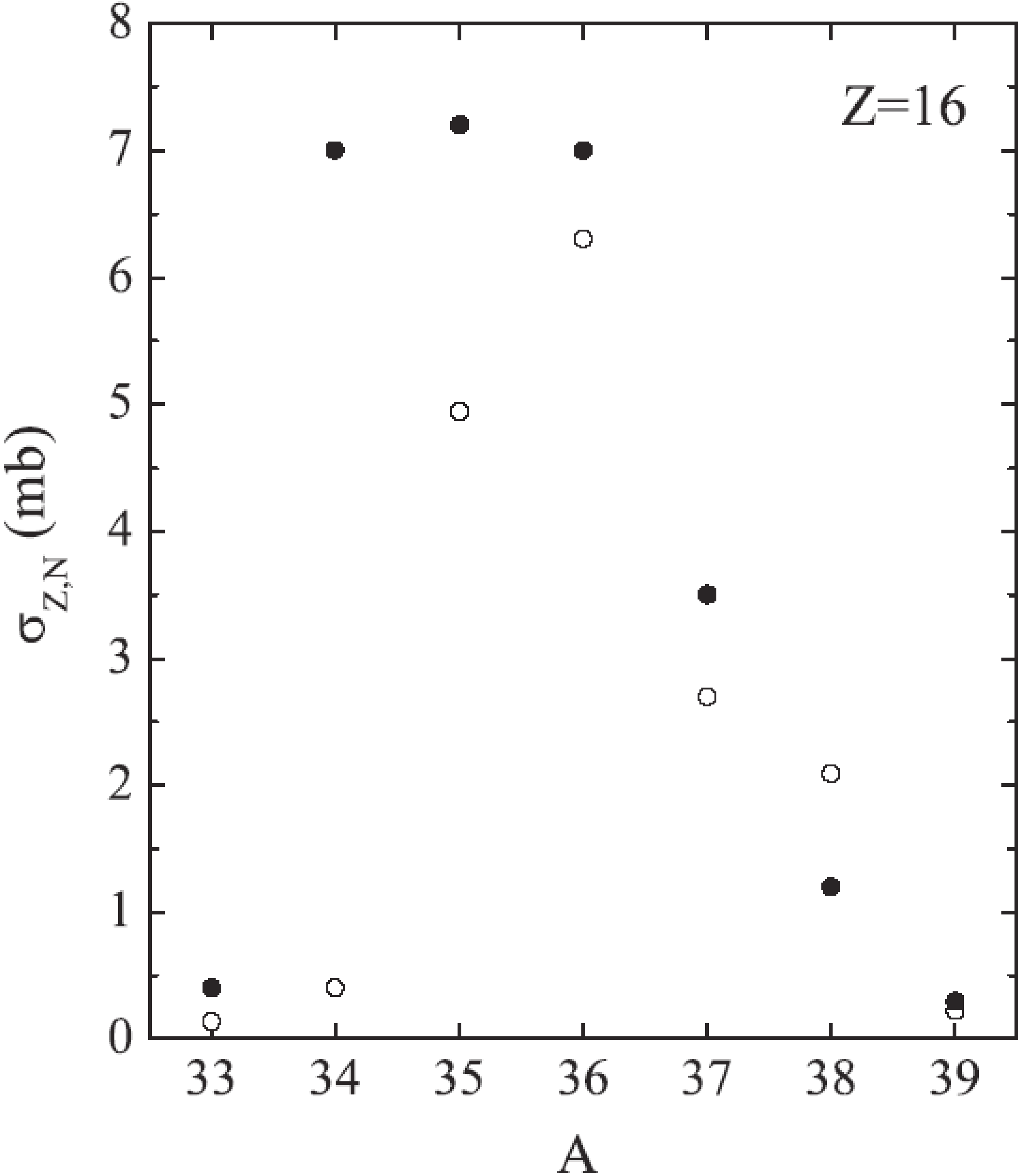
the clear signatures were observed for the formation of long-living DNS which rotates by large angles.





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

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)].

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

$^{64}Ni(E_{c.m.} = 307.4 \text{ MeV})+^{238}U$ 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.

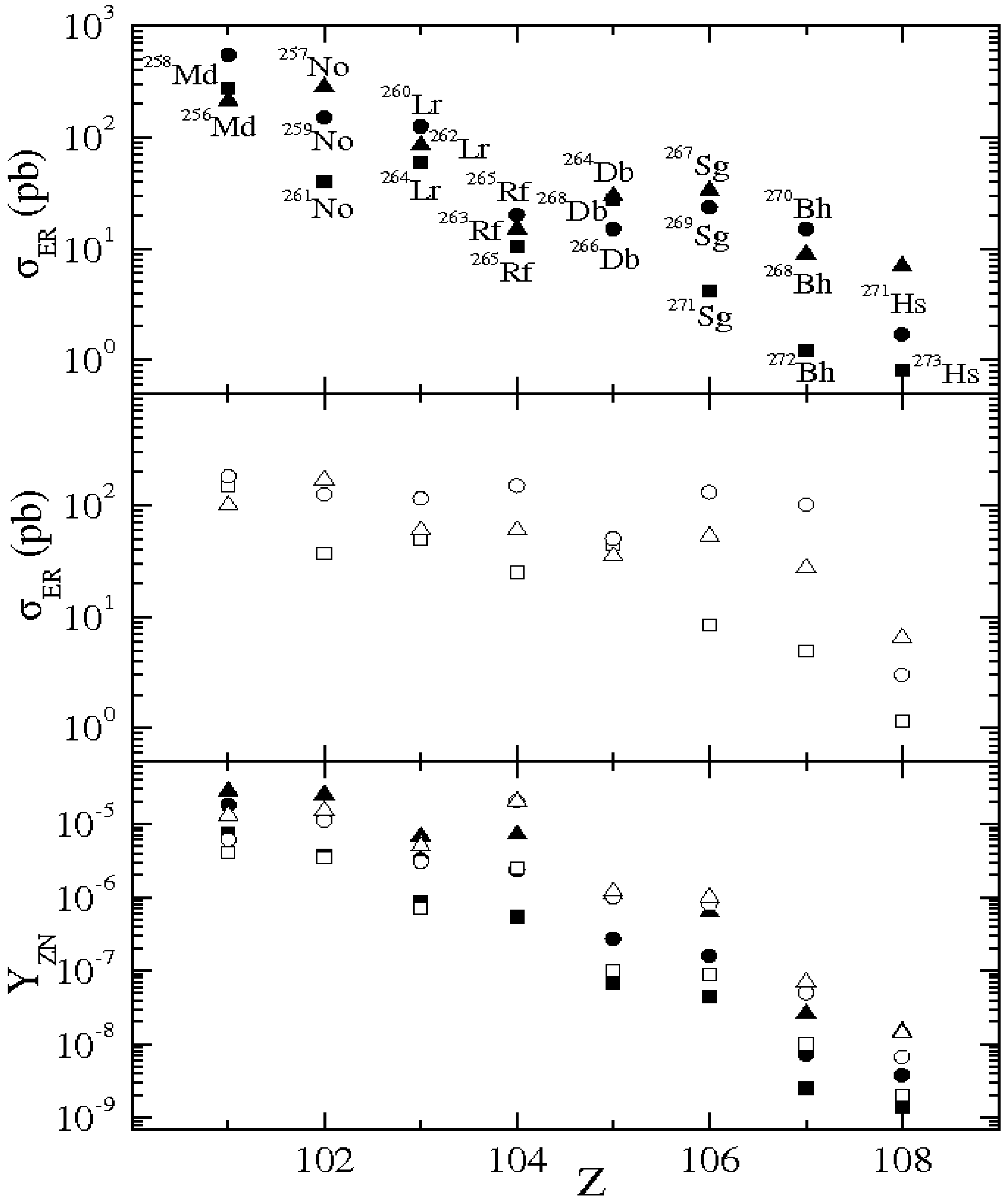
In the $^{48}Ca(E_{c.m.} = 274.6 \text{ MeV})+ ^{238}U$ reaction the experimental [S. Lunardi, *AIP Conference Proceedings* **1120**, p. 70.] and calculated ratios of secondary yields $Y(^{62}Fe)/Y(^{58}Cr)$ for the neutron-rich ^{62}Fe and ^{58}Cr isotopes are about 0.2 and 0.3, respectively.

$^{48}Ca+^{244}Cm$ ▲ E_{cm}=207 MeV

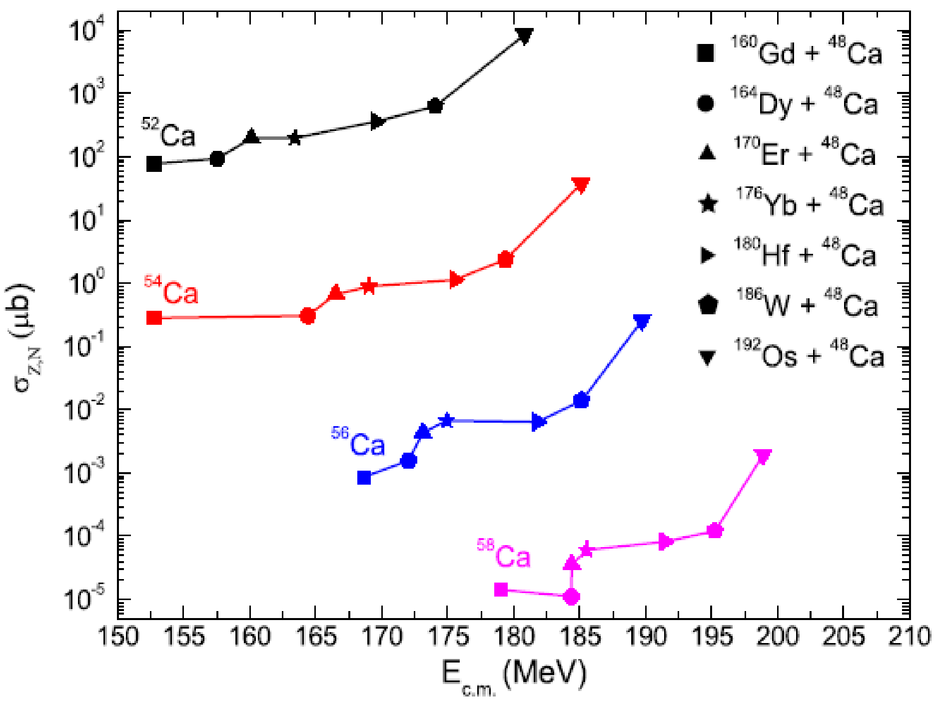
$^{48}Ca+^{246}Cm$ ● E_{cm}=205.5 MeV

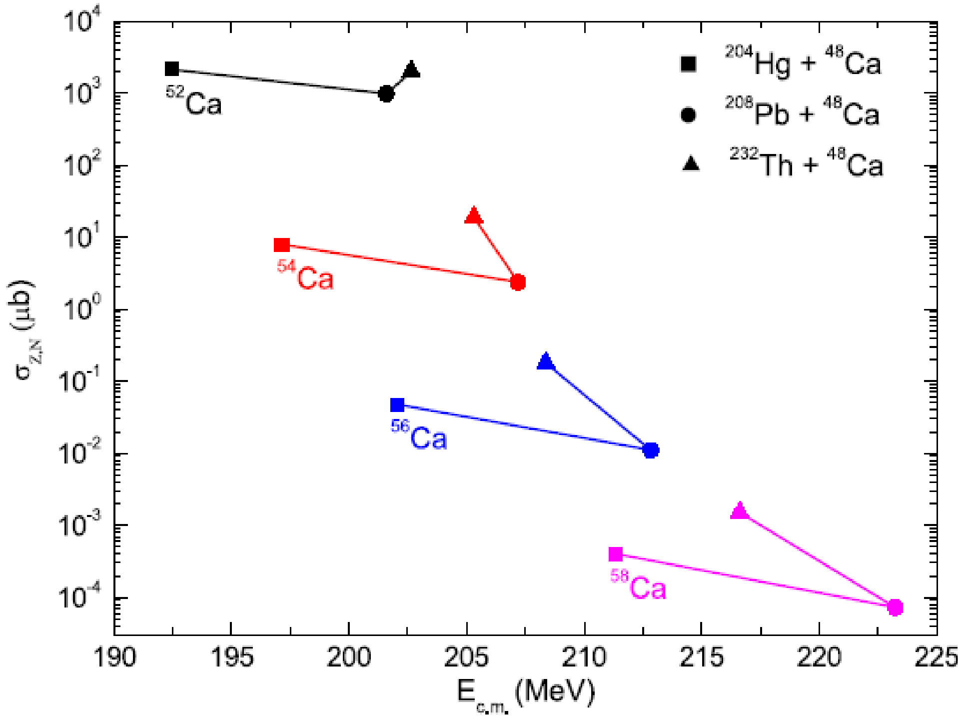
$^{48}Ca+^{248}Cm$ ■ E_{cm}=204 MeV

PRC **71** (2005) 034603

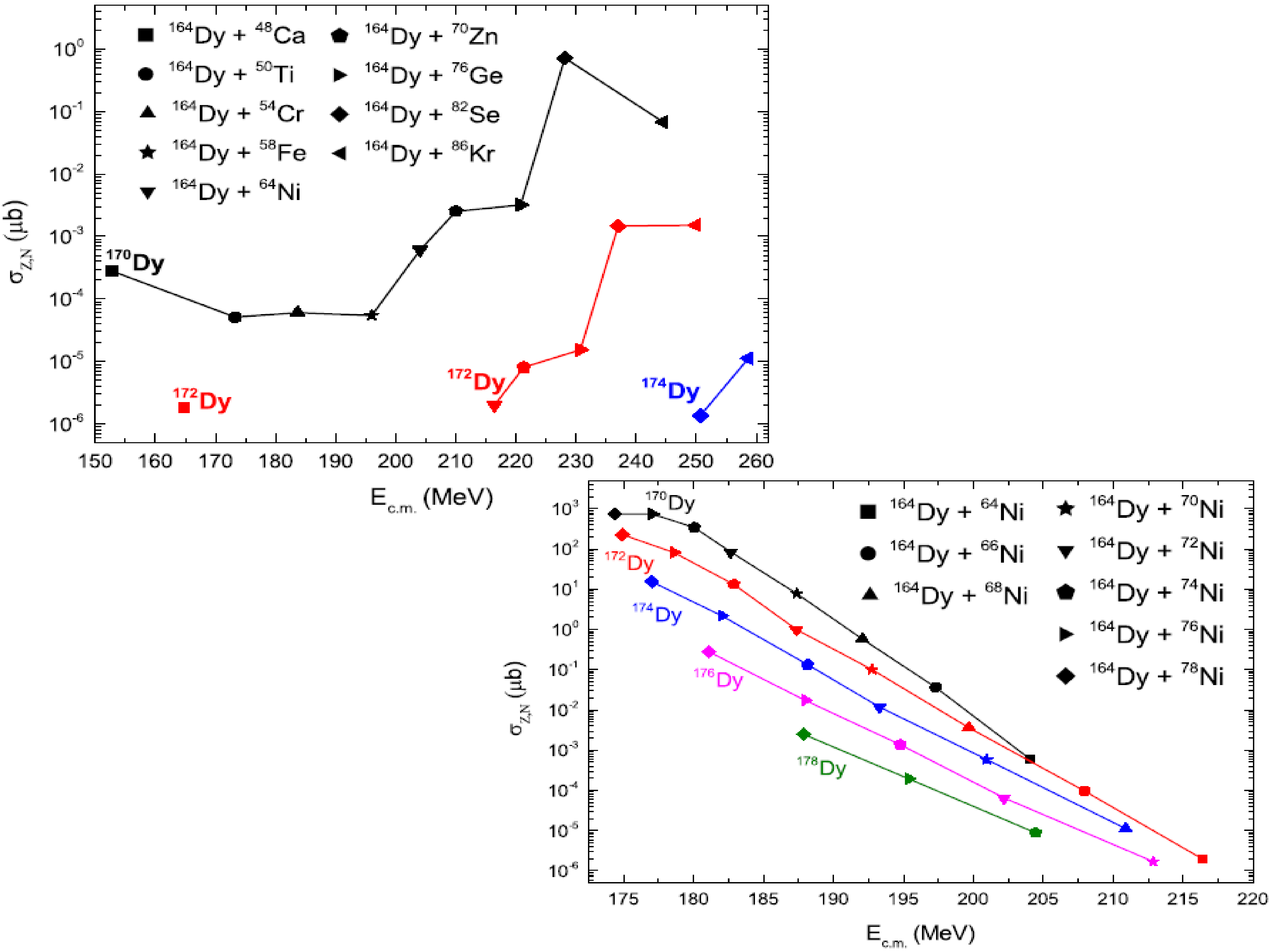


The possibilities for producing neutron-rich isotopes $^{52,54,56,58}Ca$ in the transfer reactions with rare-earth targets.

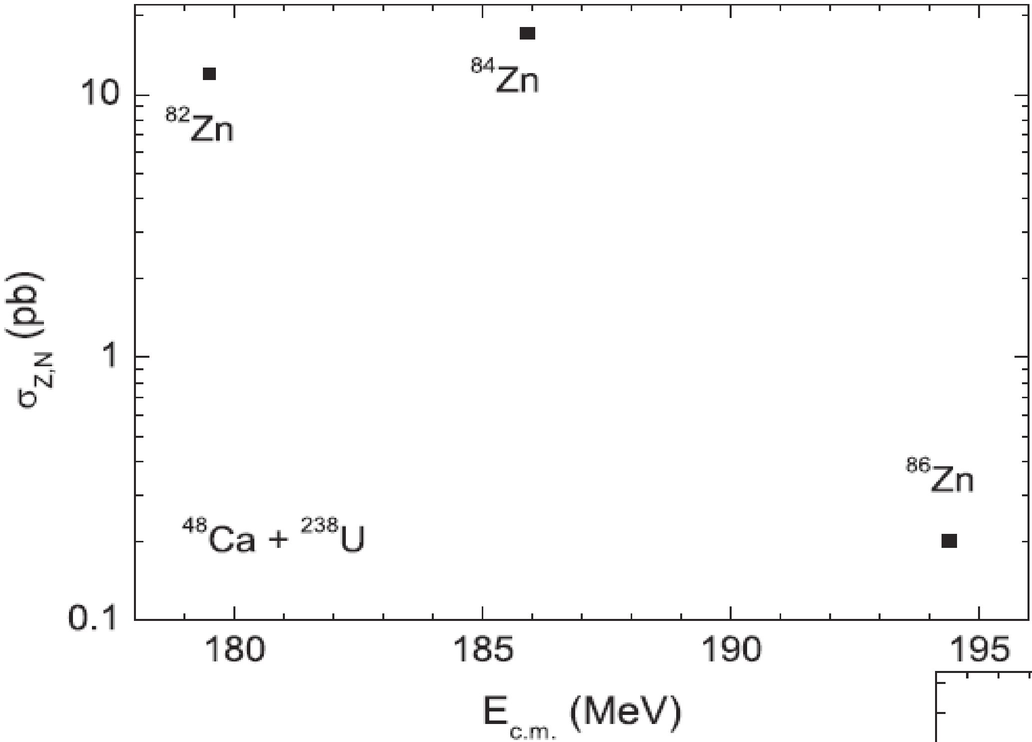




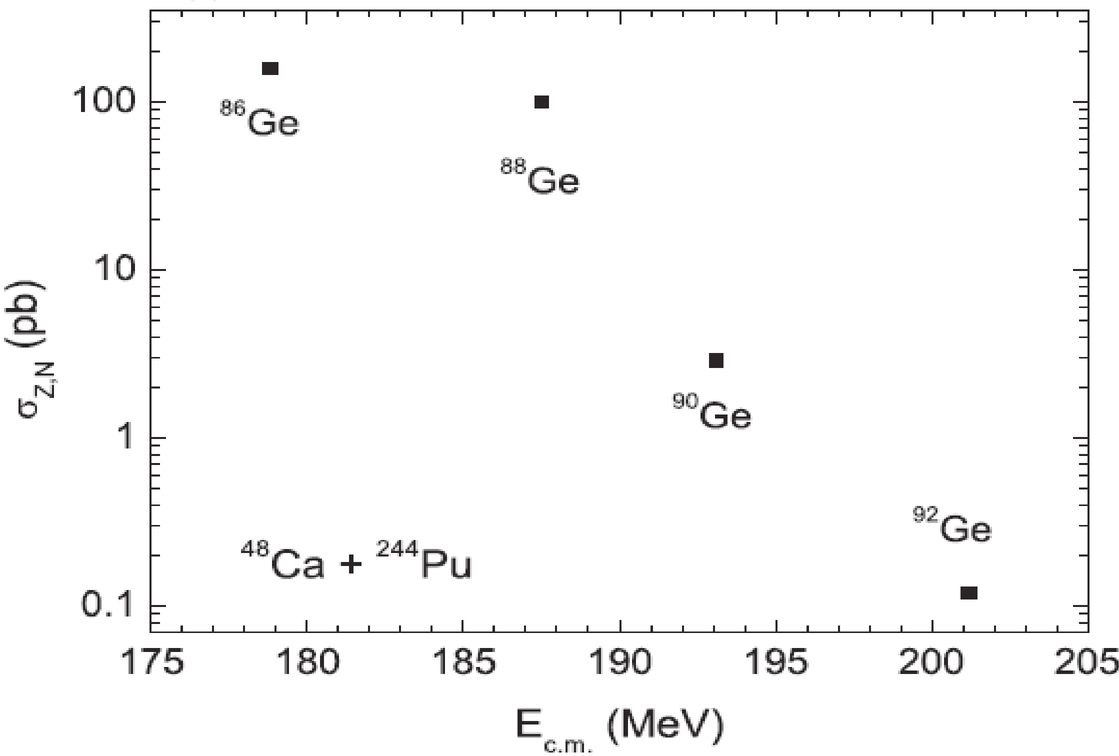
Phys. Rev. C **89** (2014) 034622
Phys. Rev. C **91** (2015) 054610



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)
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)
Ec.m. (MeV)



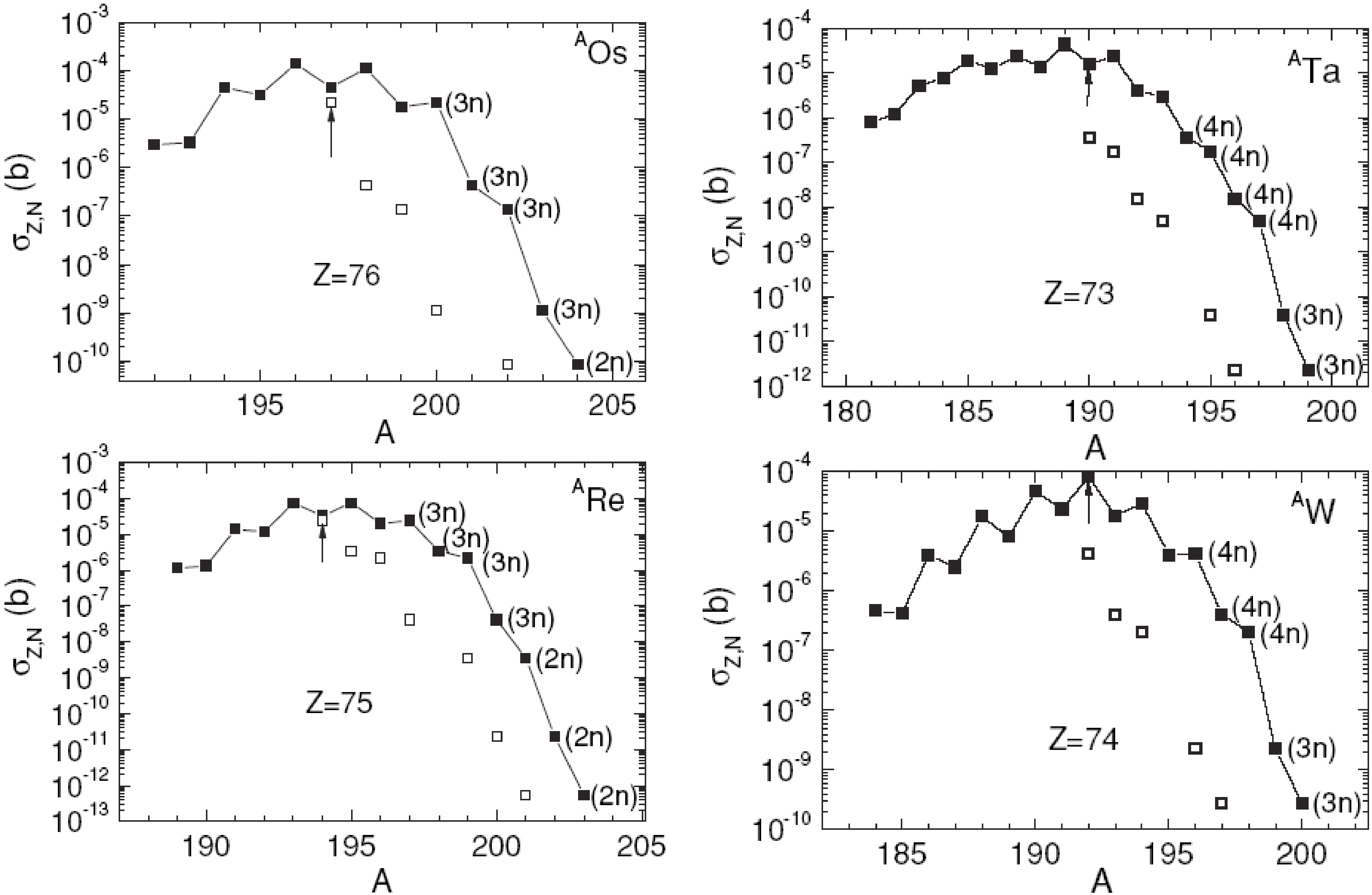
$E_{c.m.}$ provides the excitations of the isotopes equal to the corresponding threshold for the neutron emission.

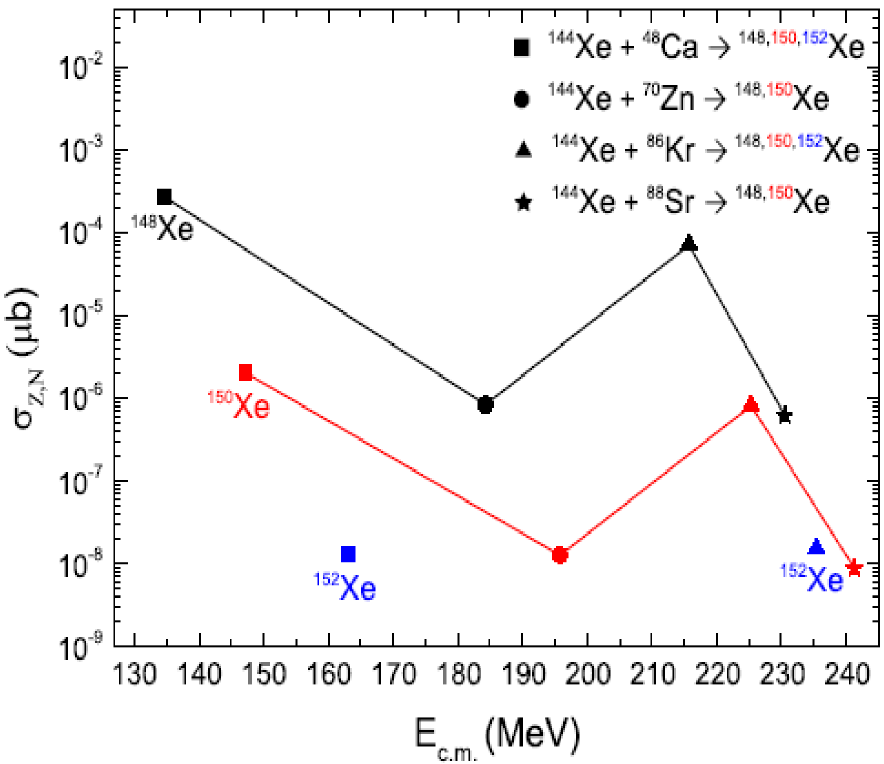


PRC **81**, 024604 (2010)

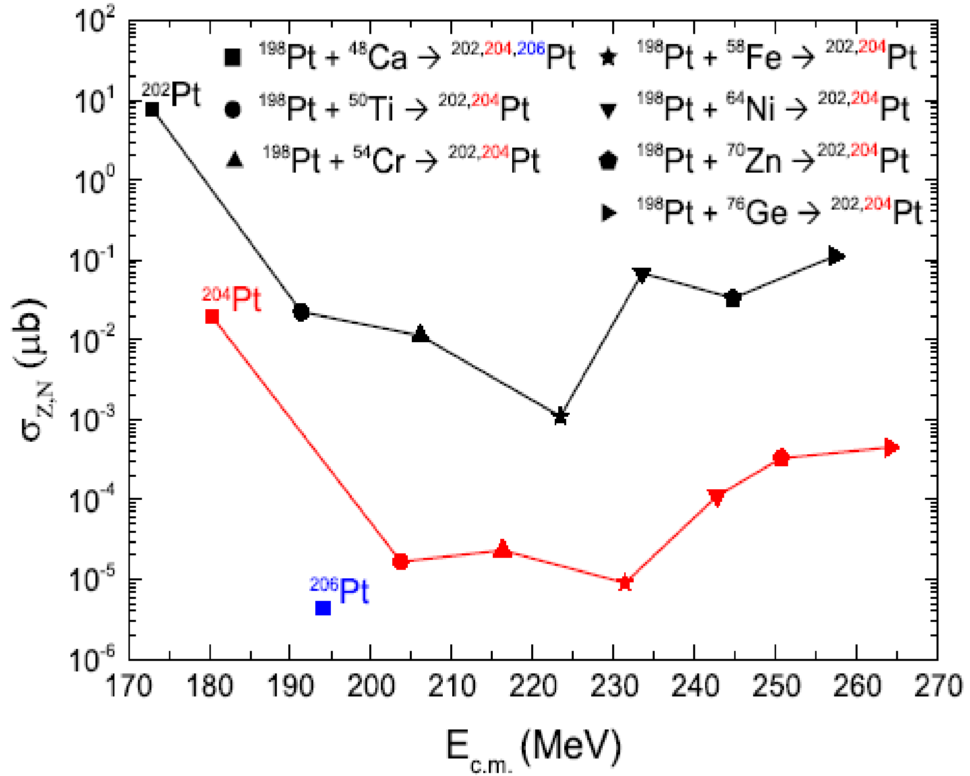
$^{48}Ca + ^{238}U$ at $E_{c.m.} = 189$ MeV

PRC **81**, 057602 (2010)



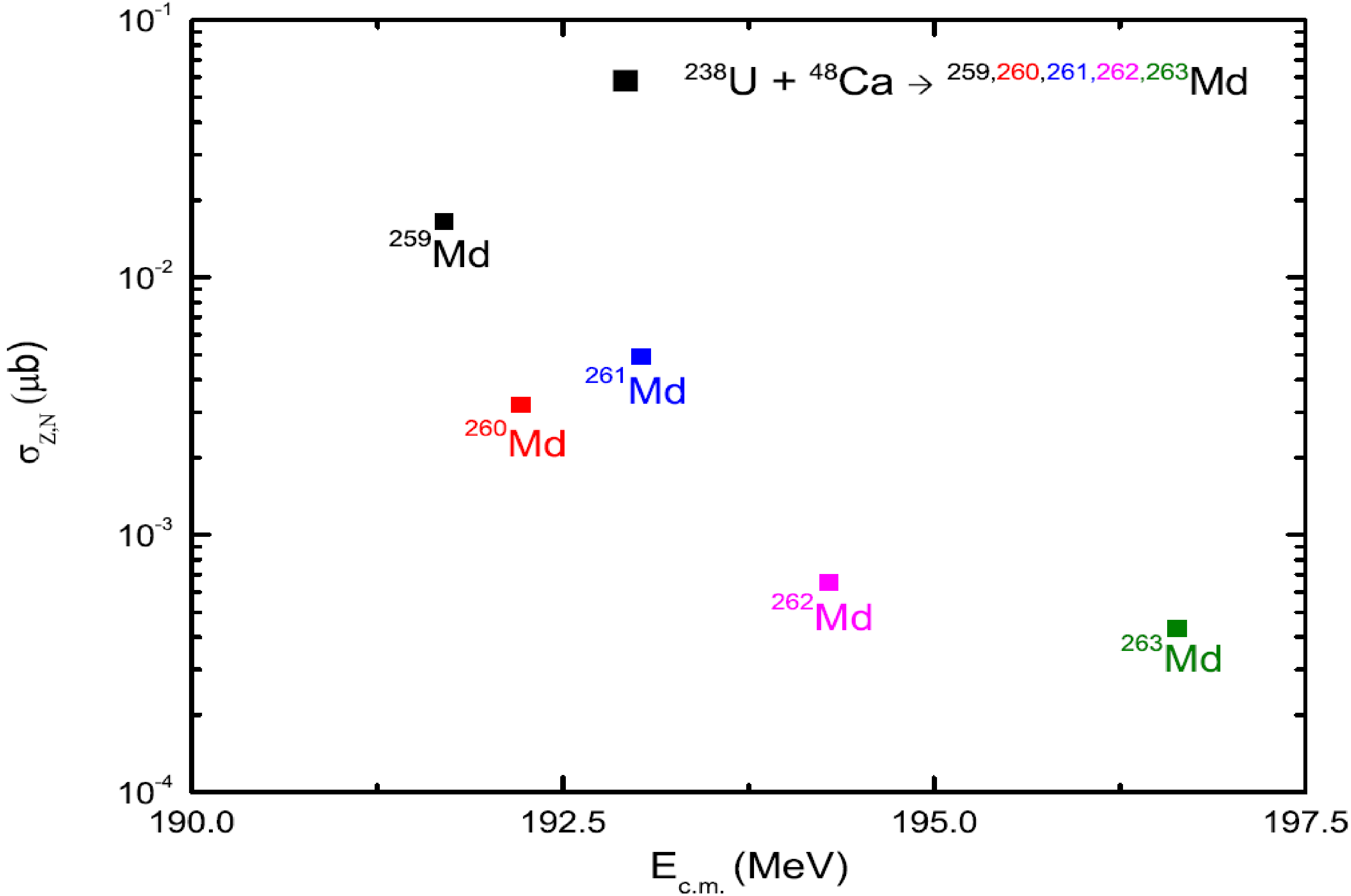


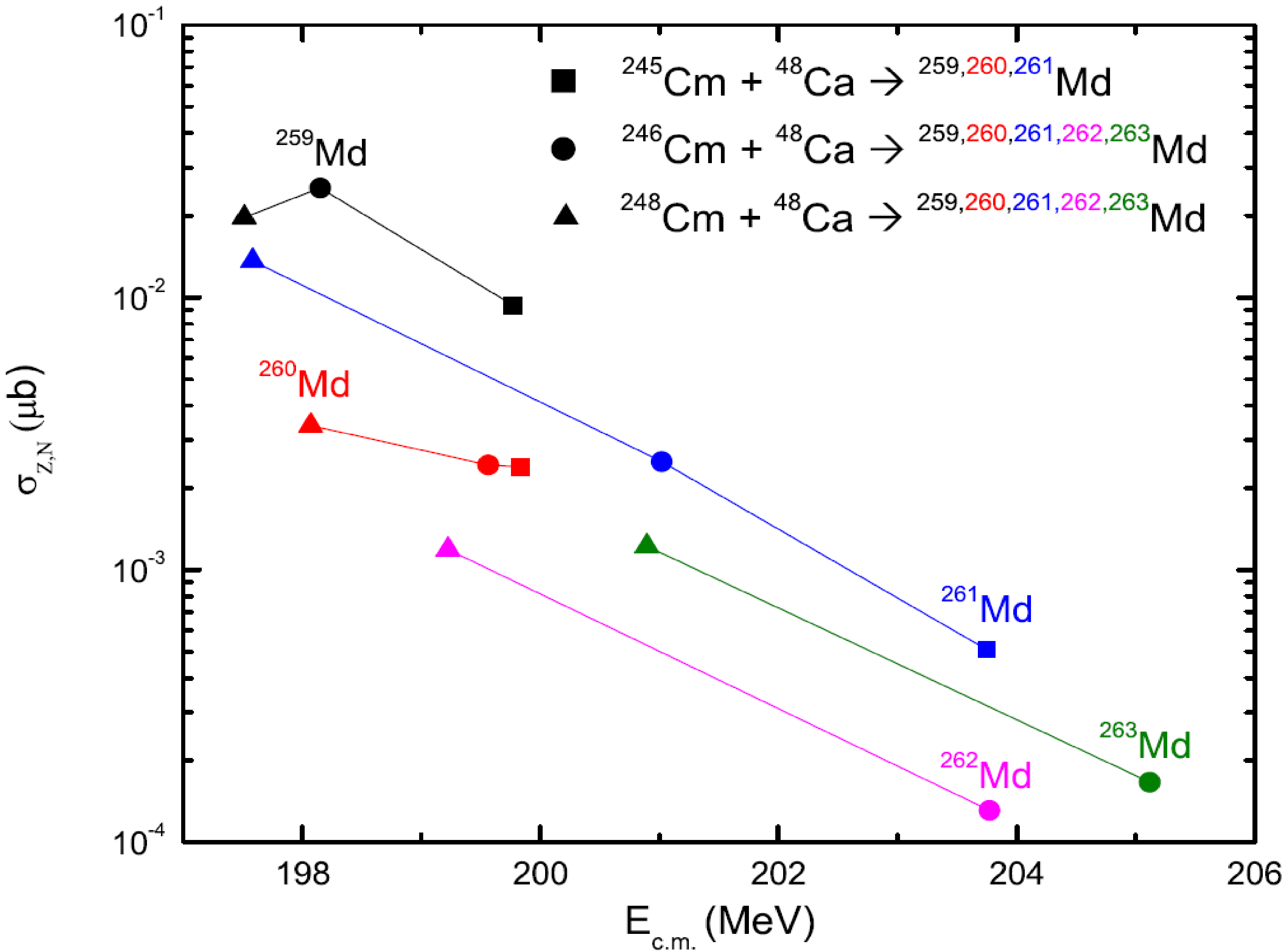
The predicted cross sections of the production of neutron-rich isotopes ^{148,150,152}Xe in the transfer reactions with the radioactive beam of ^{144}Xe. The cross sections correspond to the maxima of 0*n* evaporation channels.



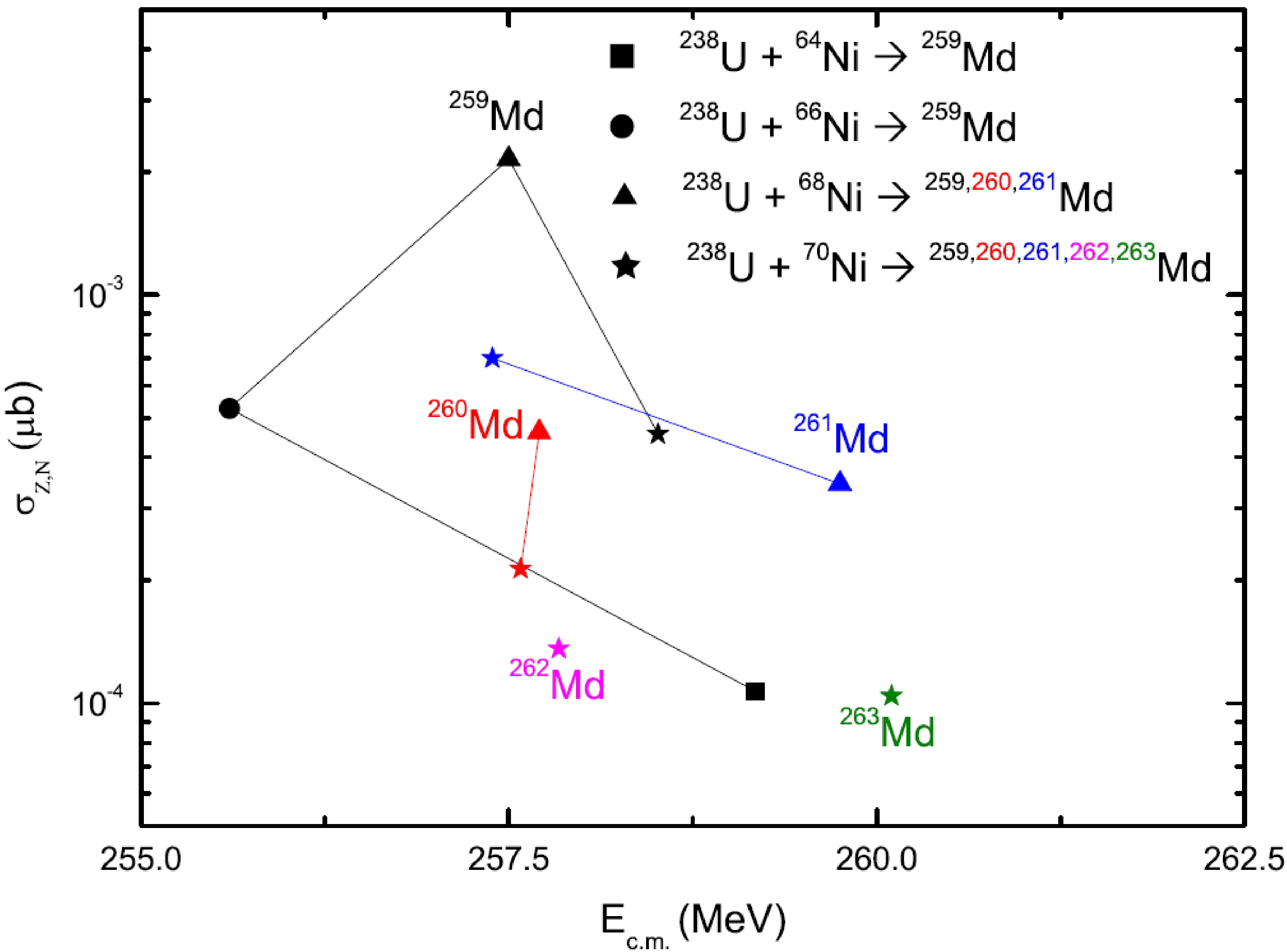
The expected maximal cross sections of the production of neutron-rich isotopes ^{202,204,206}Pt in the 0*n* evaporation channels of the listed transfer reactions.

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

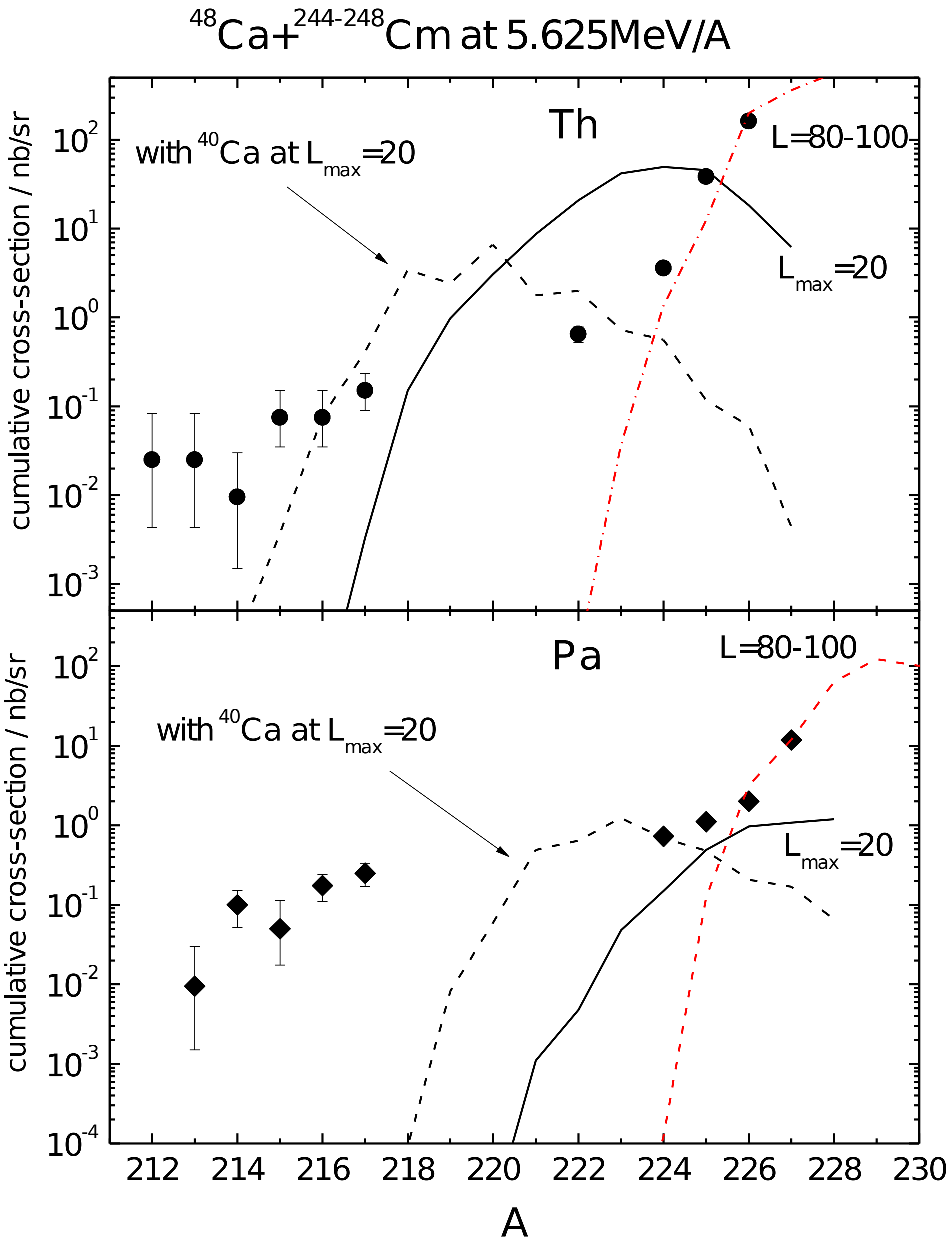




^{245}Cm + ^{48}Ca → ^{259,260,261}Md
^{246}Cm + ^{48}Ca → ^{259,260,261,262,263}Md
^{248}Cm + ^{48}Ca → ^{259,260,261,262,263}Md
^{259}Md
^{260}Md
^{261}Md
^{262}Md
^{263}Md
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\sigma_{Z,N}$ (μb)
198
200
202
204
206
$E_{c.m.}$ (MeV)



$^{238}U + ^{64}Ni \rightarrow ^{259}Md$
$^{238}U + ^{66}Ni \rightarrow ^{259}Md$
$^{238}U + ^{68}Ni \rightarrow ^{259,260,261}Md$
$^{238}U + ^{70}Ni \rightarrow ^{259,260,261,262,263}Md$
^{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)



Preliminary

exp. S.Heinz et al.

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.

Thank you.