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

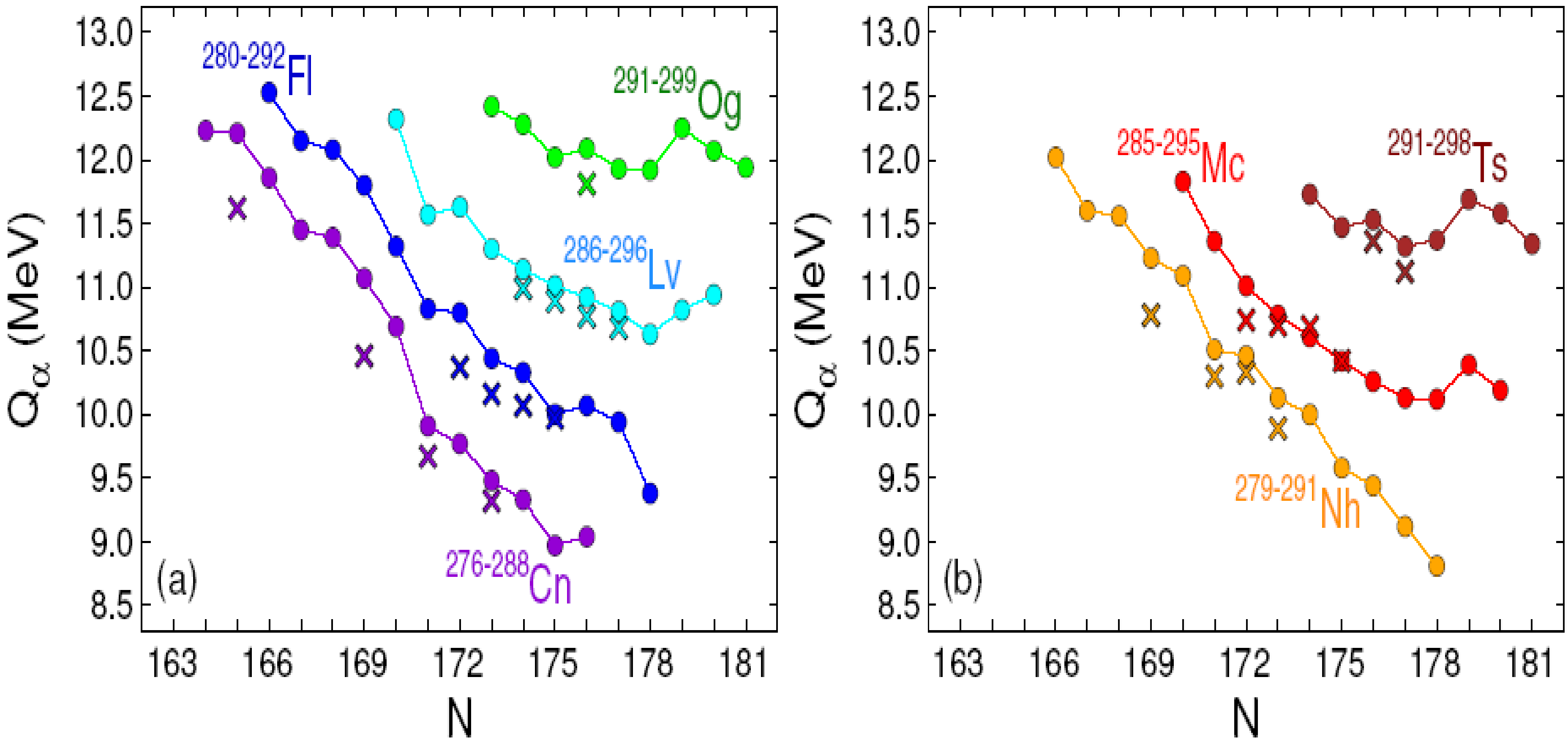
2. High energies, study xn evaporation channels with x > 4

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

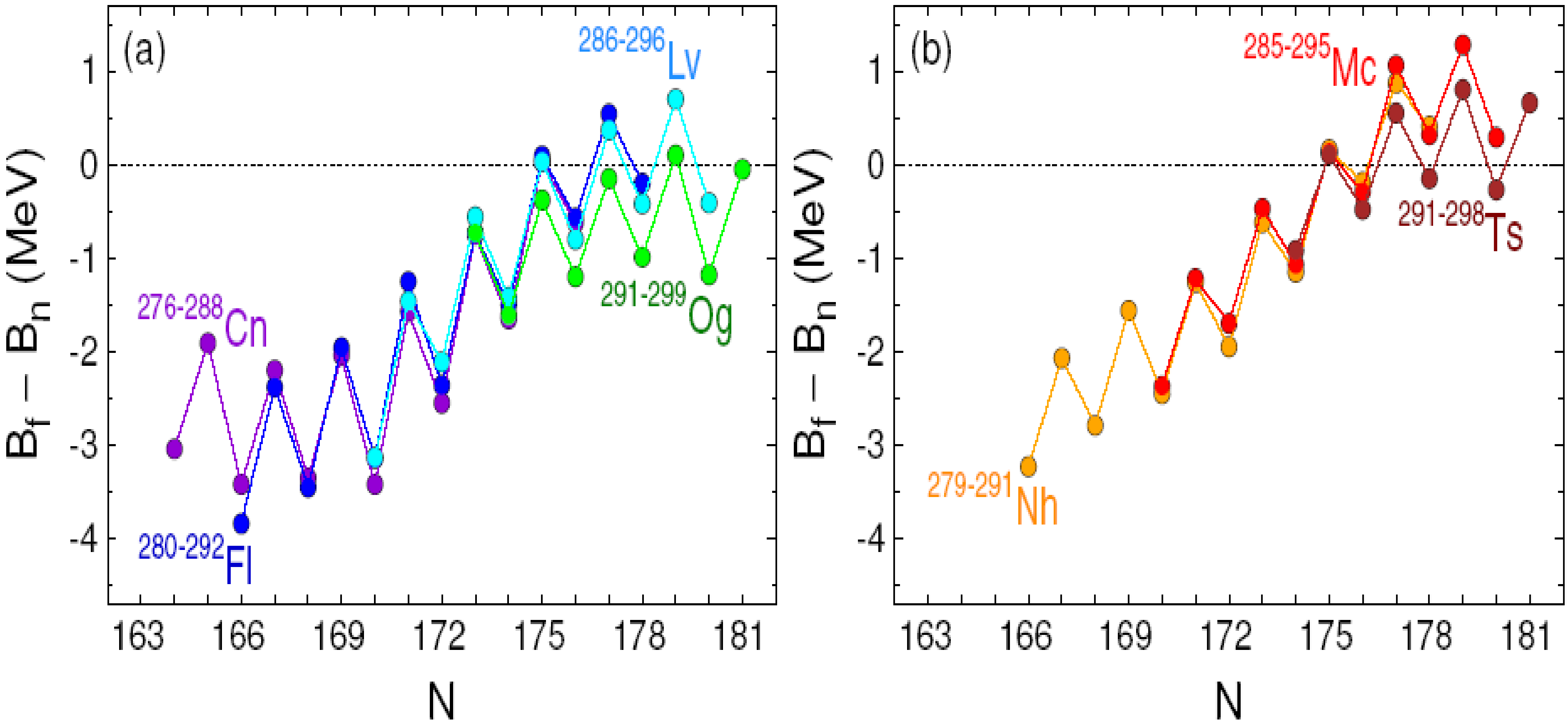
Within the dinuclear system model we analysed the production of SHN in various actinide-based complete fusion reactions with ^{48}Ca.

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



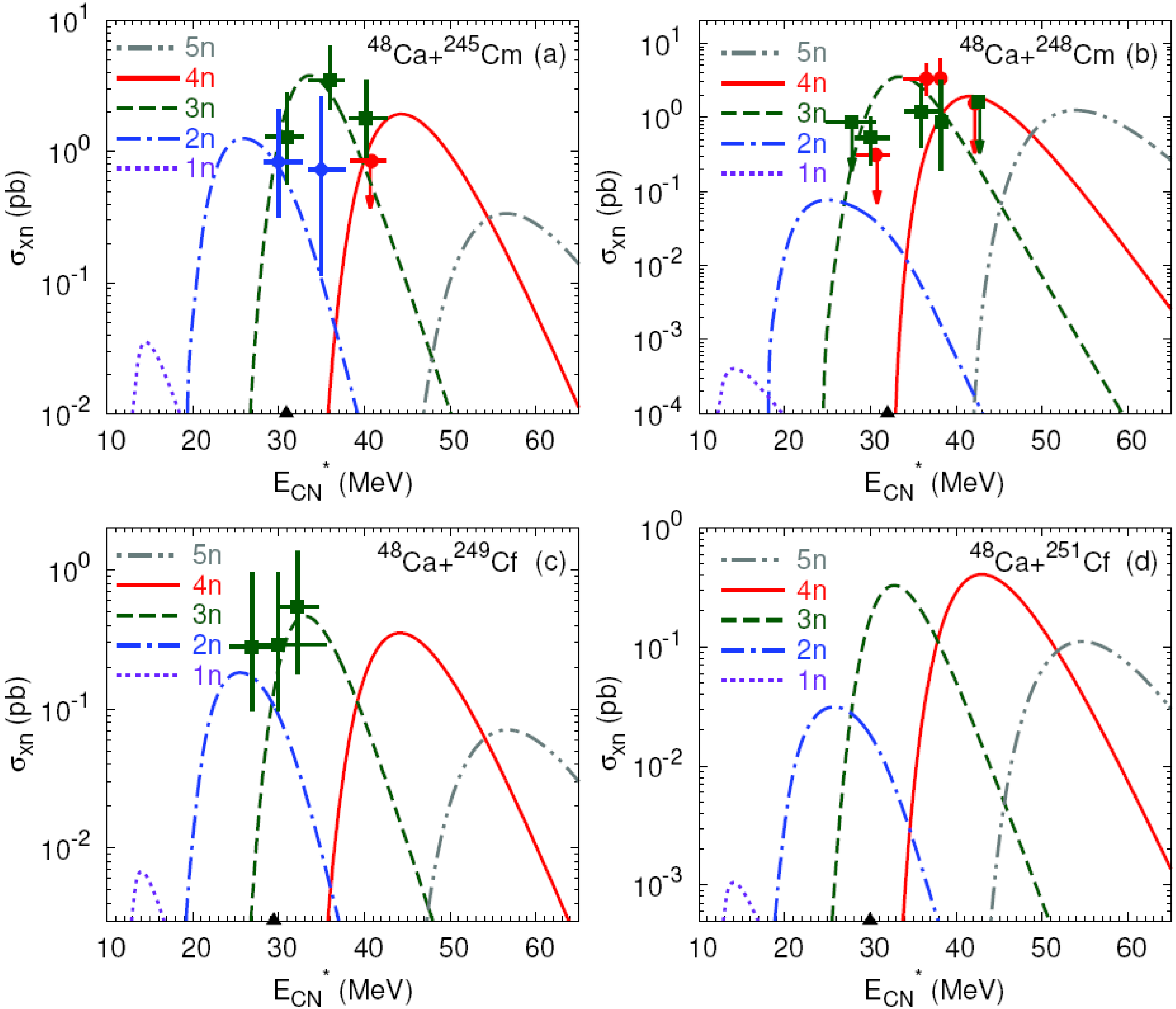
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
Qα (MeV)
280-292Fl
291-299Og
286-296Lv
276-288Cn
(a)
163
166
169
172
175
178
181
N
285-295Mc
291-298Ts
279-291Nh
(b)


(a)
$^{286\text{-}296}$Lv
$^{276\text{-}288}$Cn
$^{291\text{-}299}$Og
$^{280\text{-}292}$Fl
(b)
$^{285\text{-}295}$Mc
$^{291\text{-}298}$Ts
$^{279\text{-}291}$Nh
$B_f - B_n$ (MeV)
N
1
0
-1
-2
-3
-4
163
166
169
172
175
178
181

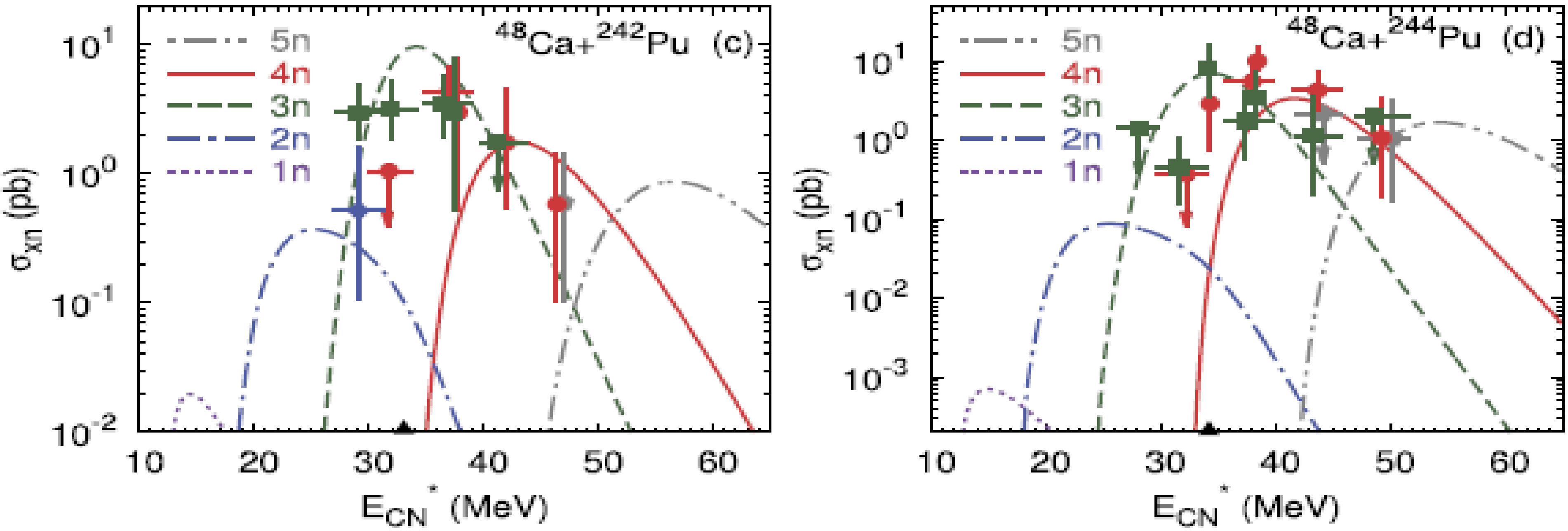
Dynamics of fusion in the dinuclear system model

Evaporation residue cross section for the production of superheavy nuclei:

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

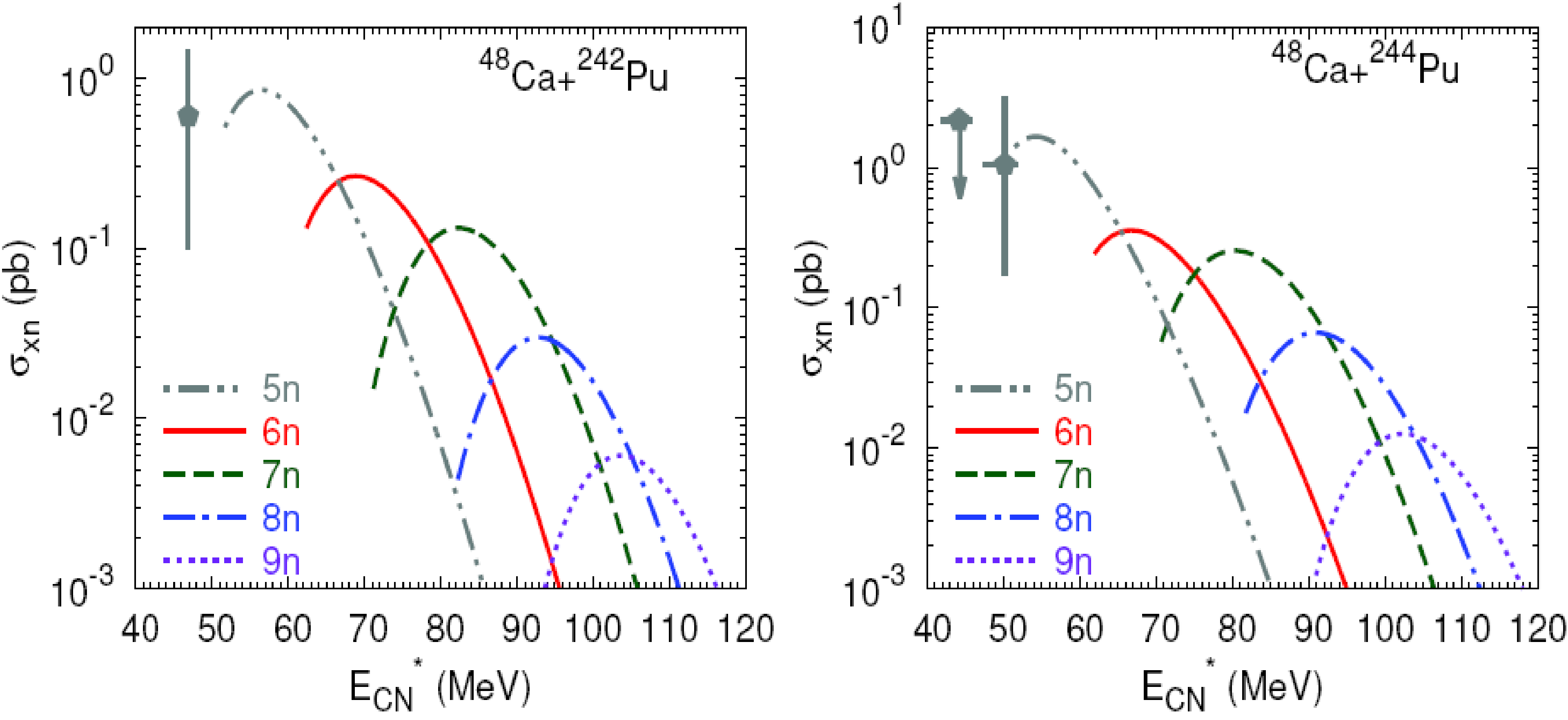


48Ca+245Cm (a)
48Ca+248Cm (b)
48Ca+249Cf (c)
48Ca+251Cf (d)
5n
4n
3n
2n
1n
σxn (pb)
ECN* (MeV)

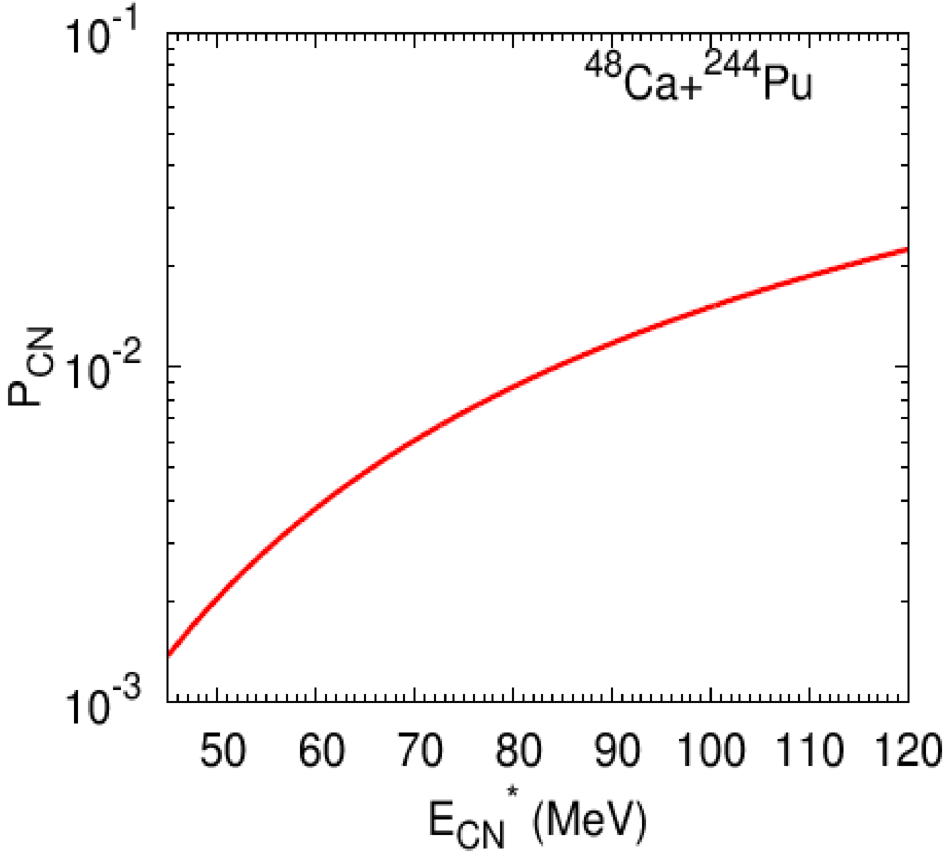


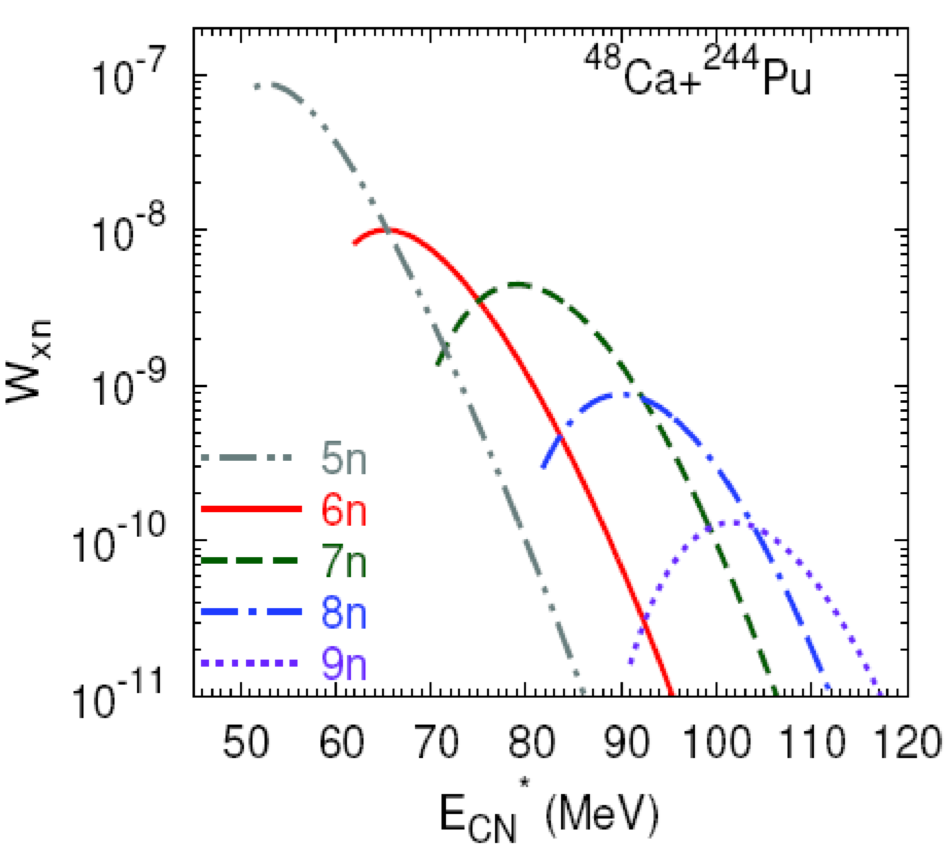
Energies of the maximum of cross section in 1n-,2n-channels are considerably smaller than the Coulomb barrier height for the sphere-side orientation plus Q-value: $V_b + Q$.

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



48Ca+242Pu
48Ca+244Pu
σxn (pb)
ECN* (MeV)
5n
6n
7n
8n
9n

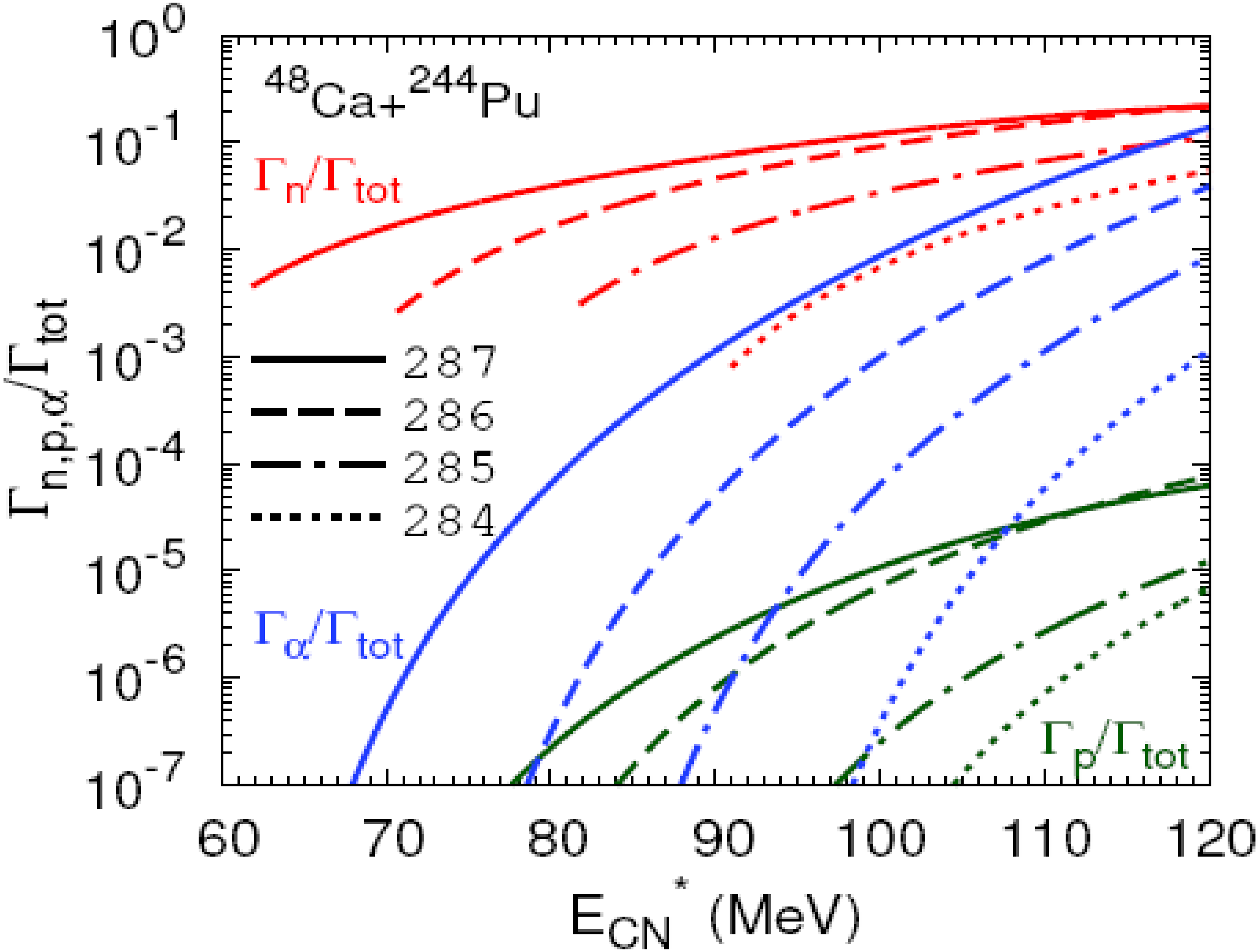




A weak drop of the cross section is due to

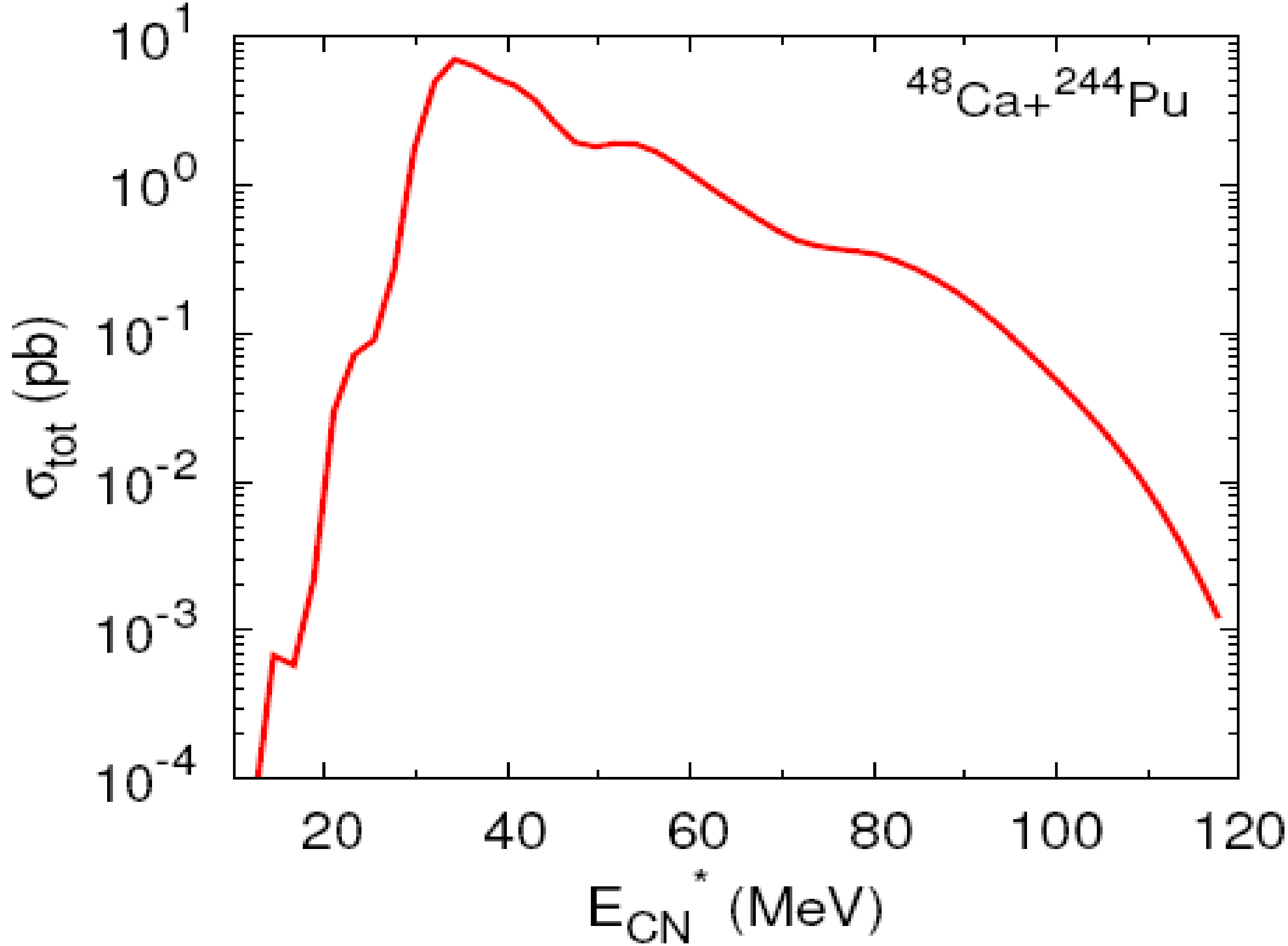
1. the interplay of fusion and survival probabilities

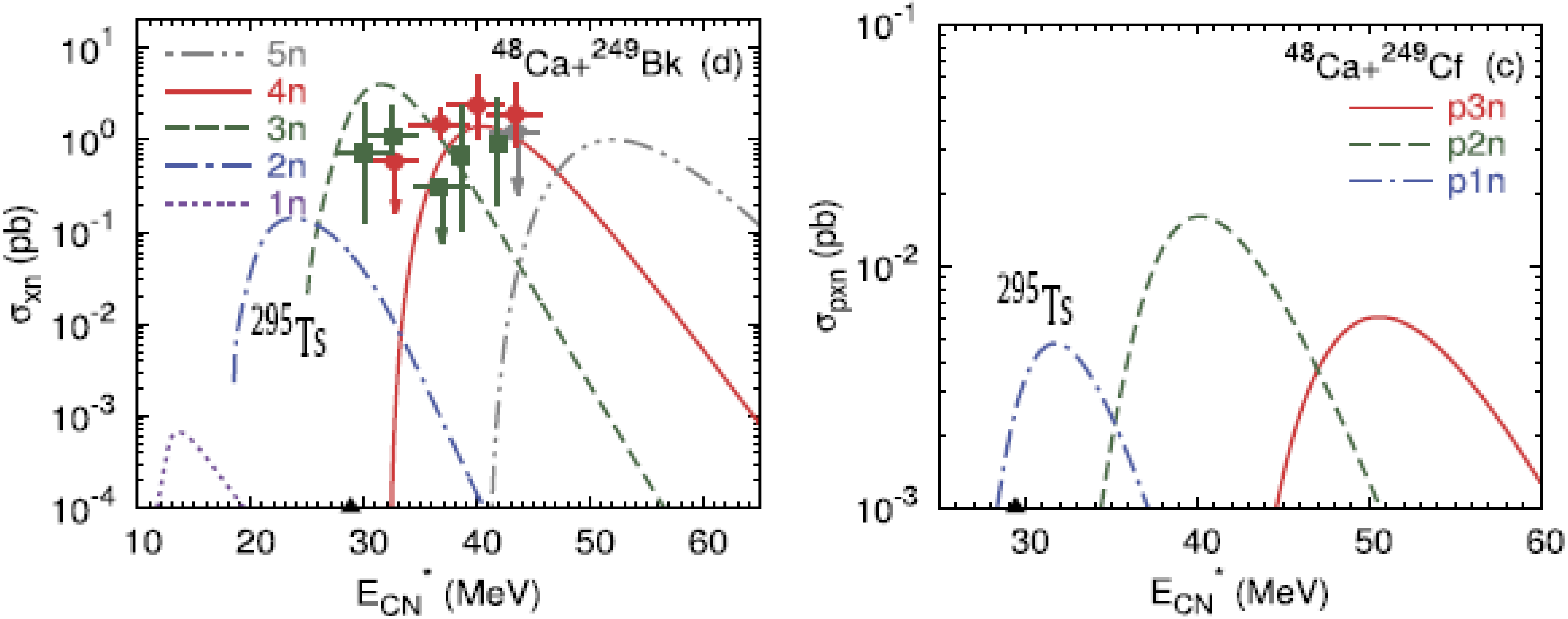
2. a weak change of the difference between the fission barrier height and neutron binding energy at 5-9 steps of n-evaporation



^{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)

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



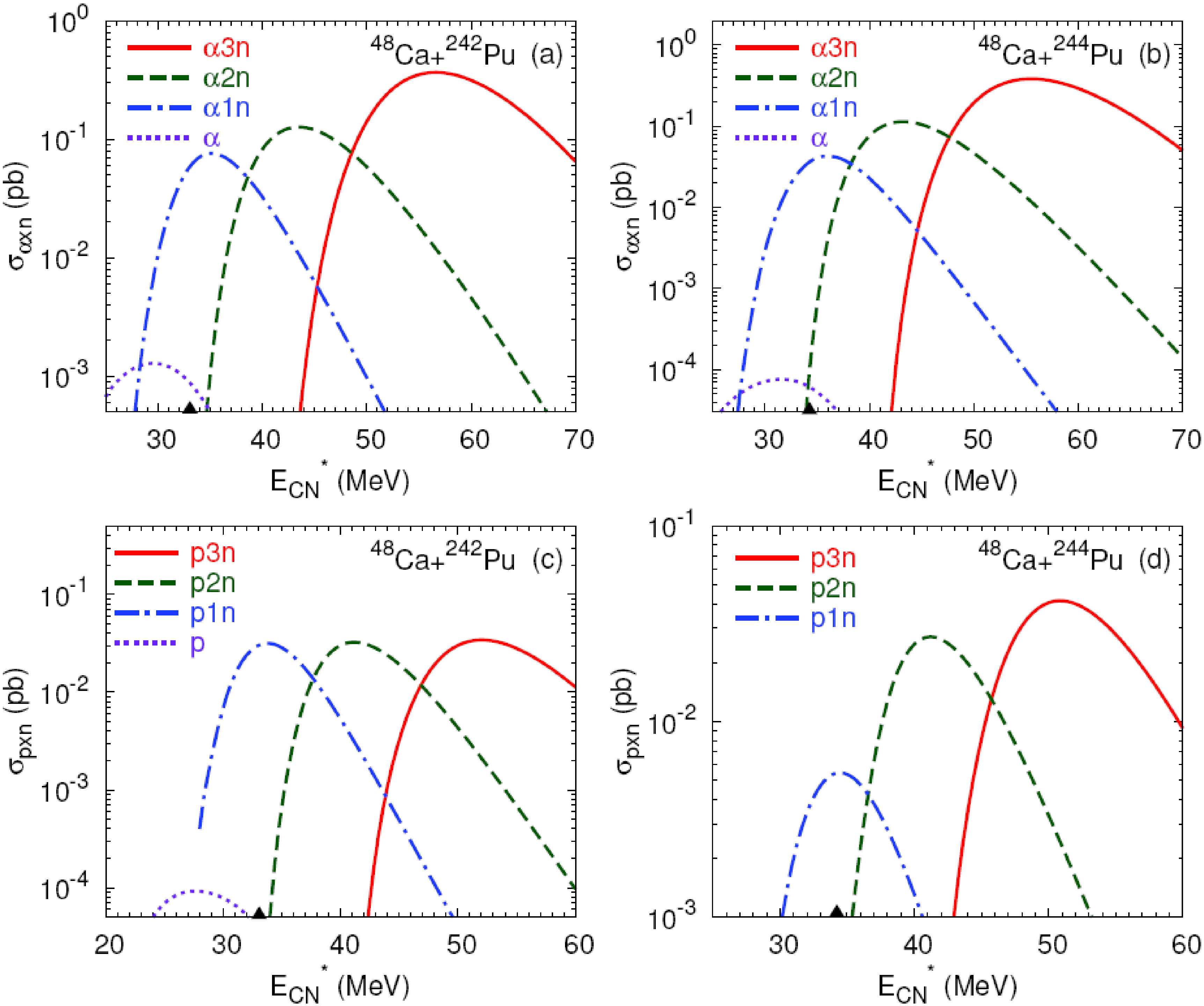


5n
4n
3n
2n
1n
^{48}Ca+^{249}Bk (d)
^{295}Ts
σ_{xn} (pb)
E_{CN}^* (MeV)
^{48}Ca+^{249}Cf (c)
p3n
p2n
p1n
^{295}Ts
σ_{pxn} (pb)
E_{CN}^* (MeV)

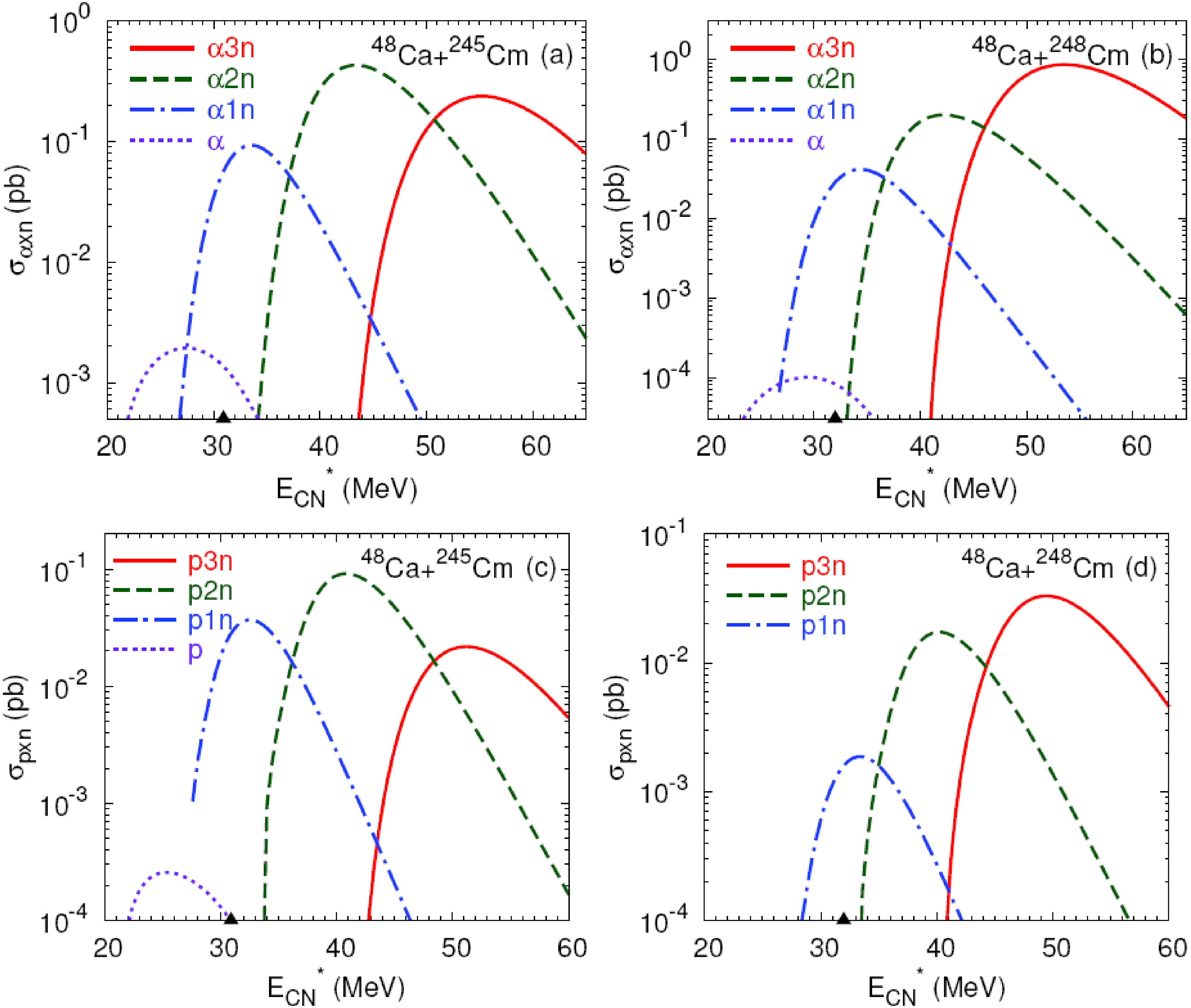
-- Imploying the reactions in 1n-,2n-channels, one can directly produce heaviest isotopes closer to the centre of "island of stability" : ^{284,285}Cn, ^{283,284}Nh, ^{294}Lv, ^{295}Ts, $^{295-297}$Og

-- 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

-- The decline of the cross section at the transition from 5n to 9n channel is relatively weak. One can produce SHN with Z=114-117 in 5n-, 6n-channels



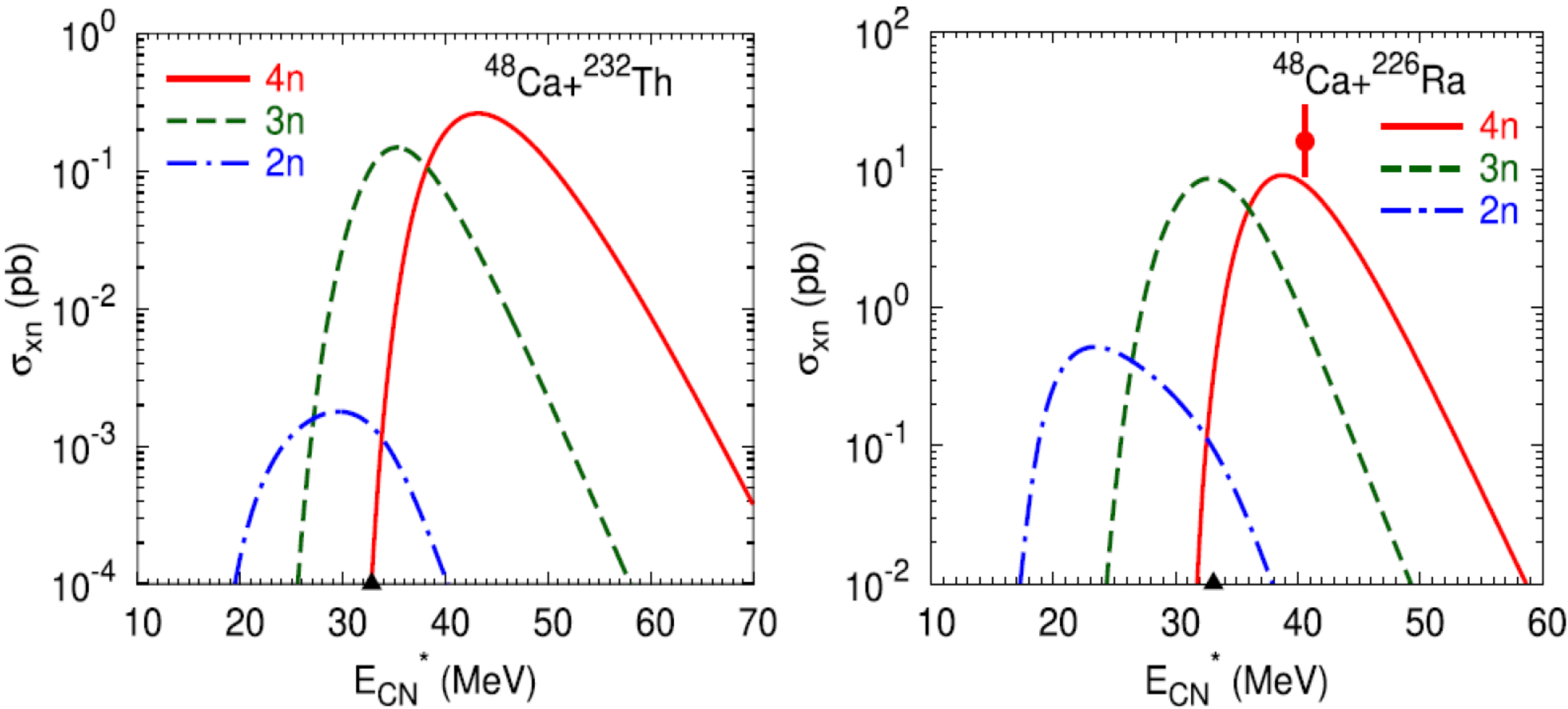
α3n
α2n
α1n
α
^{48}Ca+^{242}Pu (a)
^{48}Ca+^{244}Pu (b)
$\sigma_{\alpha xn}$ (pb)
E_{CN}^* (MeV)
p3n
p2n
p1n
p
^{48}Ca+^{242}Pu (c)
^{48}Ca+^{244}Pu (d)
σ_{pxn} (pb)


α3n
α2n
α1n
α
^{48}Ca+^{245}Cm (a)
$\sigma_{\alpha xn}$ (pb)
E_{CN}^* (MeV)
^{48}Ca+^{248}Cm (b)
p3n
p2n
p1n
p
^{48}Ca+^{245}Cm (c)
σ_{pxn} (pb)
^{48}Ca+^{248}Cm (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

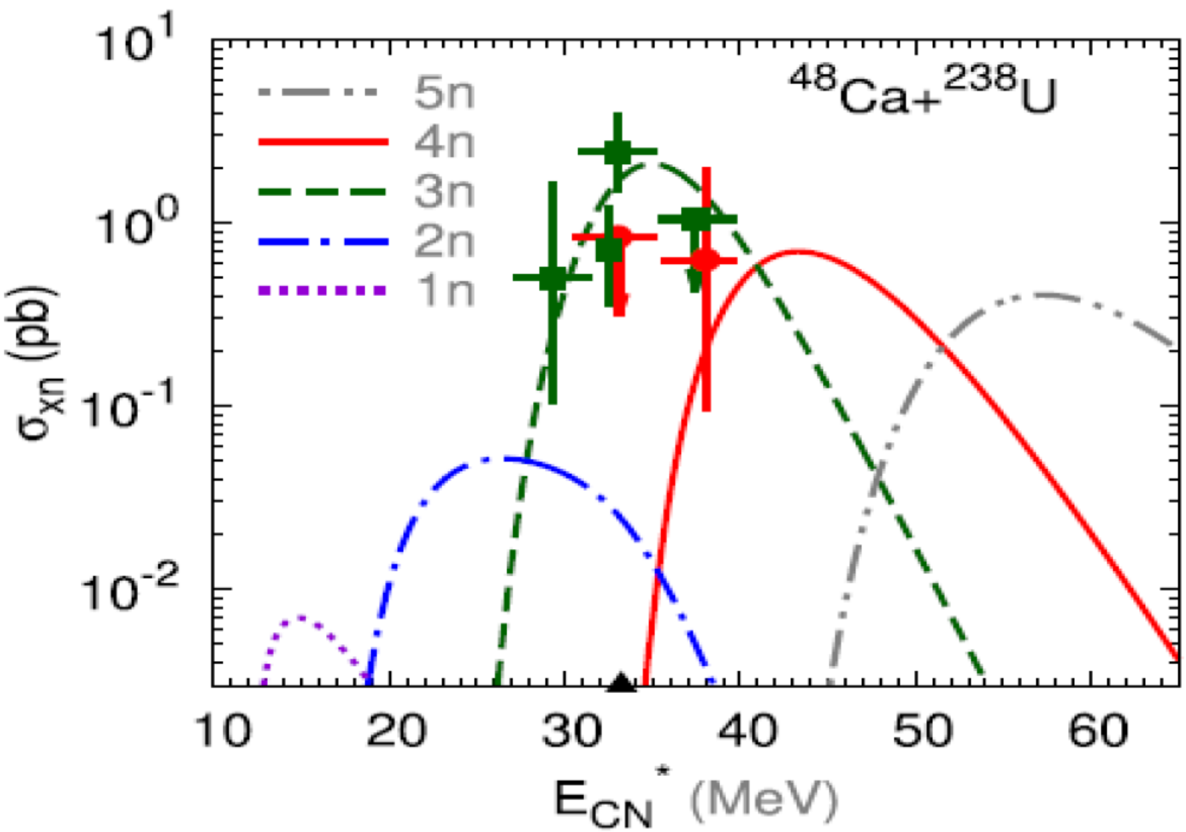
The charged evap. channels allow us to increase the mass of nuclei with Z=114,115,117 by 1 unit with respect to xn-channels.

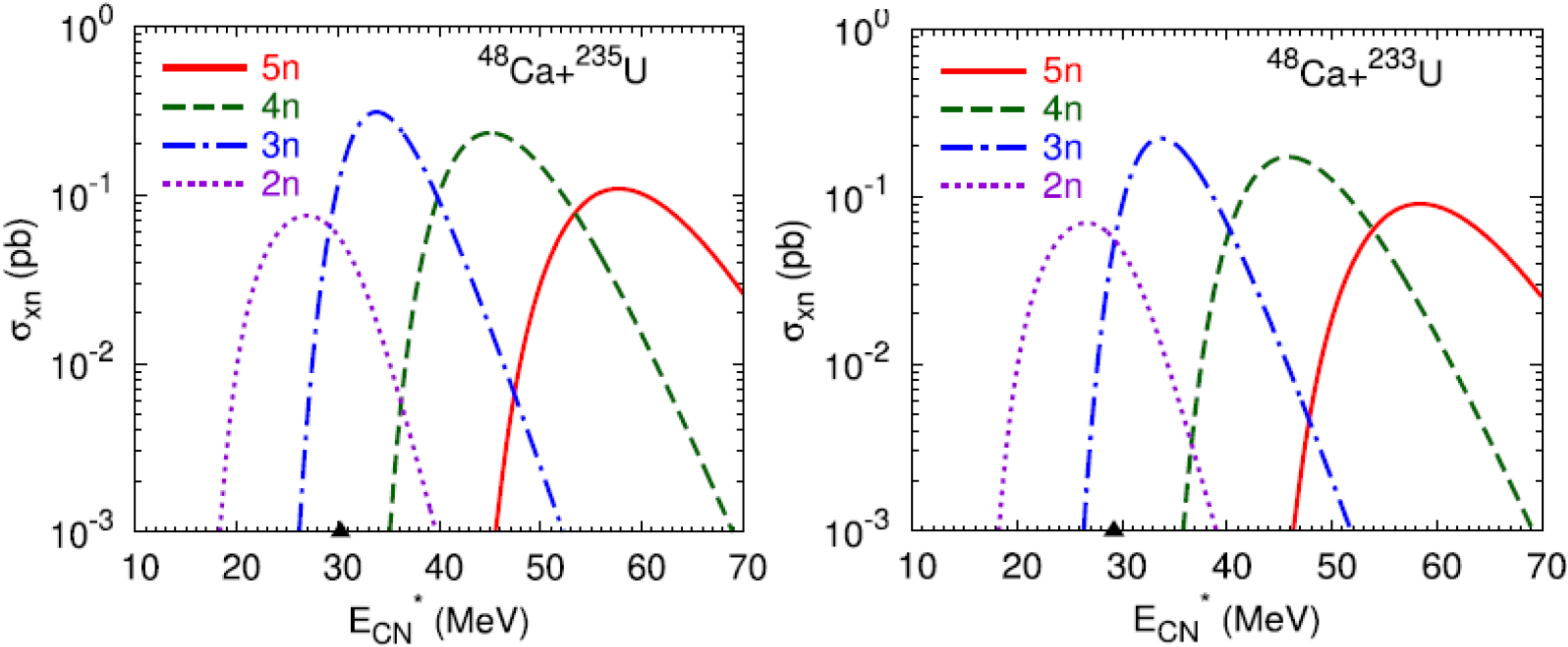
4. Isthmus connecting mainland and island of stability of SHN



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.

Theory expects remarkable experimental results in the near future