Interesting fusion reactions in superheavy region

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What interesting experiments can still be done with ^{48}Ca beams and actinide targets?

1. Low energies, explore **1n** and **2n** evap. channels - **new isotopes of SHN**

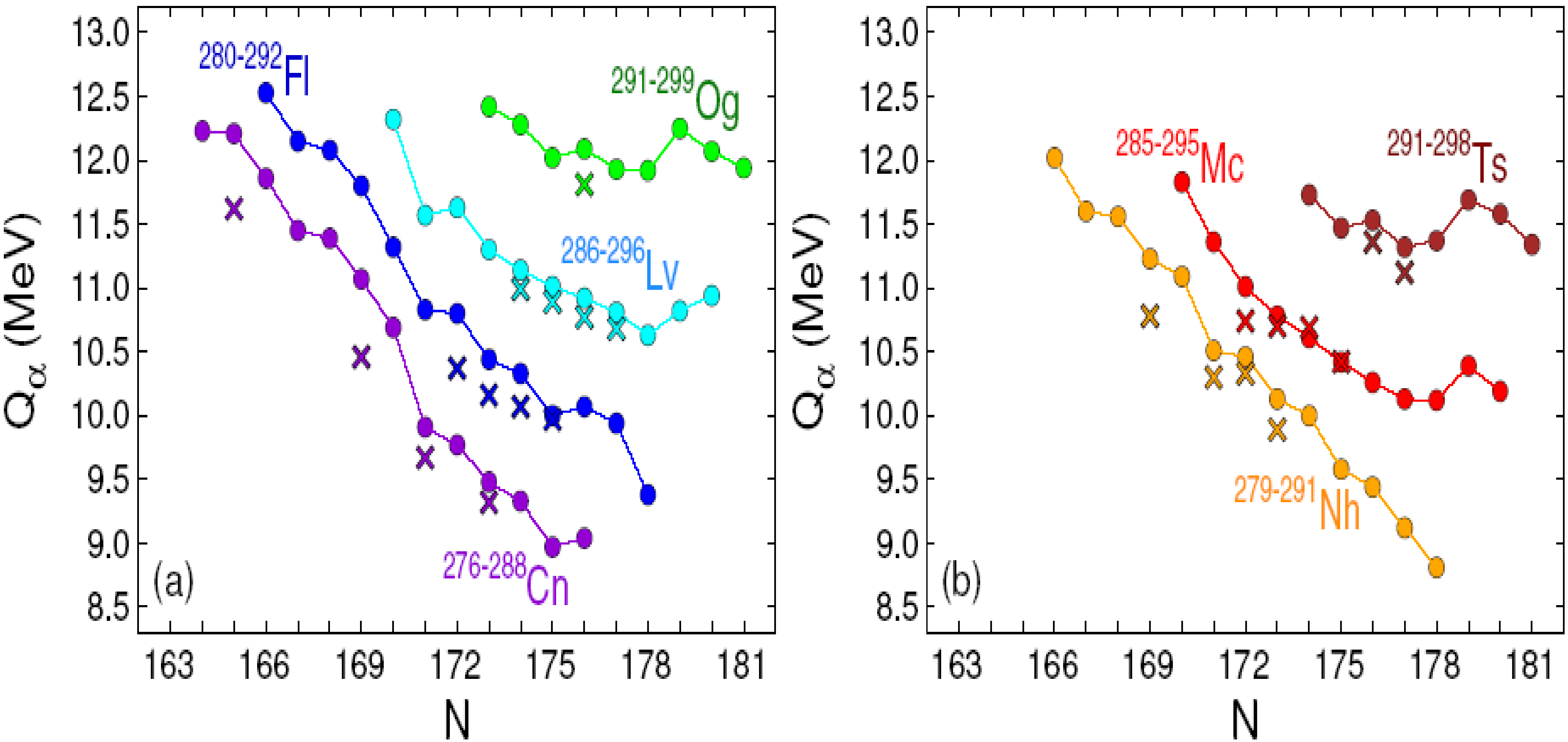
2. High energies, study **xn** evaporation channels with **x** > **4**

3. Production of new isotopes in the evaporation channels with the emission of a charged particle (alpha particle, proton) - **new isotopes of SHN**

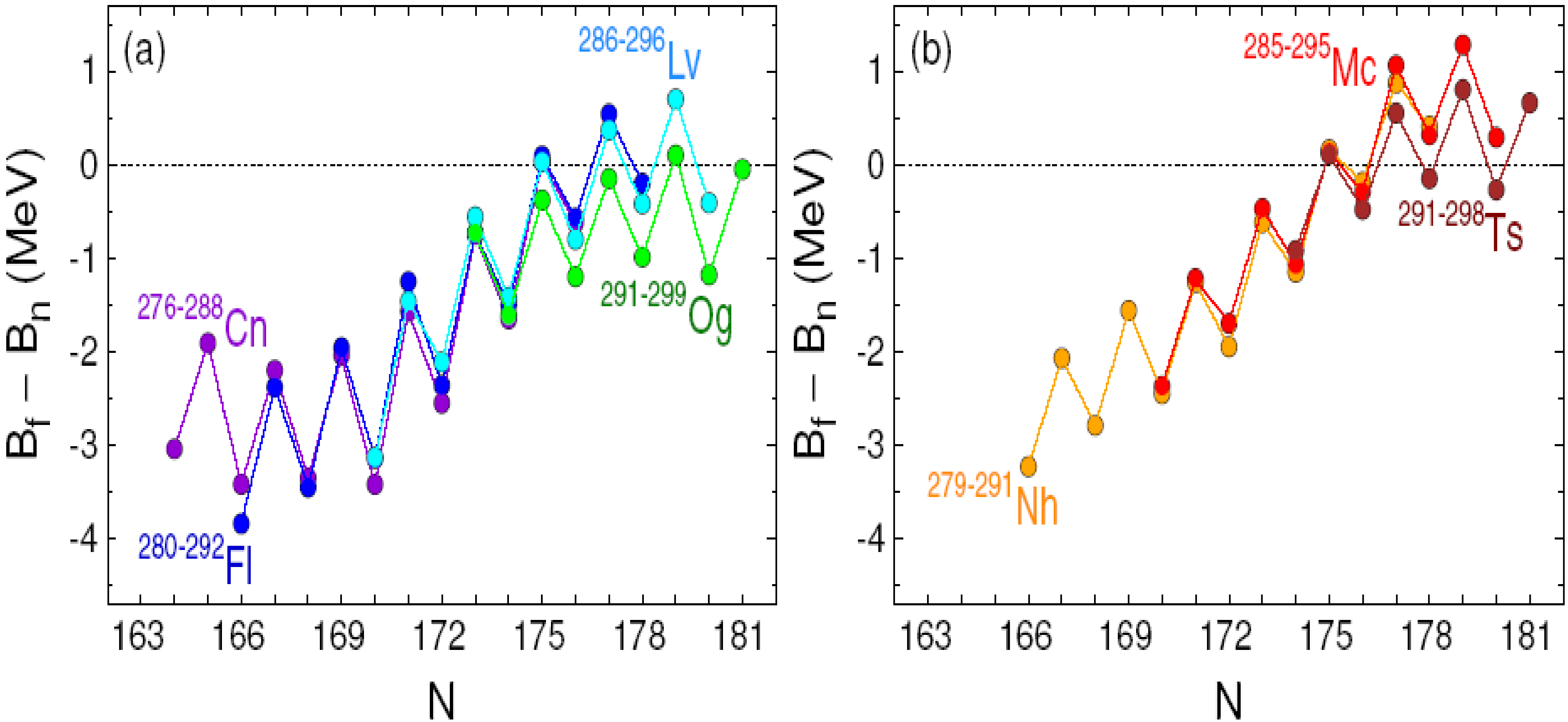
Within the dinuclear system model we analysed the production of SHN in various actinide-based complete fusion reactions with ^{48}Ca.

Predictions of the properties of heaviest nuclei are based on the Macro-Micro Model:

Mass Table by
P.Jachimowicz, M.Kowal, J.Skalski,
At. Data Nucl. Data Tables 138 (2021) 101393



280-292Fl
291-299Og
286-296Lv
276-288Cn
(a)
Qα (MeV)
N
285-295Mc
291-298Ts
279-291Nh
(b)
Qα (MeV)
N

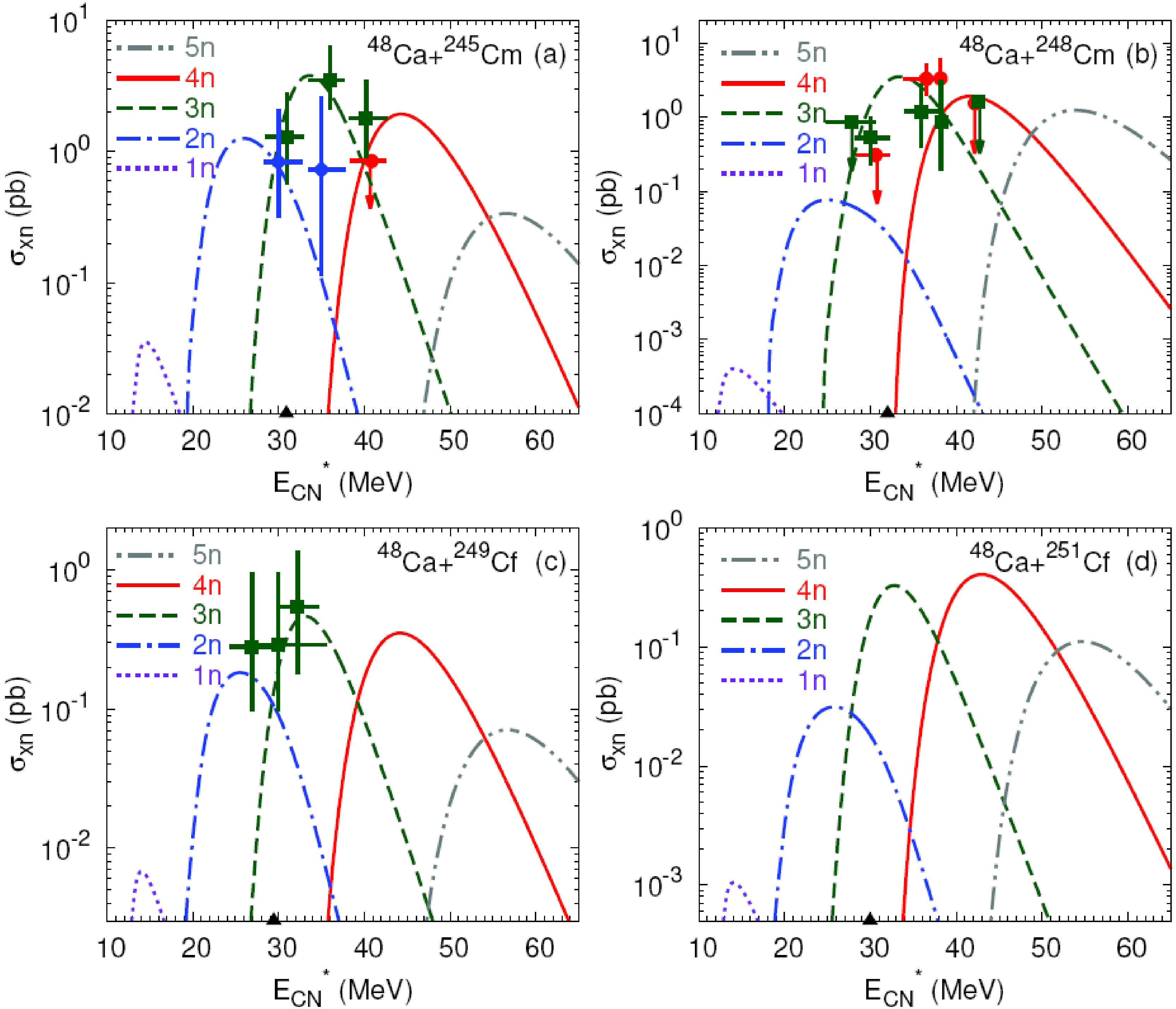


(a)
(b)
$B_f - B_n$ (MeV)
N
$^{276-288}$Cn
$^{280-292}$Fl
$^{286-296}$Lv
$^{291-299}$Og
$^{279-291}$Nh
$^{285-295}$Mc
$^{291-298}$Ts

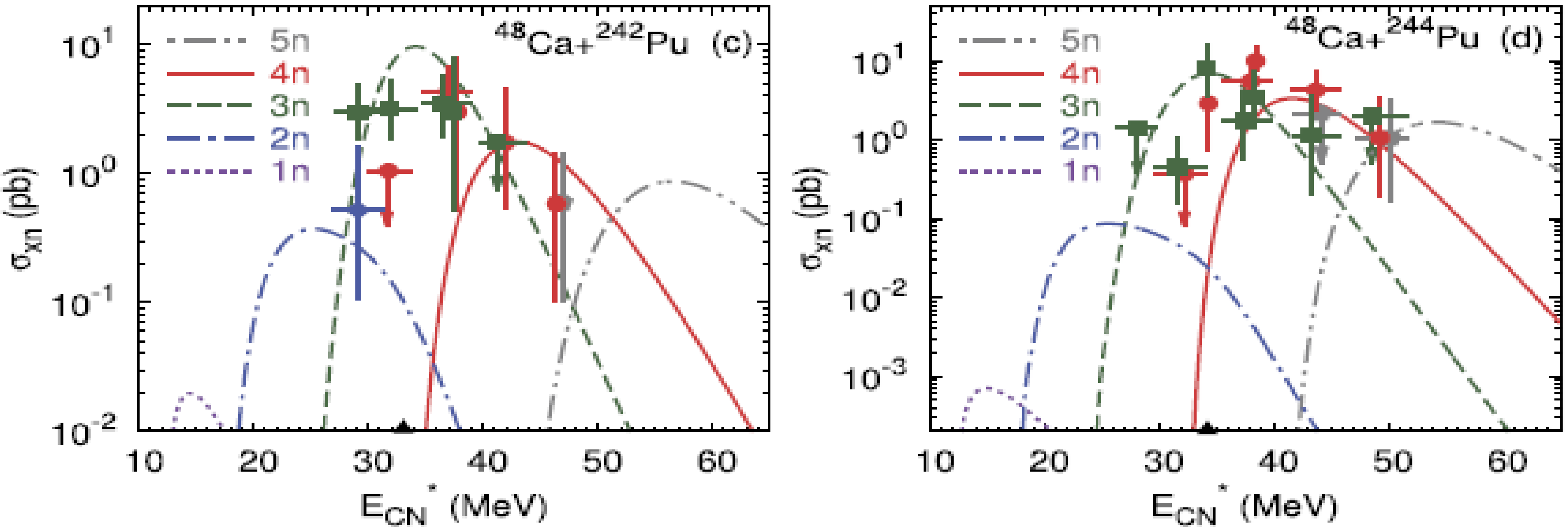
Dynamics of fusion in the dinuclear system model

Evaporation residue cross section for the production of superheavy nuclei:

$$\sigma^{s}_{ER}(E_{c.m.})=\sum_{J}\sigma_{c}(E_{c.m.},J)\,P_{CN}(E_{c.m.},J)\,W^{s}_{sur}(E_{c.m.},J)$$

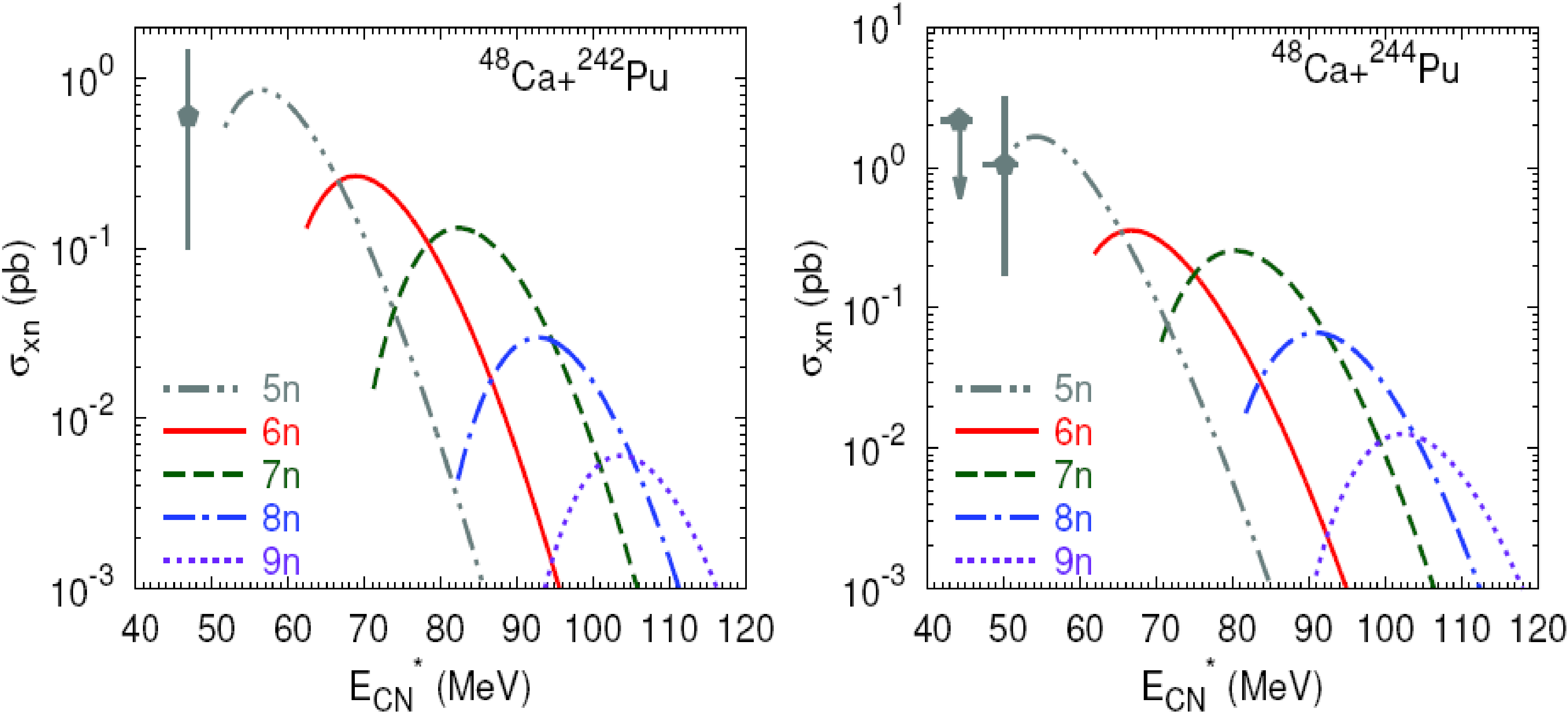


5n
4n
3n
2n
1n
^{48}Ca+^{245}Cm (a)
^{48}Ca+^{248}Cm (b)
^{48}Ca+^{249}Cf (c)
^{48}Ca+^{251}Cf (d)
σ_{xn} (pb)
E_{CN}^* (MeV)

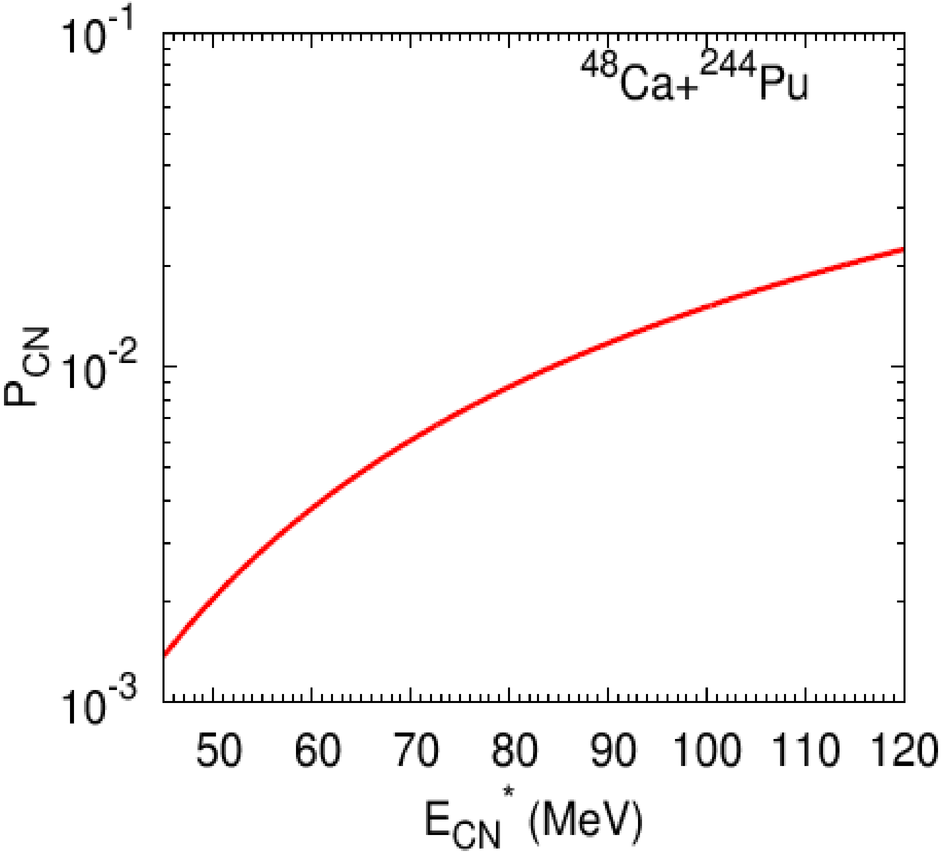


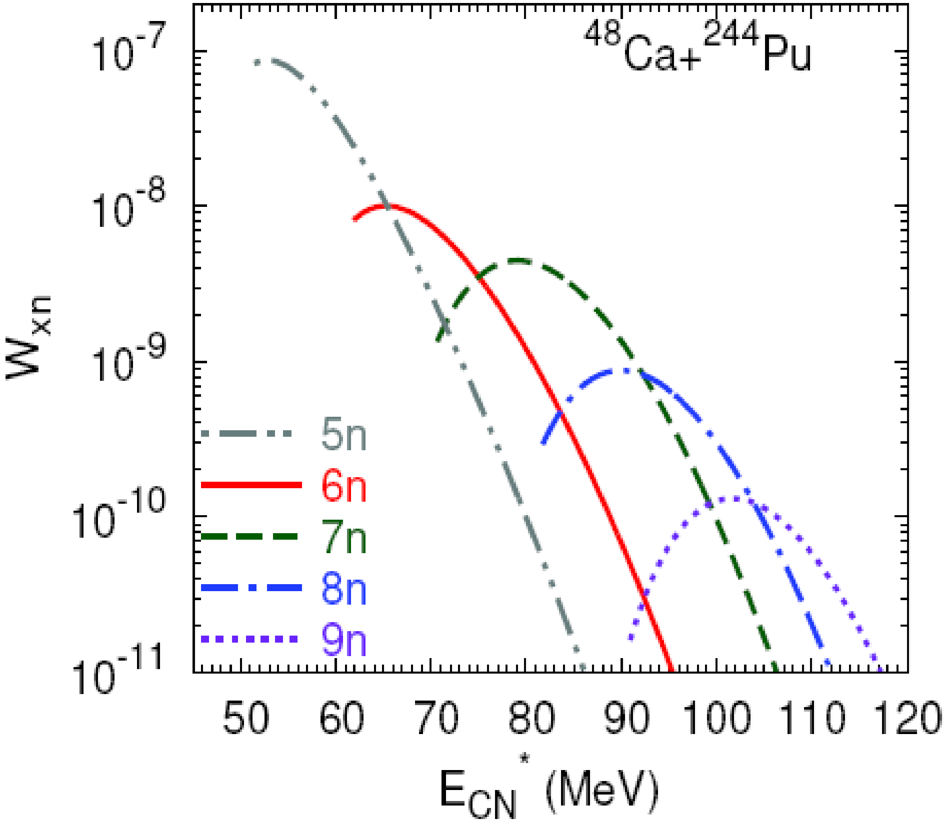
Energies of the maximum of cross section in 1n-,2n-channels are considerably smaller than the Coulomb barrier height for the sphere-side orientation plus Q-value: $V_b + Q$.

The larger the value of $V_b + Q$, the smaller the cross sections are for 1n-,2n-channels



^{48}Ca+^{242}Pu
10^{0}
10^{-1}
10^{-2}
10^{-3}
σ_{xn} (pb)
5n
6n
7n
8n
9n
40 50 60 70 80 90 100 110 120
E_{CN}^* (MeV)
^{48}Ca+^{244}Pu
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
σ_{xn} (pb)
5n
6n
7n
8n
9n
40 50 60 70 80 90 100 110 120
E_{CN}^* (MeV)



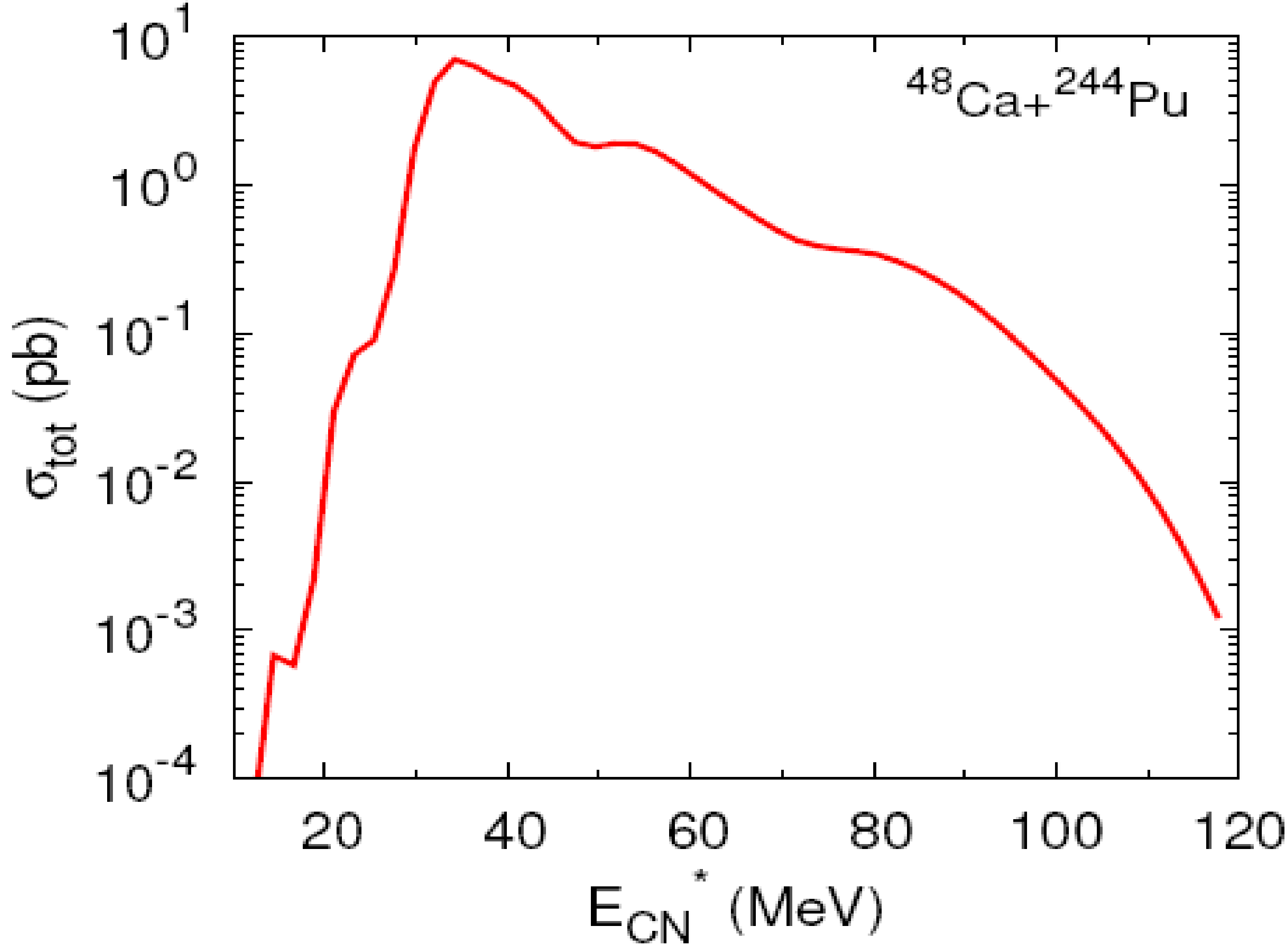


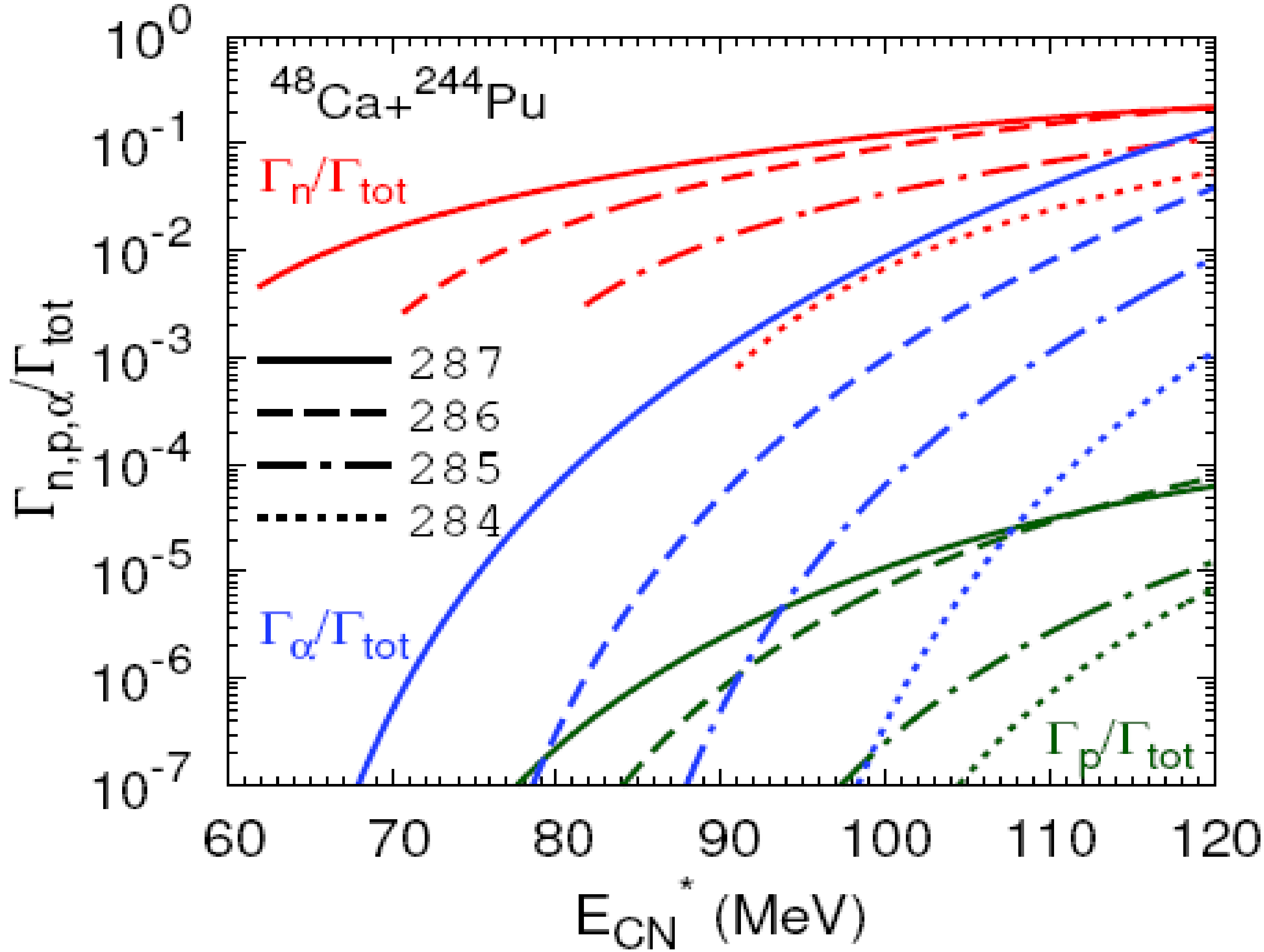
A weak drop of the cross section is due to

1. the interplay of fusion and survival probabilities

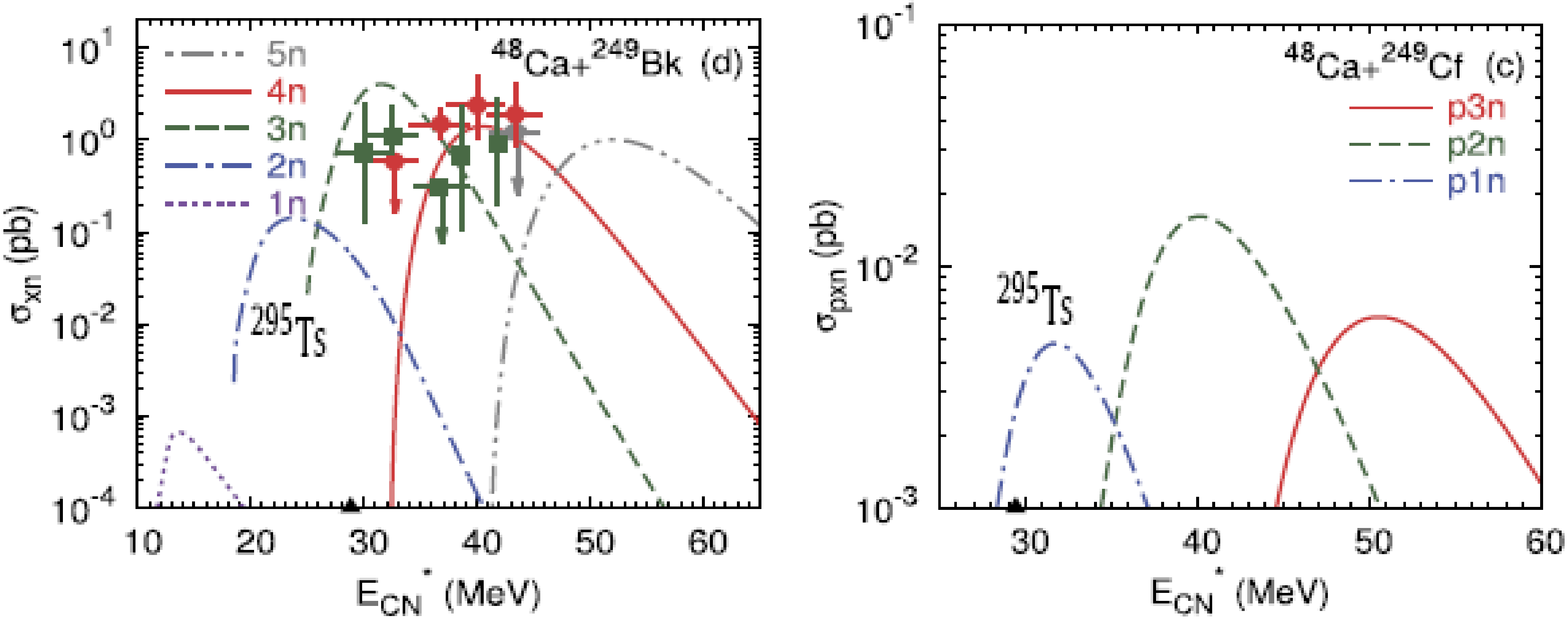
2. a weak change of the difference between the fission barrier height and neutron binding energy at 5-9 steps of n-evaporation

$$\sigma_{tot}(E_{\mathrm{c.m.}}) = \sum_x \sigma_{xn}(E_{\mathrm{c.m.}})$$





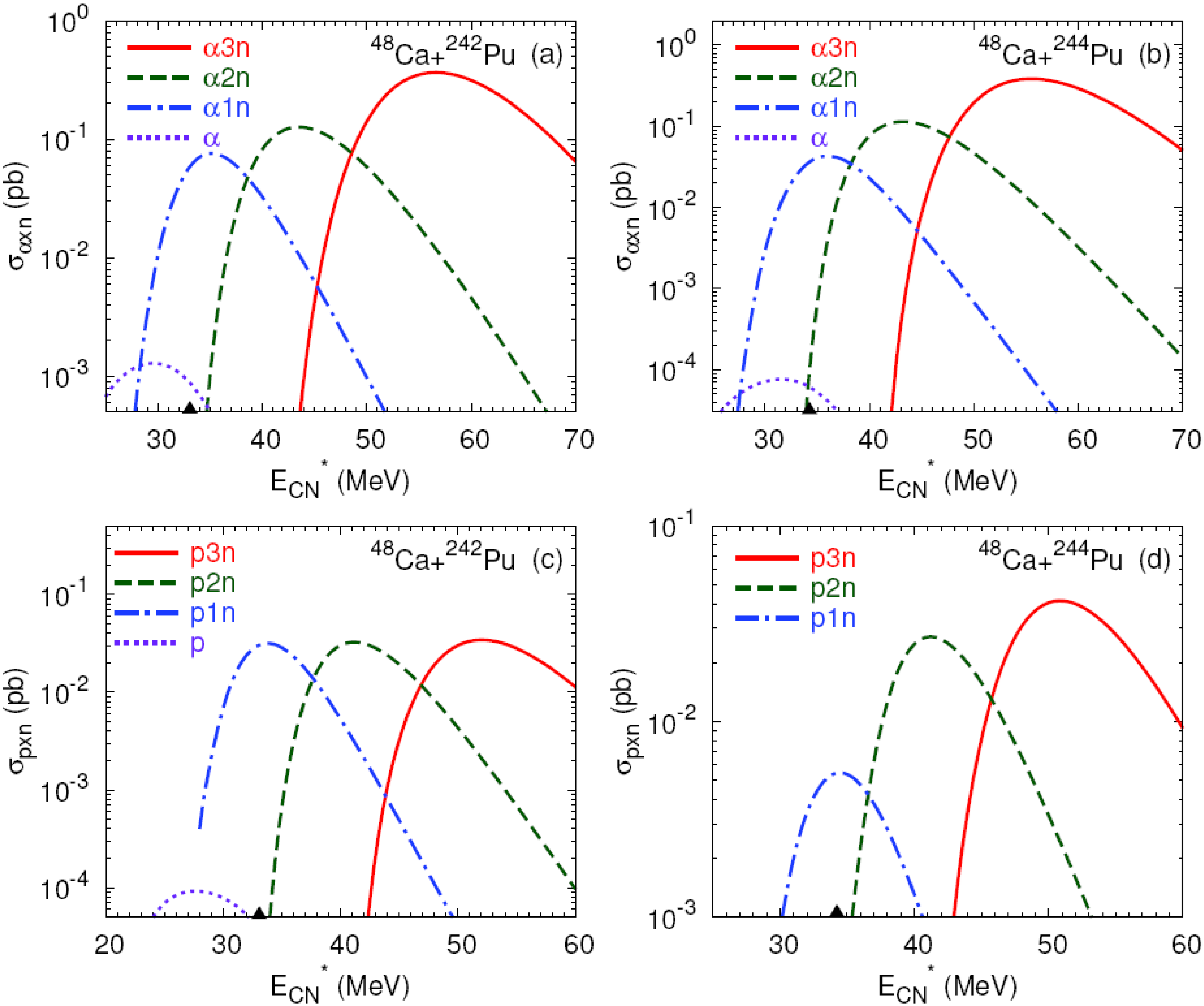
$^{48}Ca+^{244}Pu$
Γ_n/Γ_{tot}
$\Gamma_\alpha/\Gamma_{tot}$
Γ_p/Γ_{tot}
287
286
285
284
$\Gamma_{n,p,\alpha}/\Gamma_{tot}$
E_{CN}^* (MeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
60
70
80
90
100
110
120



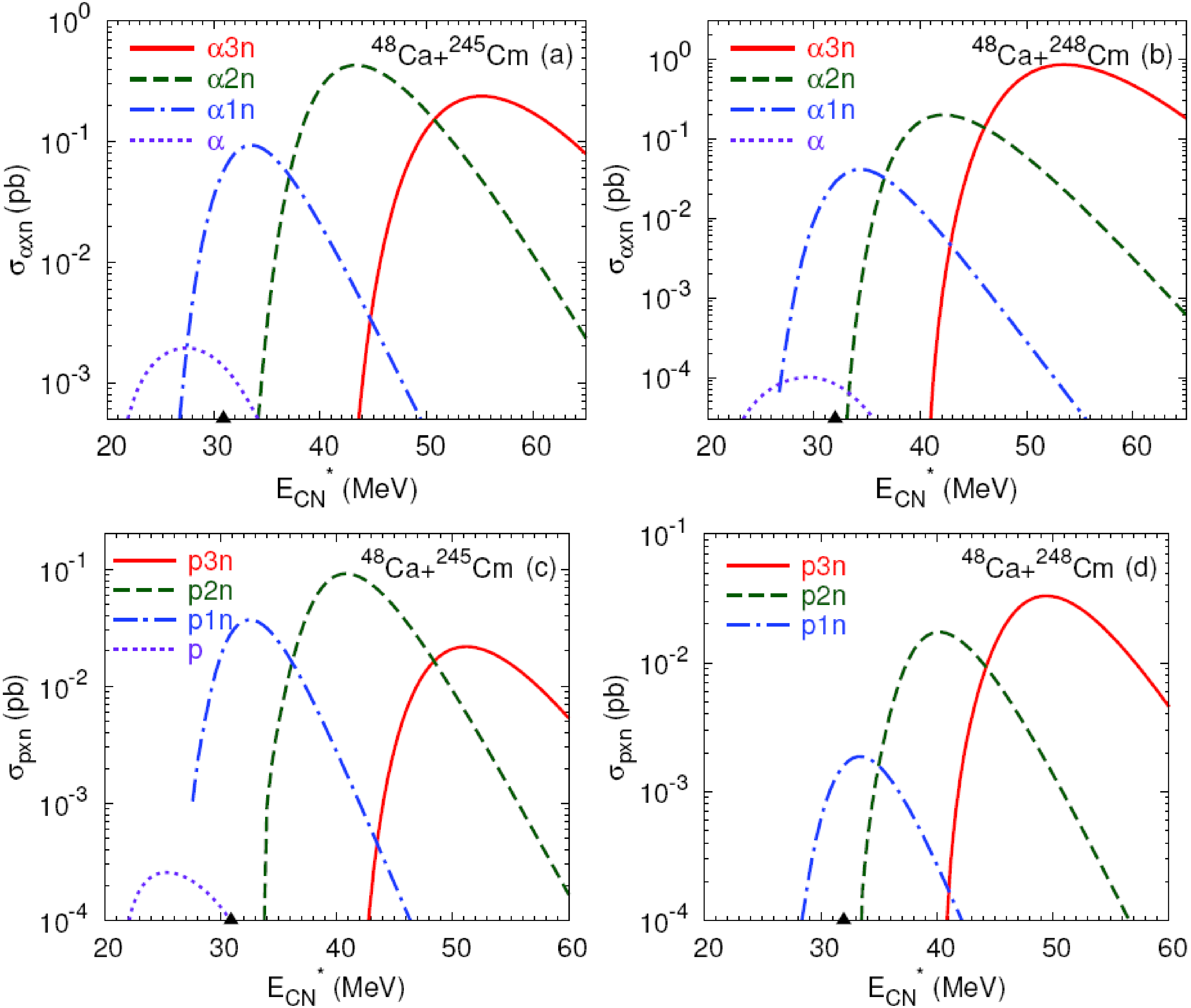
5n
4n
3n
2n
1n
48Ca+249Bk (d)
295Ts
σxn (pb)
ECN* (MeV)
48Ca+249Cf (c)
p3n
p2n
p1n
295Ts
σpxn (pb)
ECN* (MeV)

-- Imploying the reactions in 1n-,2n-channels, one can directly produce heaviest isotopes closer to the center of "island of stability" : $^{284,285}Cn$, $^{283,284}Nh$, ^{294}Lv, ^{295}Ts, $^{295-297}Og$

-- Cross sections of almost all of SHN in xn-channels are comparable or even larger than those in the charged particle evap.-n channels, 1n: 0.5fb-0.1pb ; 2n: 30fb-1pb



α3n
α2n
α1n
α
^{48}Ca+^{242}Pu (a)
^{48}Ca+^{244}Pu (b)
σ$_{αxn}$ (pb)
E$_{CN}$* (MeV)
p3n
p2n
p1n
p
^{48}Ca+^{242}Pu (c)
^{48}Ca+^{244}Pu (d)
σ$_{pxn}$ (pb)

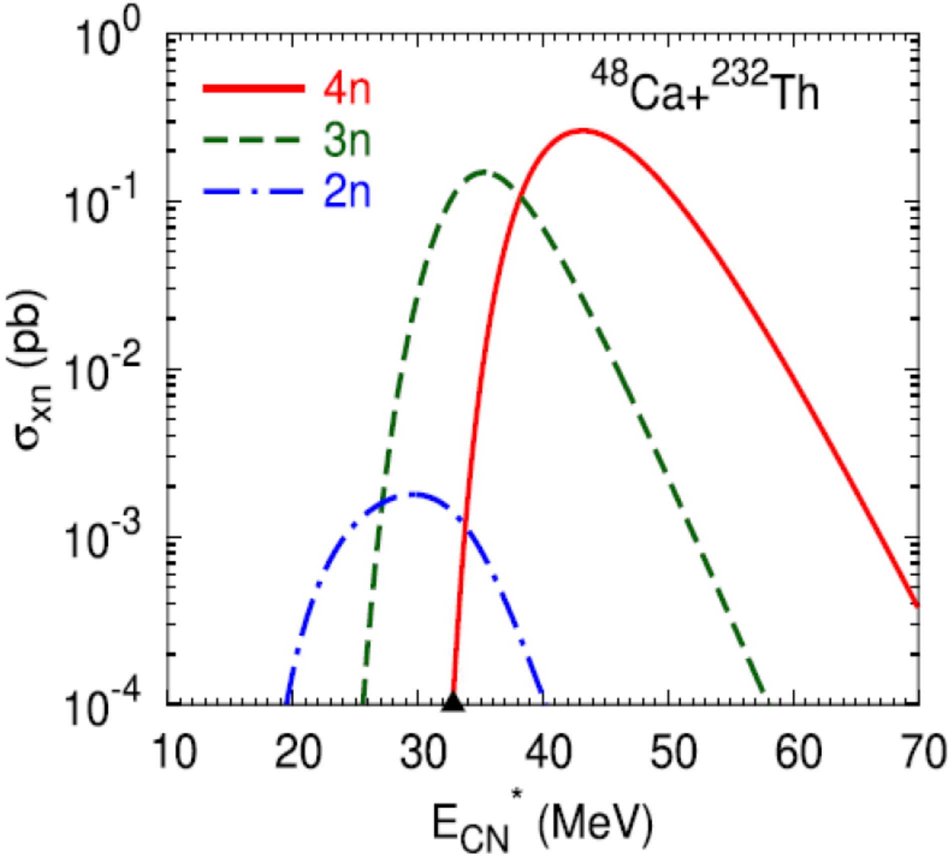


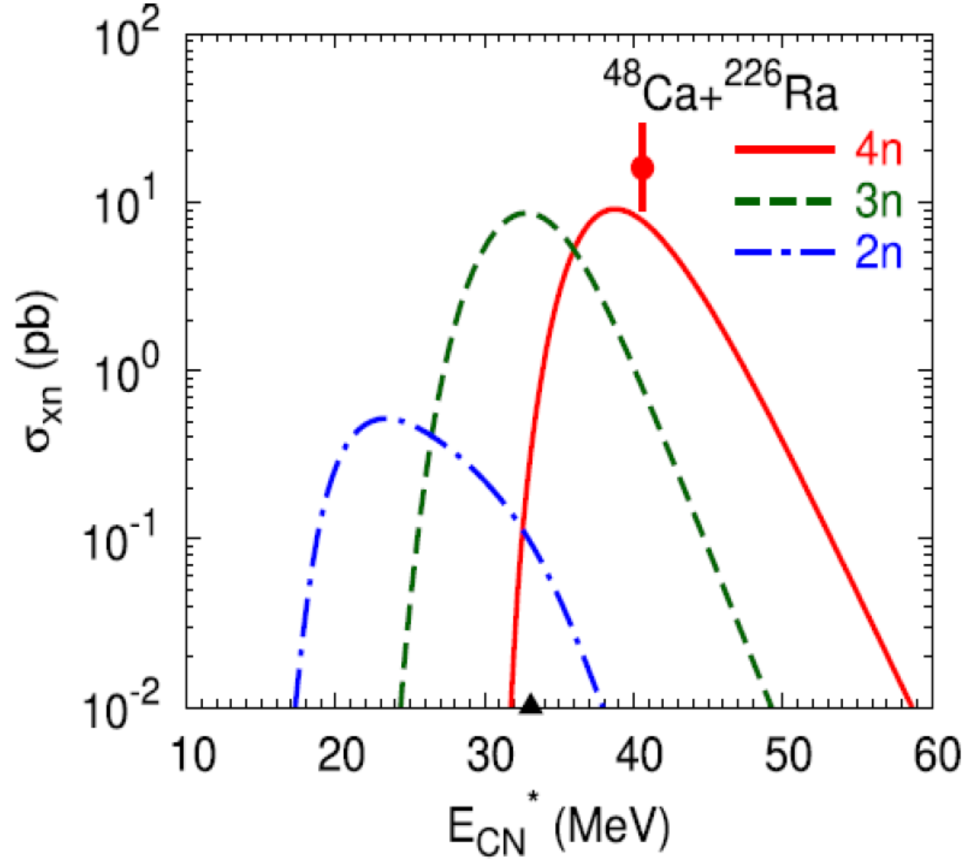
α3n
α2n
α1n
α
48Ca+245Cm (a)
σαxn (pb)
ECN* (MeV)
48Ca+248Cm (b)
p3n
p2n
p1n
p
48Ca+245Cm (c)
σpxn (pb)
48Ca+248Cm (d)

The charged evap. channels allow us to obtain an access to the isotopes which are unreachable in xn-channels due to the lack of proper projectile-target combinations

The charged evap. channels allow us to increase the mass of nuclei with Z=114,115,117 by 1 unit with respect to xn-channels.

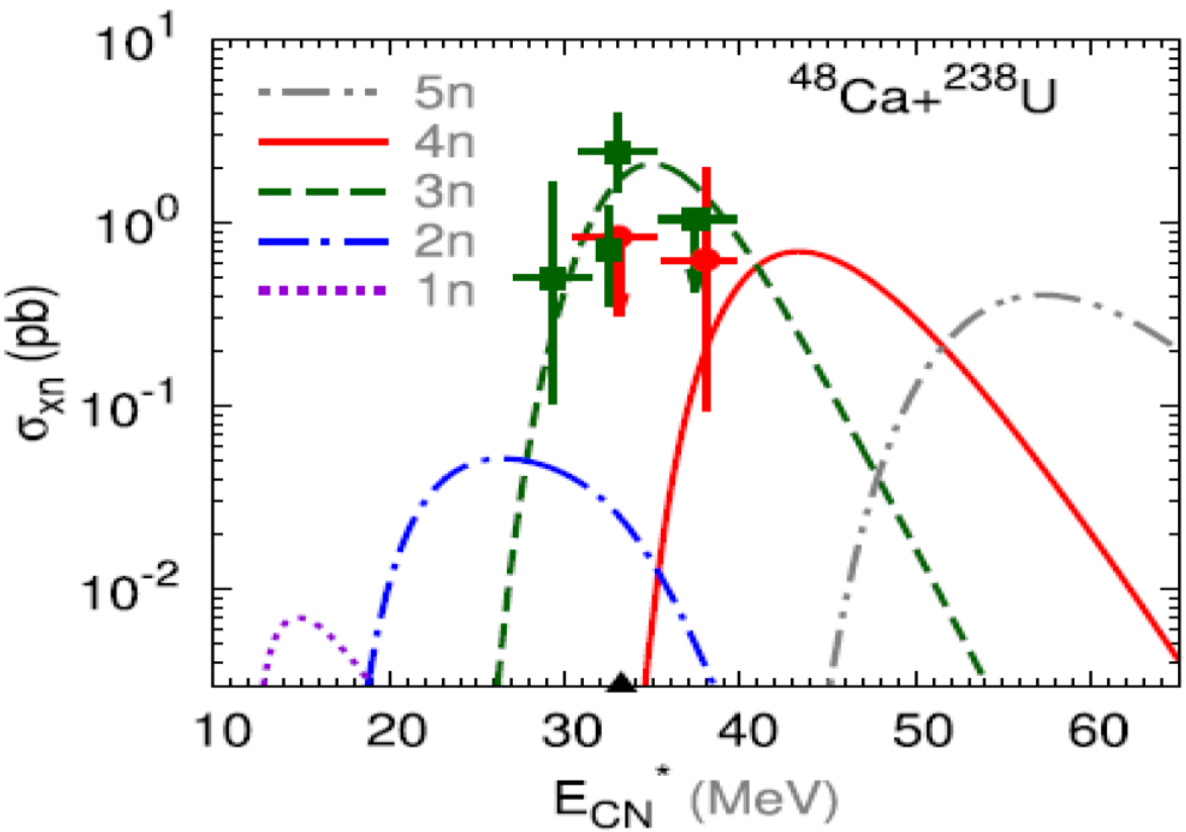
4. Isthmus connecting mainland and island of stability of SHN

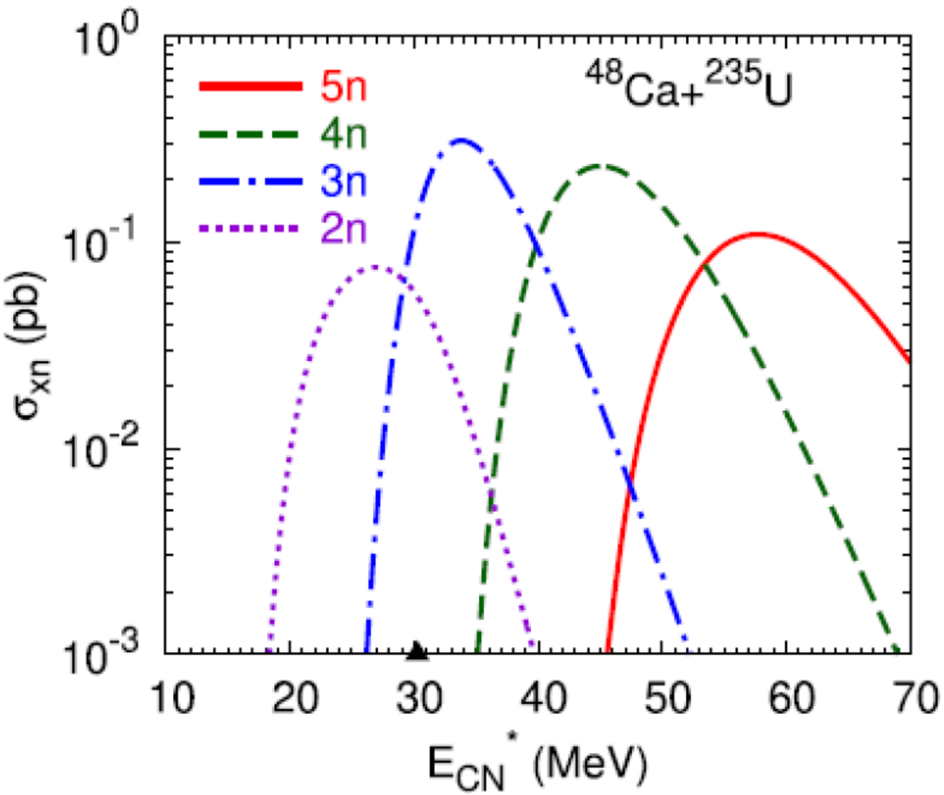


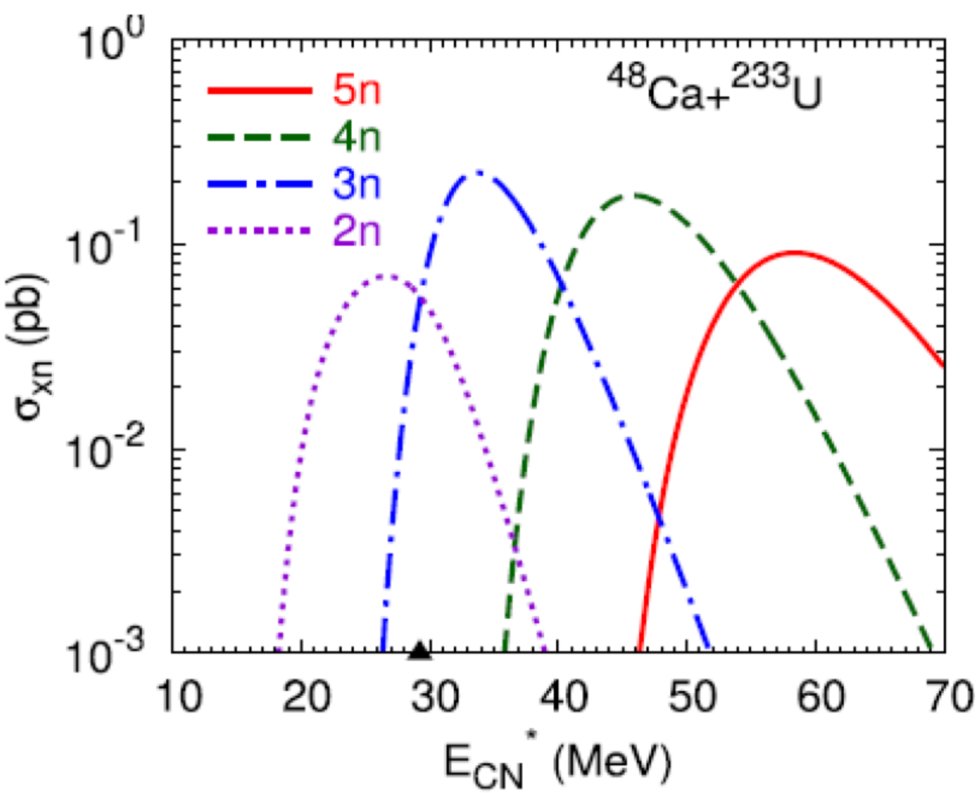


The dependence of cross section on Z from Hs to Lv has a minimum in the Ds nucleus

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





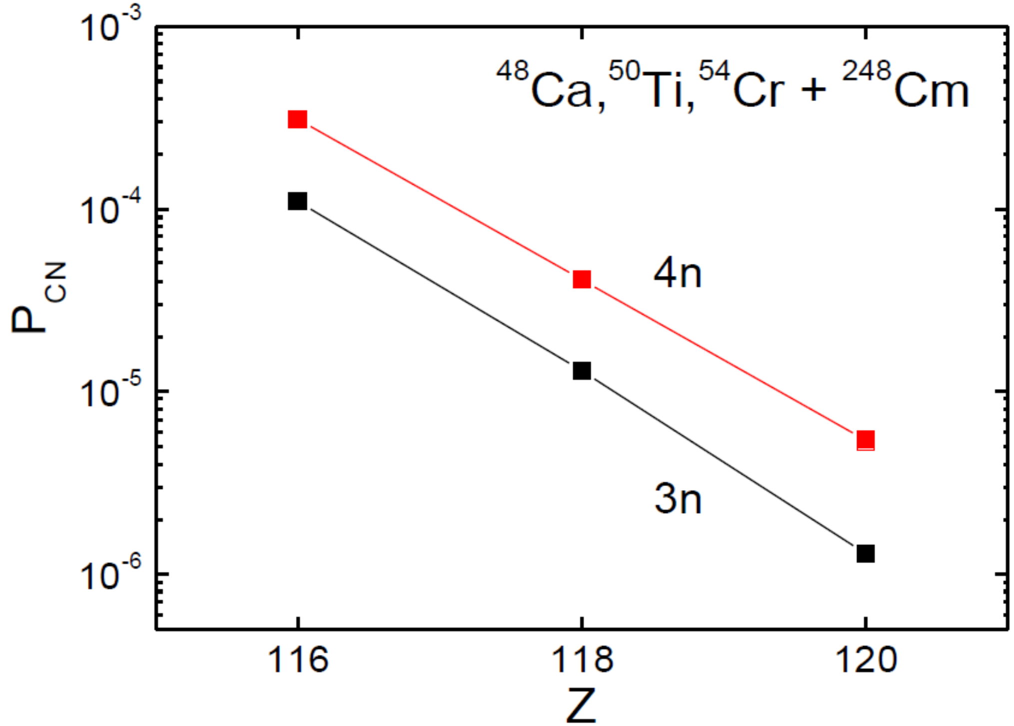


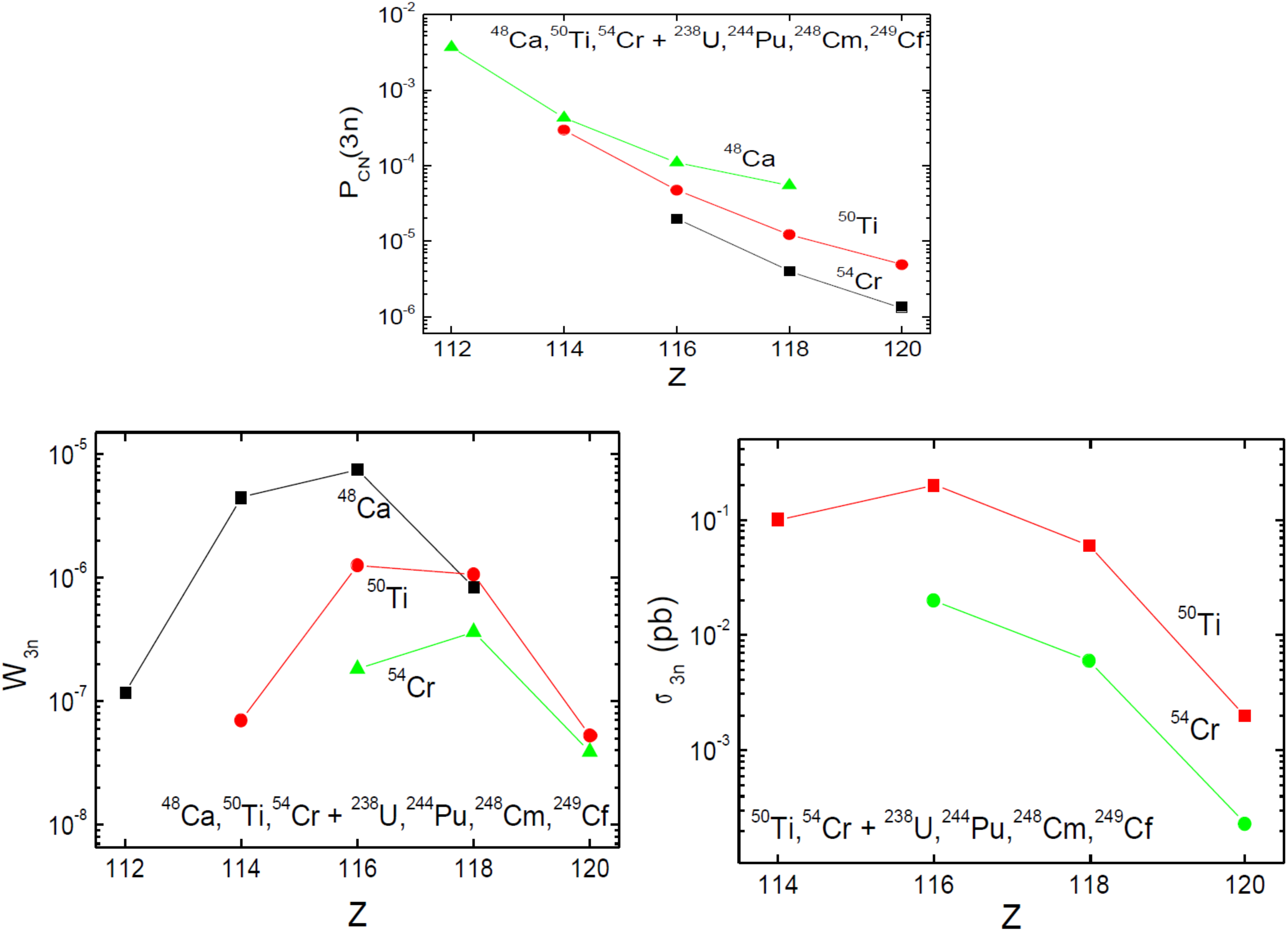
Cross section in $^{48}Ca+^{233}U \rightarrow ^{277}Cn+4n$ is comparable to one in $^{70}Zn+^{208}Pb \rightarrow ^{277}Cn+1n$, in which is 0.5 pb

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

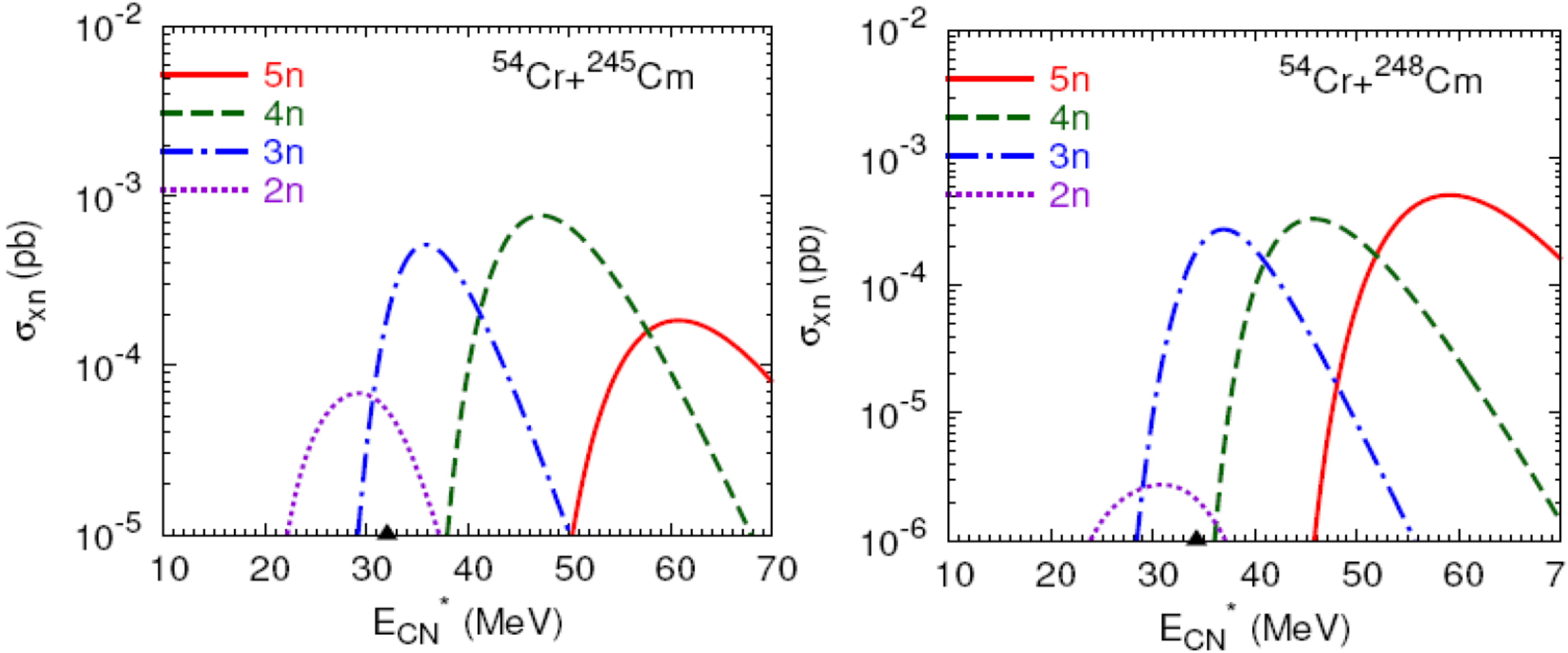
For the hot fusion reaction ^{48}Ca+^{239}Pu→^{283}Fl+4n and cold fusion reaction ^{76}Ge+^{208}Pb→^{283}Fl+1n, we also obtain the close production cross sections of the ^{283}Fl isotope. Using the measured cross section $\sigma_{3n} = 0.23^{+0.59}_{-0.20}$ pb [13,14] and the theoretical ratio $\sigma_{3n}/\sigma_{4n} = 2.3$ for the ^{48}Ca+^{239}Pu reaction, we estimate the production cross section as $0.1^{+0.26}_{-0.09}$ pb in the 4n-evaporation channel which is close to the cross section calculated for the ^{76}Ge+^{208}Pb→^{283}Fl+1n reaction.

6. Production of new SHN

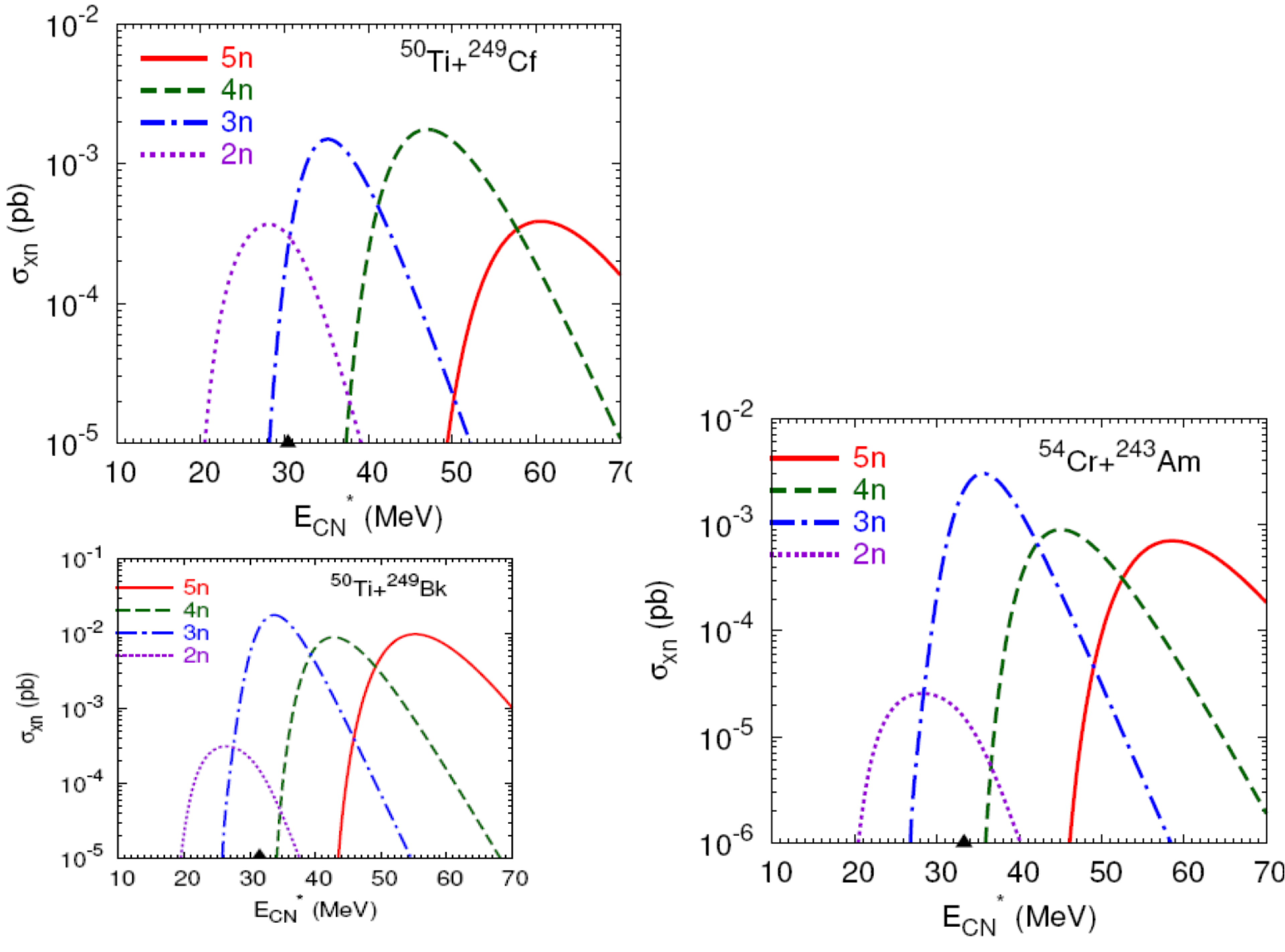




^{48}Ca,^{50}Ti,^{54}Cr + ^{238}U,^{244}Pu,^{248}Cm,^{249}Cf
P_{CN}(3n)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
^{48}Ca
^{50}Ti
^{54}Cr
112
114
116
118
120
Z
W_{3n}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
^{48}Ca
^{50}Ti
^{54}Cr
^{48}Ca,^{50}Ti,^{54}Cr + ^{238}U,^{244}Pu,^{248}Cm,^{249}Cf
112
114
116
118
120
Z
σ_{3n} (pb)
10^{-1}
10^{-2}
10^{-3}
^{50}Ti
^{54}Cr
^{50}Ti,^{54}Cr + ^{238}U,^{244}Pu,^{248}Cm,^{249}Cf
114
116
118
120
Z

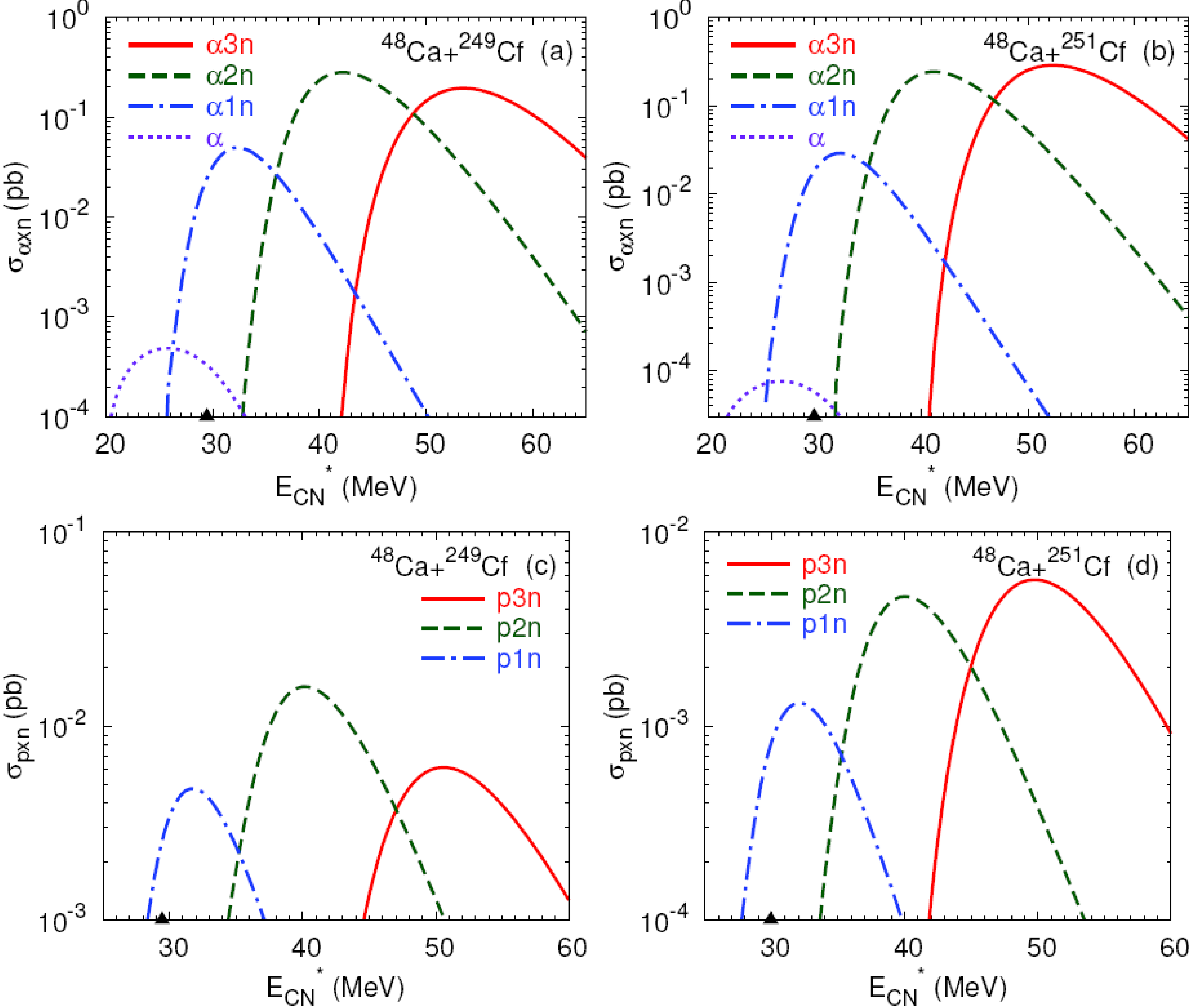


$^{54}Cr+^{245}Cm$
5n
4n
3n
2n
10^{-2}
10^{-3}
10^{-4}
10^{-5}
σ_{xn} (pb)
10
20
30
40
50
60
70
E_{CN}^* (MeV)
$^{54}Cr+^{248}Cm$
5n
4n
3n
2n
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
σ_{xn} (pb)
10
20
30
40
50
60
7
E_{CN}^* (MeV)

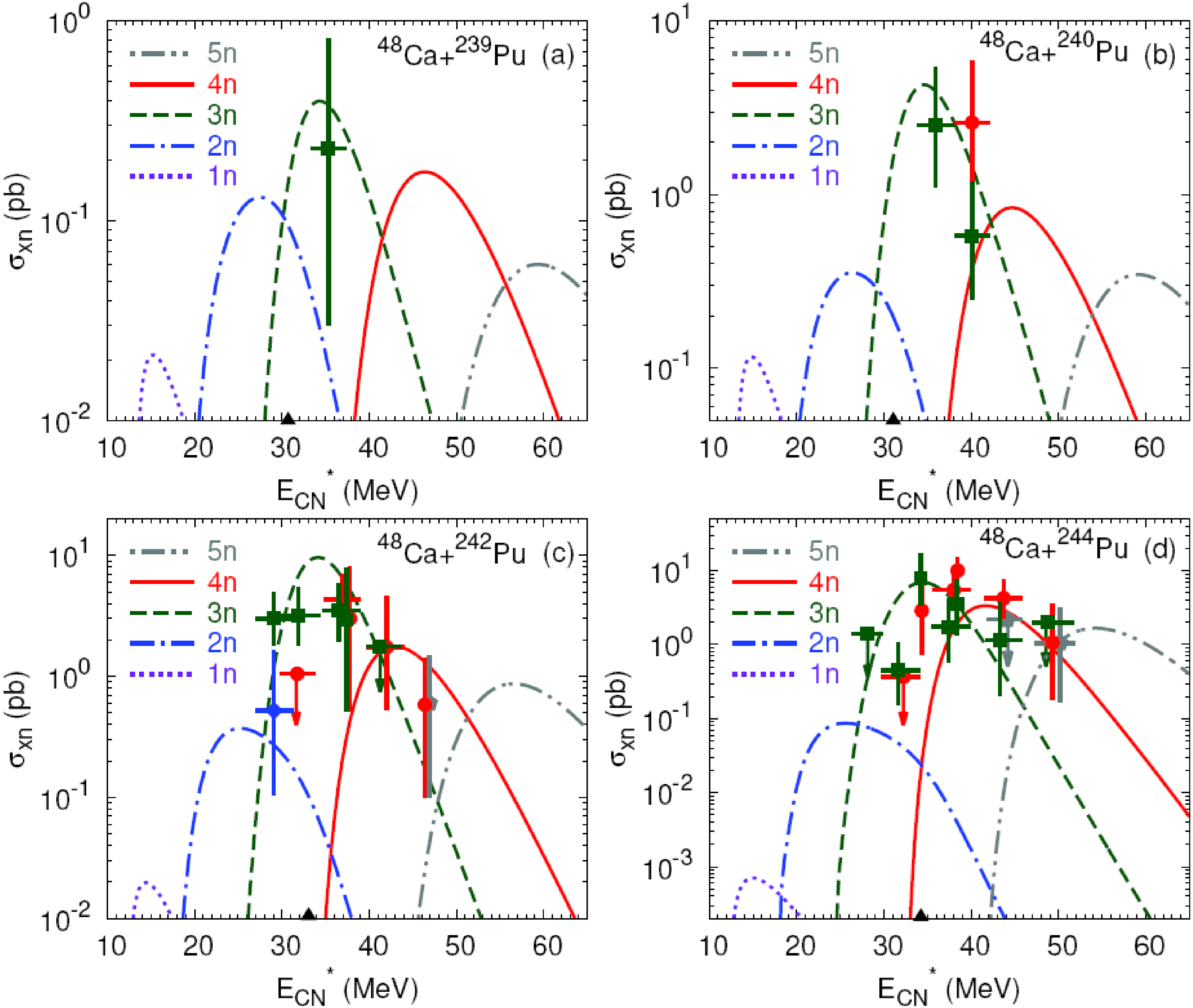


50Ti+249Cf
5n
4n
3n
2n
σxn (pb)
ECN* (MeV)
10-2
10-3
10-4
10-5
10 20 30 40 50 60 70
50Ti+249Bk
5n
4n
3n
2n
σxn (pb)
ECN* (MeV)
10-1
10-2
10-3
10-4
10-5
10 20 30 40 50 60 70
54Cr+243Am
5n
4n
3n
2n
σxn (pb)
ECN* (MeV)
10-2
10-3
10-4
10-5
10-6
10 20 30 40 50 60 70

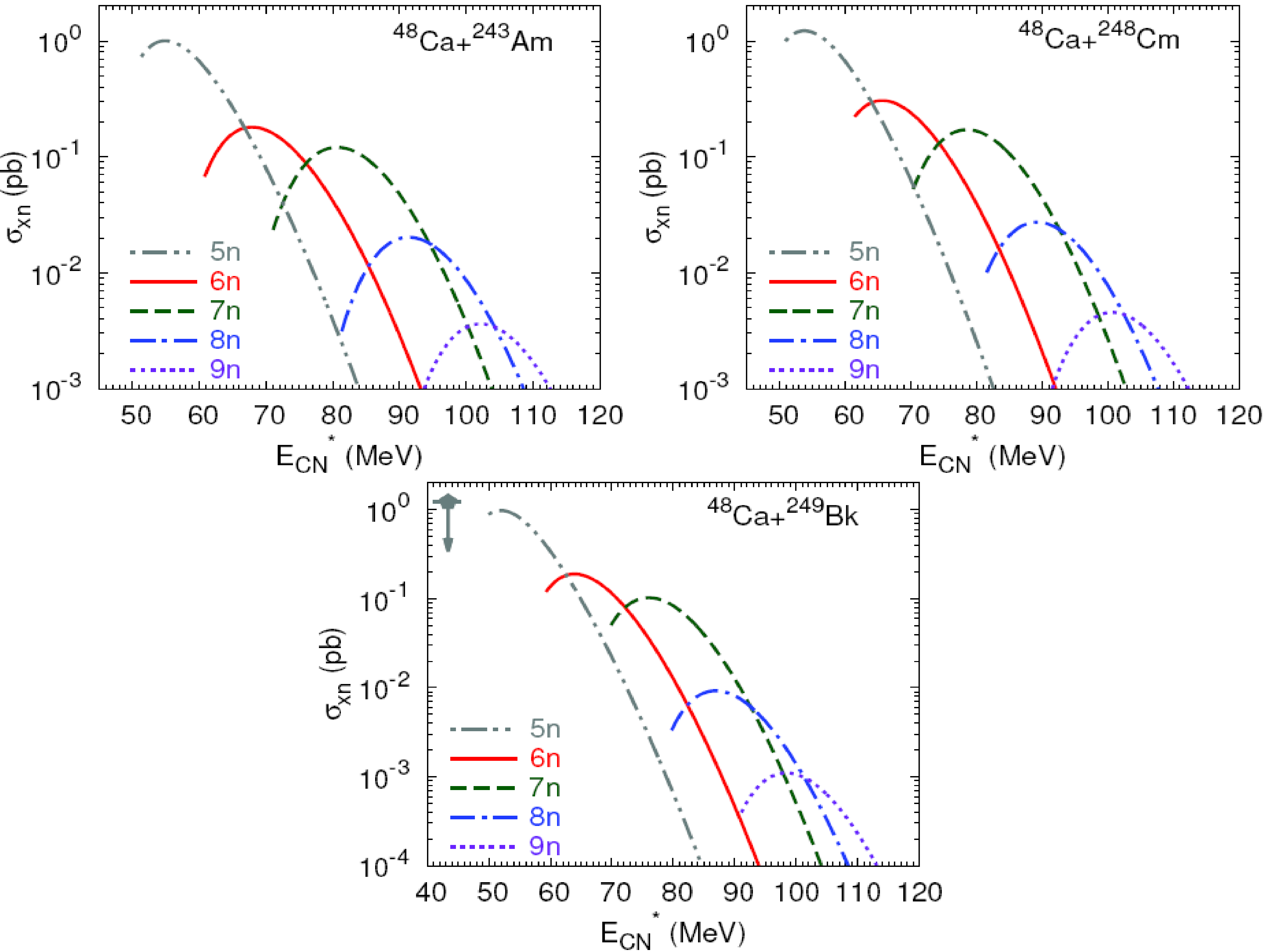
Theory expects remarkable experimental results in the near future



^{48}Ca+^{249}Cf (a)
α3n
α2n
α1n
α
$\sigma_{\alpha xn}$ (pb)
E_{CN}^* (MeV)
^{48}Ca+^{251}Cf (b)
α3n
α2n
α1n
α
$\sigma_{\alpha xn}$ (pb)
E_{CN}^* (MeV)
^{48}Ca+^{249}Cf (c)
p3n
p2n
p1n
σ_{pxn} (pb)
E_{CN}^* (MeV)
^{48}Ca+^{251}Cf (d)
p3n
p2n
p1n
σ_{pxn} (pb)
E_{CN}^* (MeV)



5n
4n
3n
2n
1n
^{48}Ca+^{239}Pu (a)
^{48}Ca+^{240}Pu (b)
^{48}Ca+^{242}Pu (c)
^{48}Ca+^{244}Pu (d)
σ_{xn} (pb)
E_{CN}^* (MeV)



^{48}Ca+^{243}Am
^{48}Ca+^{248}Cm
^{48}Ca+^{249}Bk
σ_{xn} (pb)
E_{CN}^* (MeV)
5n
6n
7n
8n
9n
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
40
50
60
70
80
90
100
110
120