Perspective cold fusion reactions for synthesis of superheavy nuclei

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P.Jachimowicz, M.Kowal

What interesting fusion reactions can still be done with targets ^{204,206,207,208}Pb?

1. Study of xn (neutron) evaporation channels with x > 1

2. Production of new neutron-deficient isotopes and study of fissility vs isospin of SHN (Factory of SHN)

3. Study of fusion (quasi-fission) probability

Dynamics of fusion in the dinuclear system model

Evaporation residue cross section for the production of superheavy nuclei:

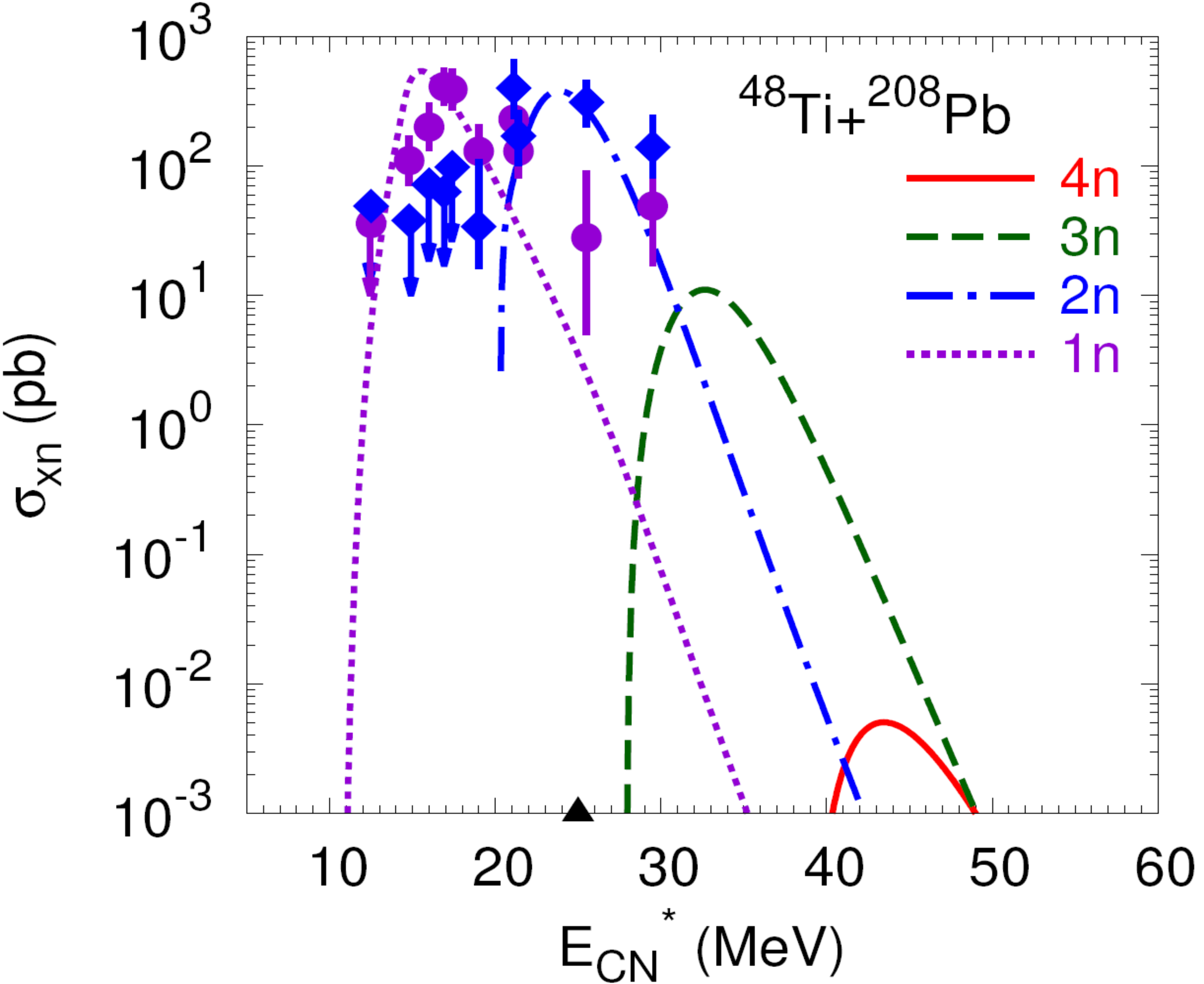
$$\sigma^{s}_{ER}(E_{c.m.})=\sum_{J}\sigma_c(E_{c.m.},J)\,P_{CN}(E_{c.m.},J)\,W^{s}_{sur}(E_{c.m.},J)$$

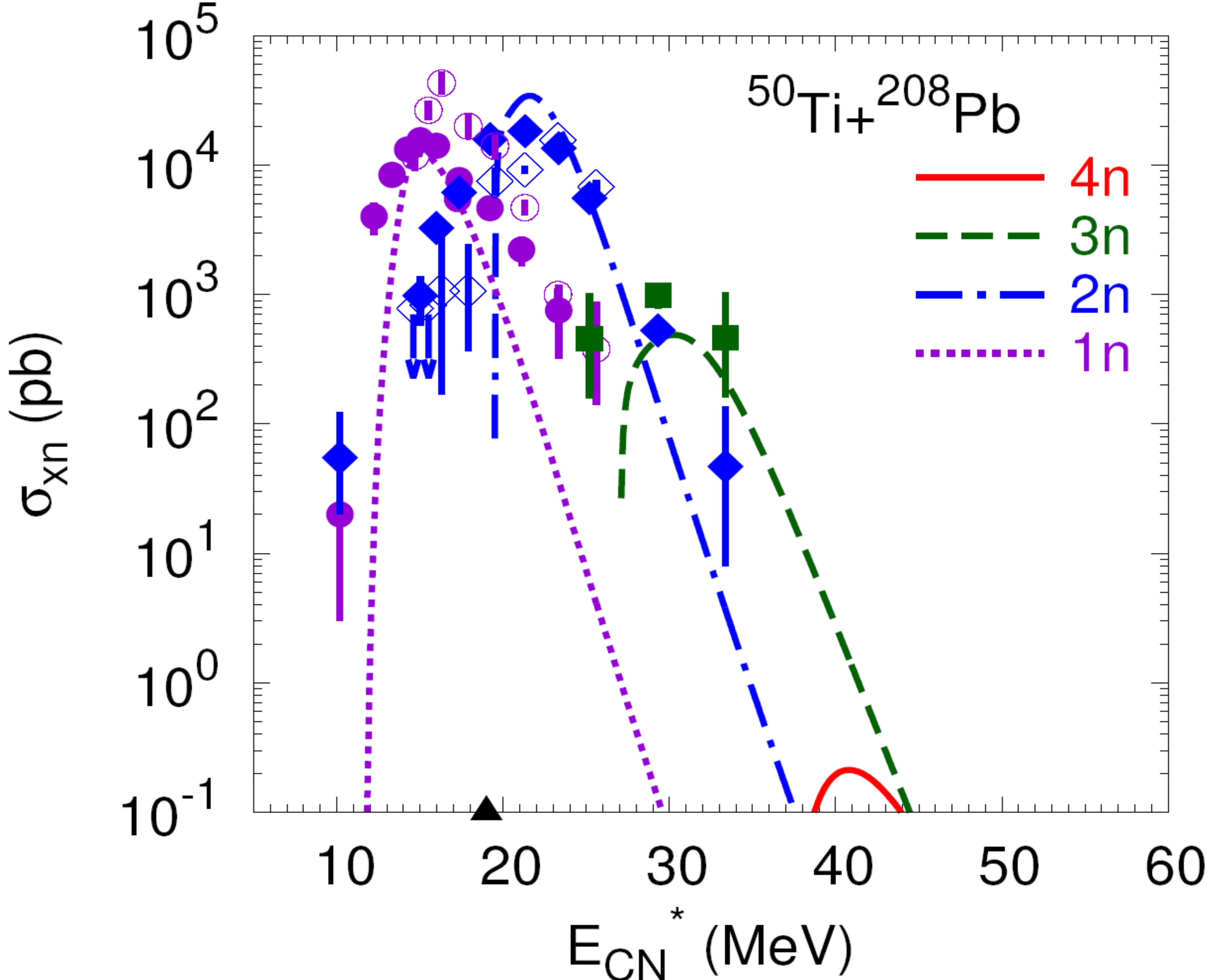
interplay of capture, fusion, survival probabilities

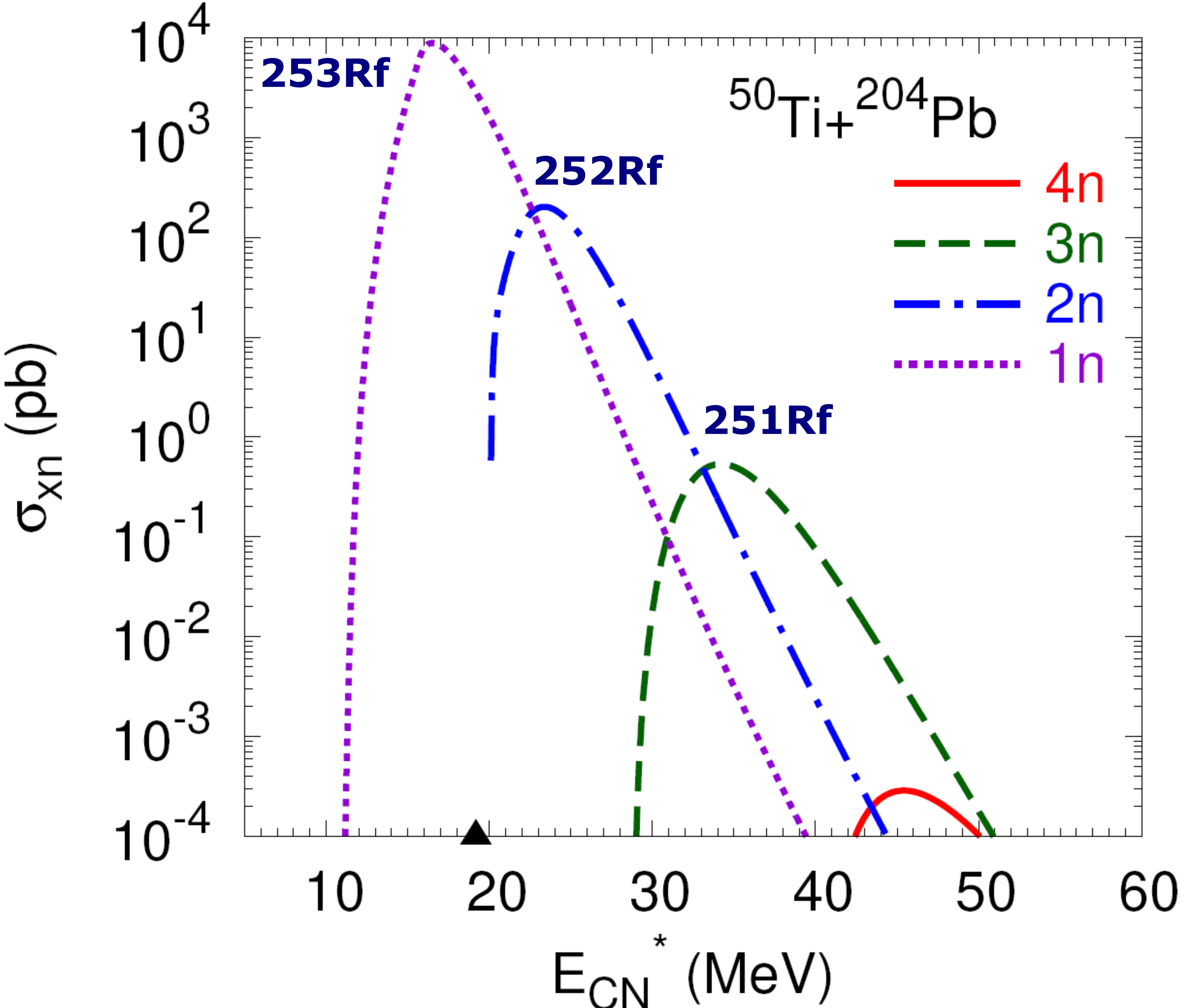
Q-value of fusion: 1n-channel is the sub-barrier in fusion with Ti, Cr, Fe

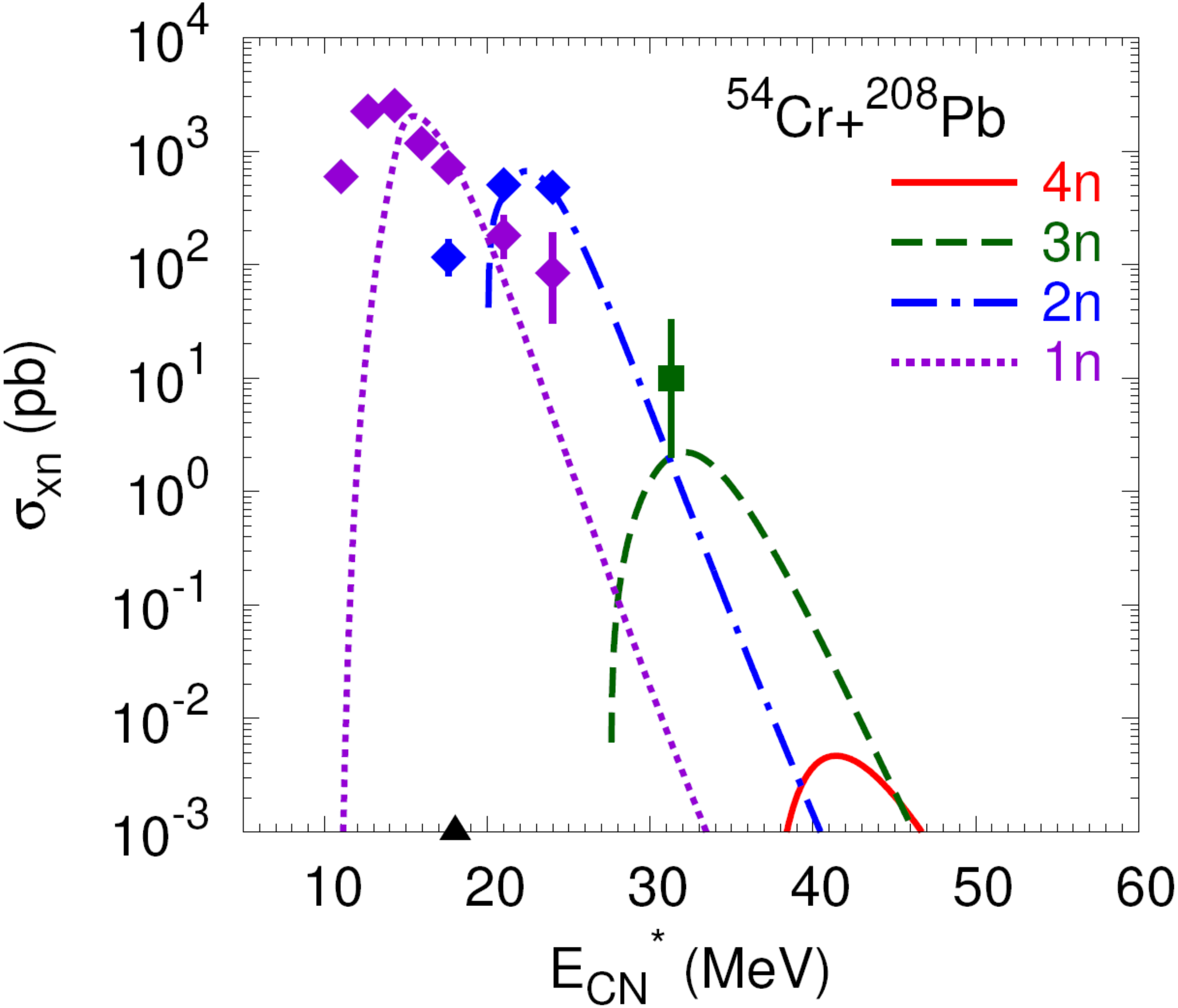
Predictions of the properties of heaviest nuclei are based on the Macroscopic-Microscopic Model:

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

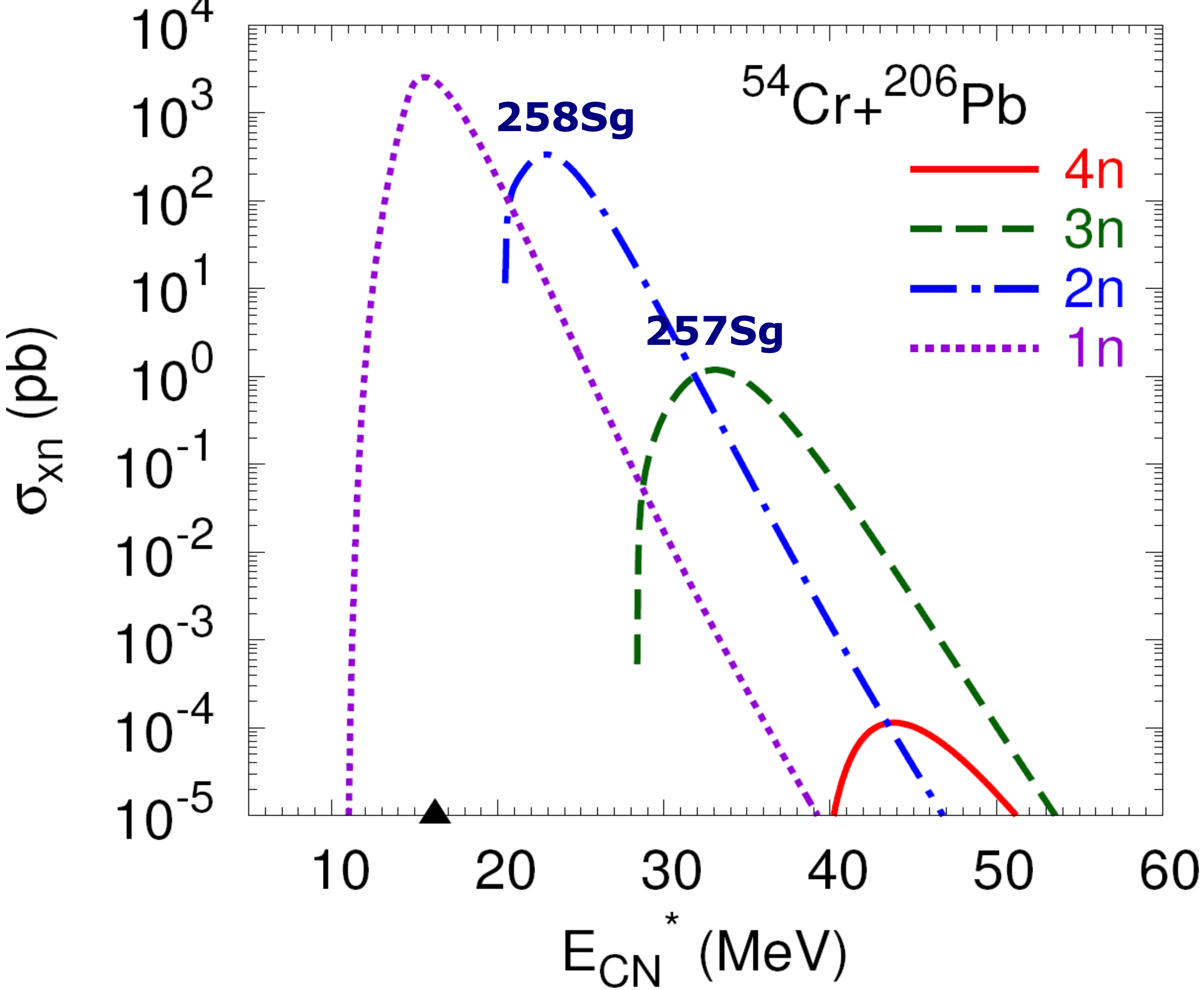

^{48}Ti+^{208}Pb
4n
3n
2n
1n
σ_{xn} (pb)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

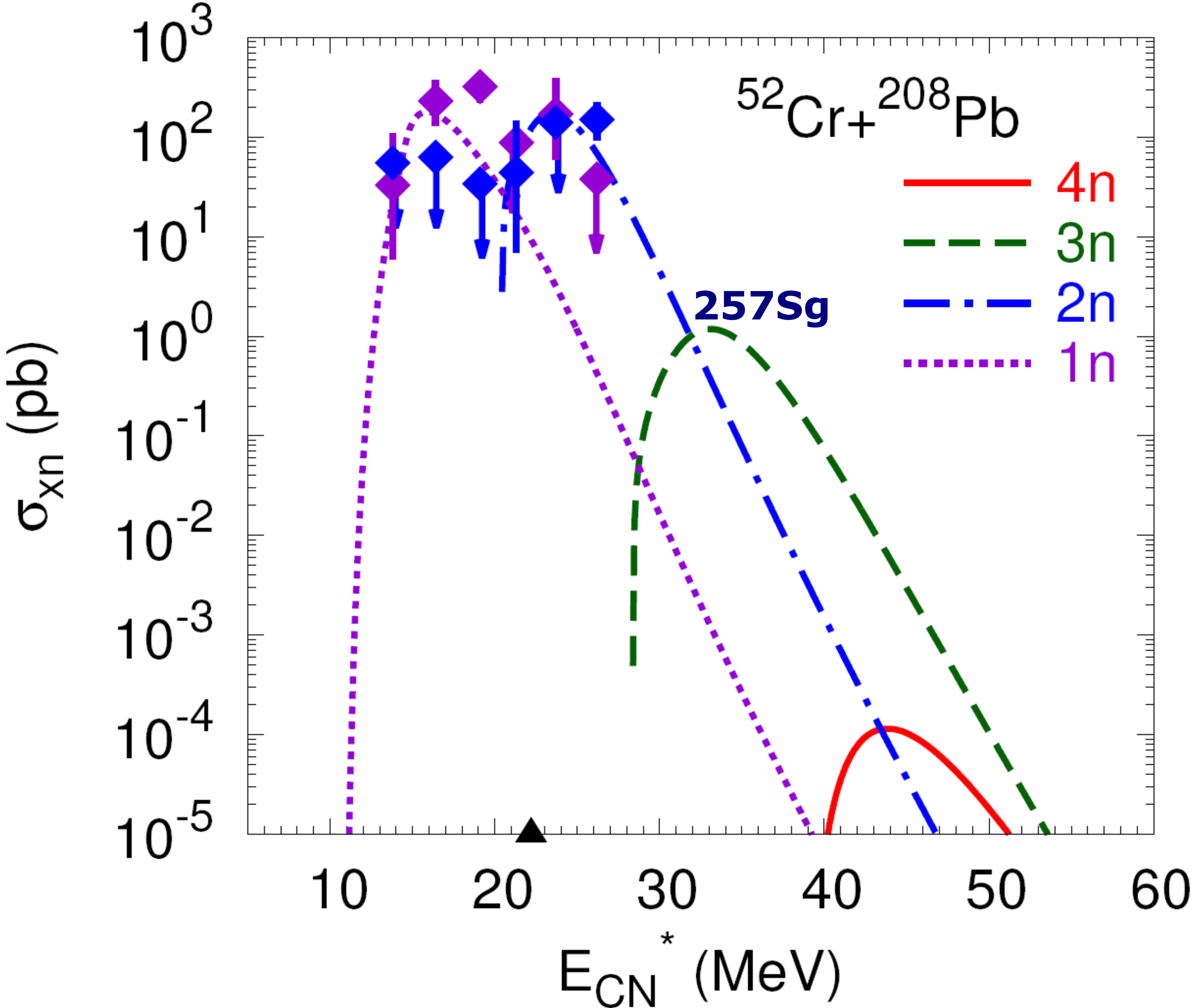

$^{50}Ti+^{208}Pb$
4n
3n
2n
1n
σ_{xn} (pb)
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

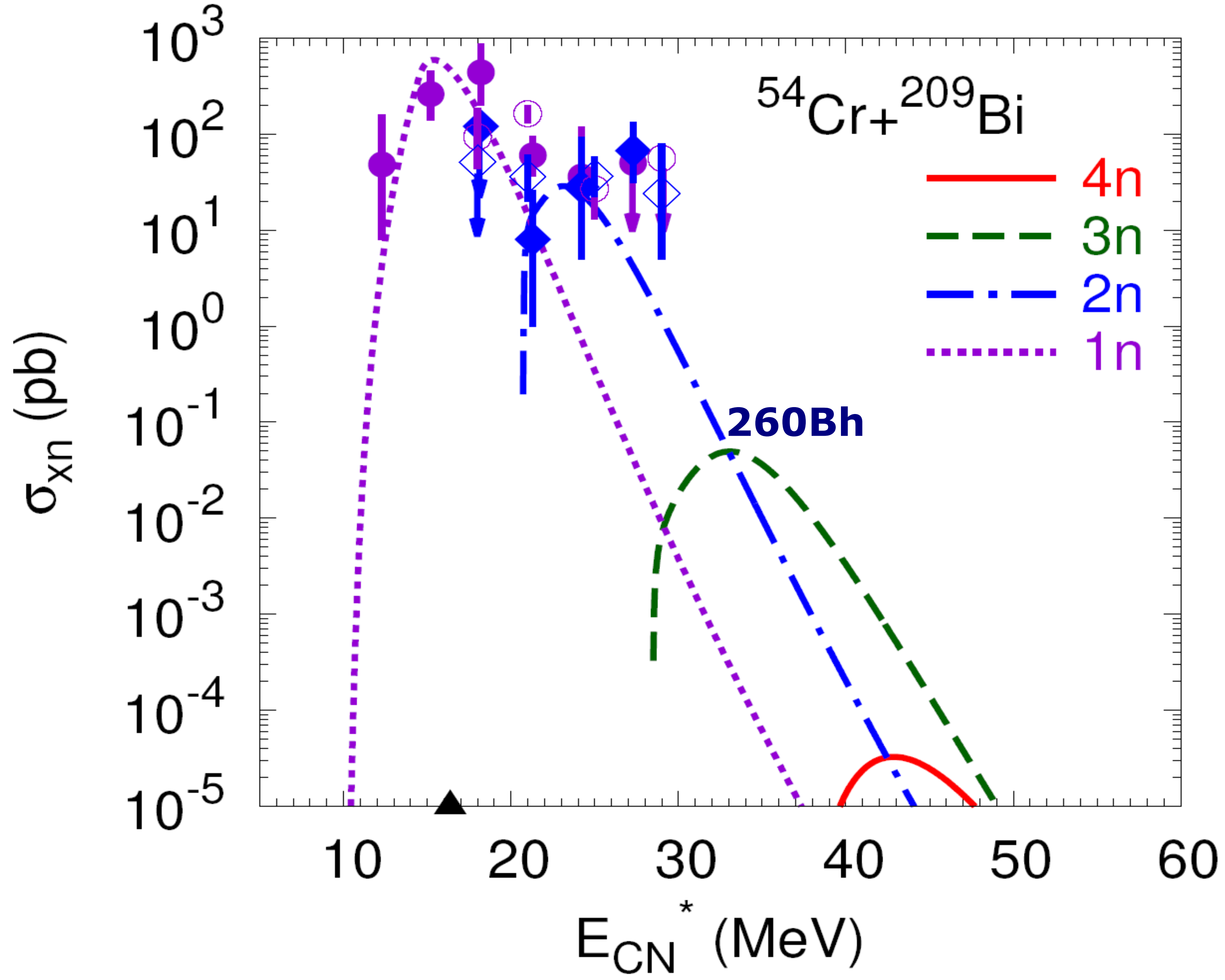

$^{50}Ti+^{204}Pb$
4n
3n
2n
1n
253Rf
252Rf
251Rf
σ_{xn} (pb)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

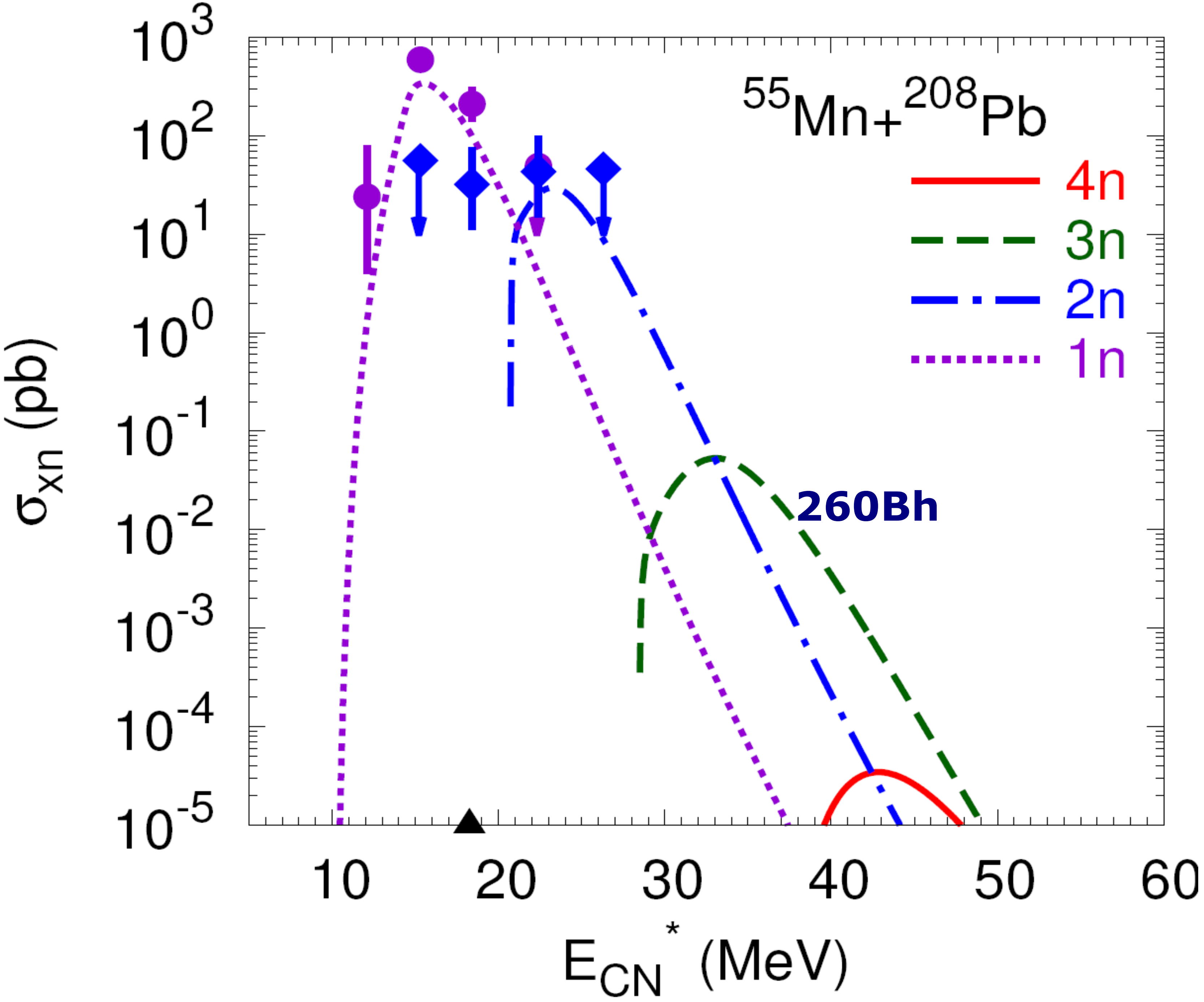


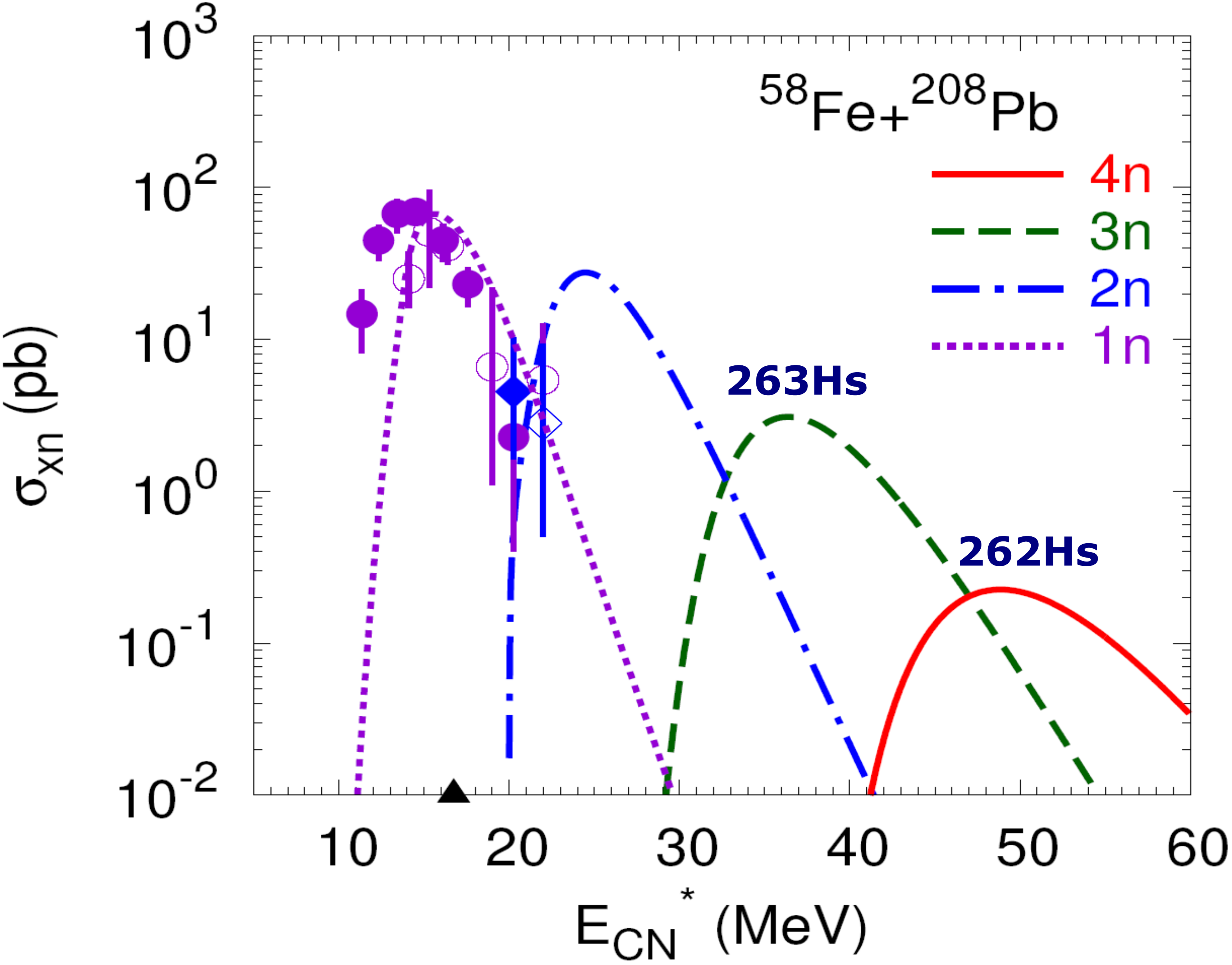
^{54}Cr+^{208}Pb
4n
3n
2n
1n
σ_{xn} (pb)
E_{CN}^{*} (MeV)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10
20
30
40
50
60

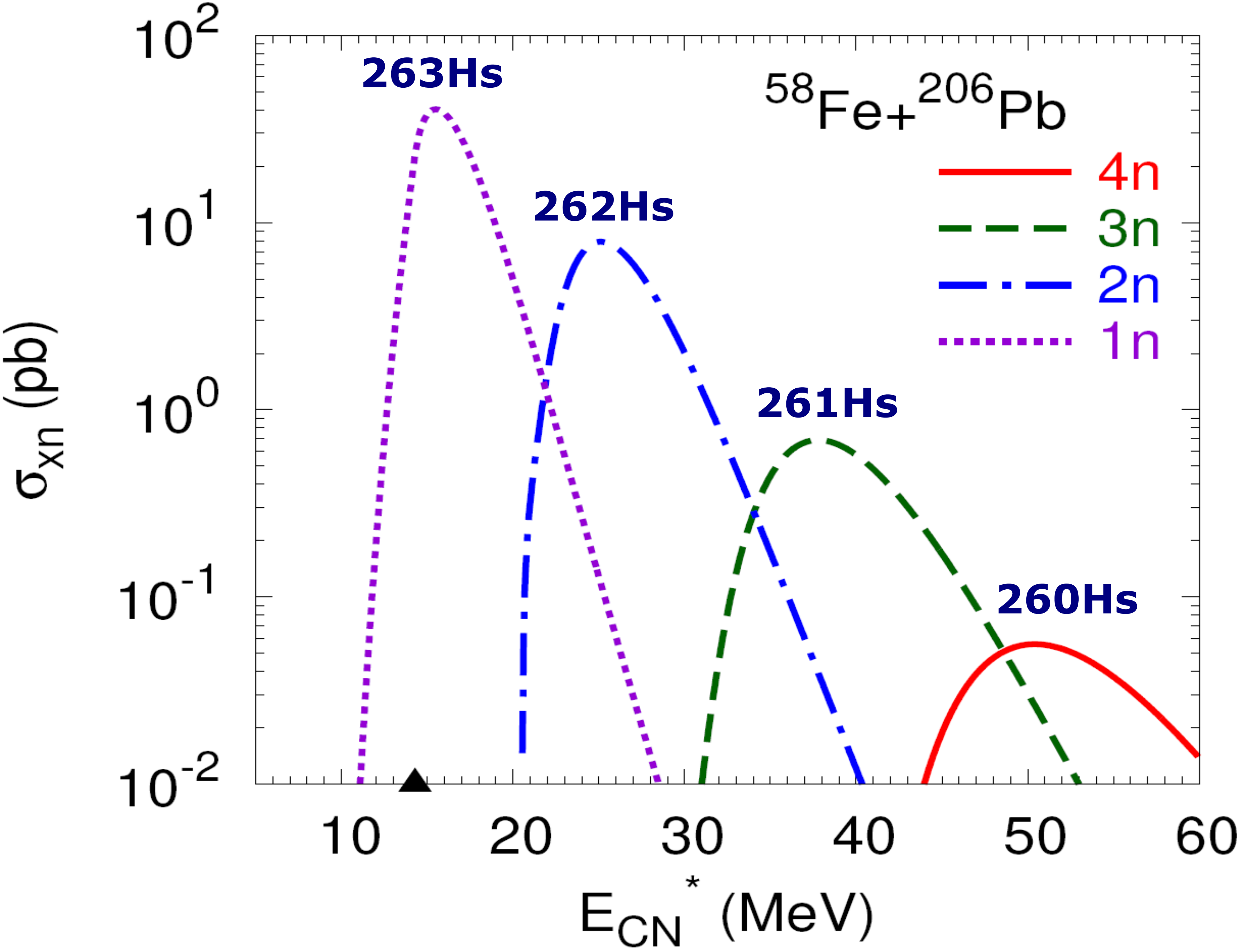

^{54}Cr+^{206}Pb
258Sg
257Sg
4n
3n
2n
1n
σ_{xn} (pb)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

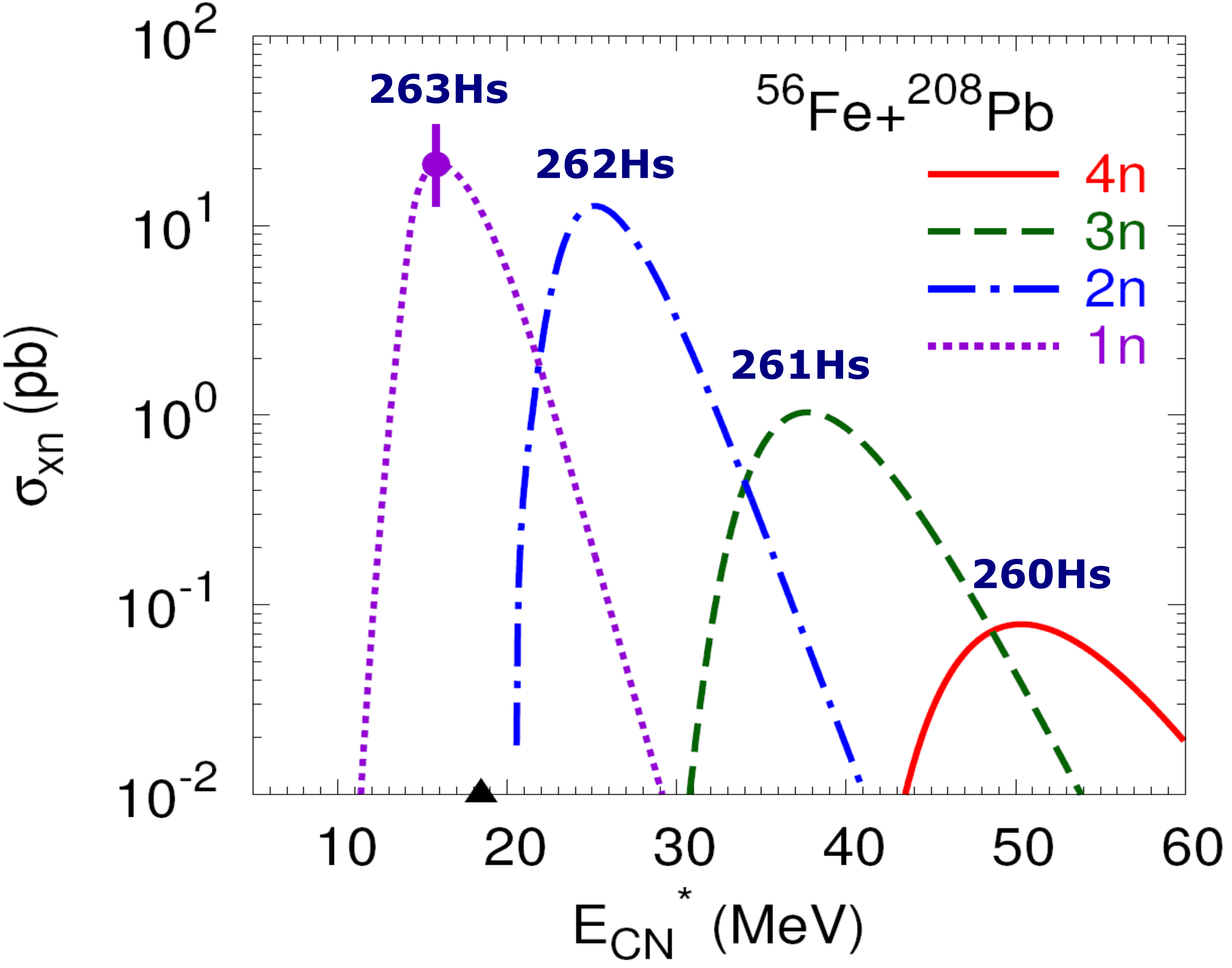

^{52}Cr+^{208}Pb
4n
3n
2n
1n
257Sg
σ_{xn} (pb)
E_{CN}^* (MeV)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10
20
30
40
50
60

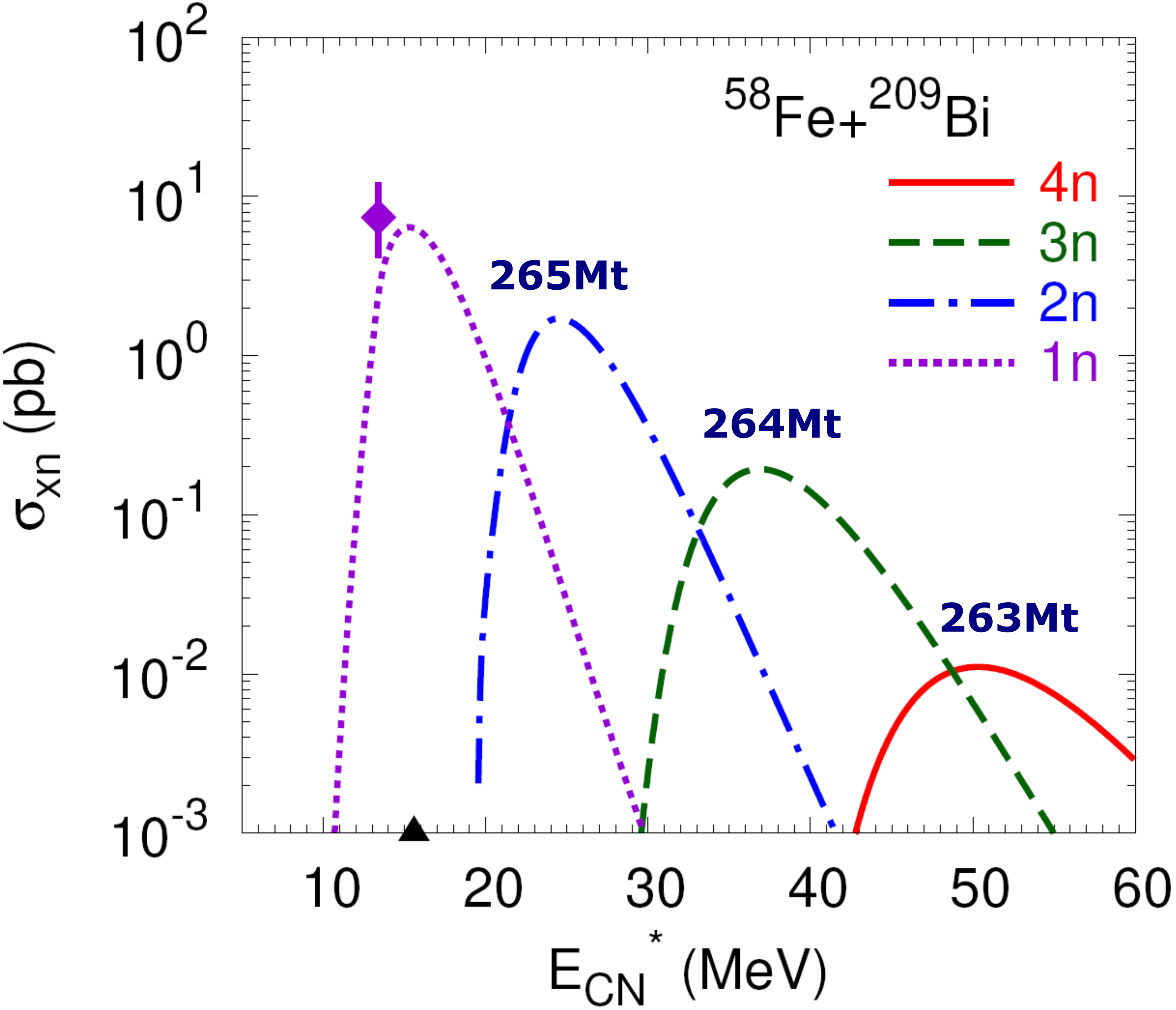

10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^* (MeV)
$^{54}Cr+^{209}Bi$
4n
3n
2n
1n
260Bh

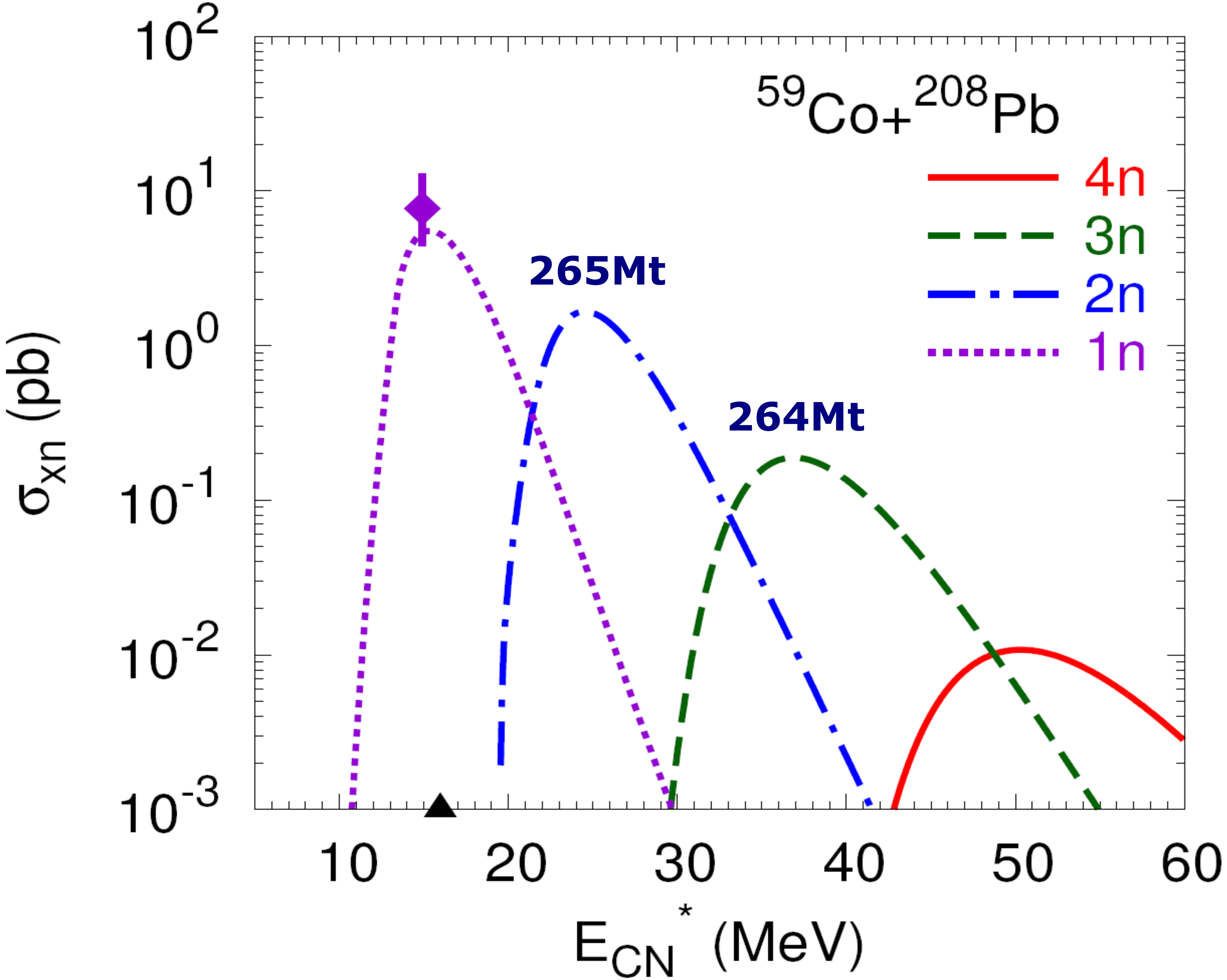

^{55}Mn+^{208}Pb
4n
3n
2n
1n
260Bh
σ_{xn} (pb)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10
20
30
40
50
60
$E_{CN}{}^{*}$ (MeV)

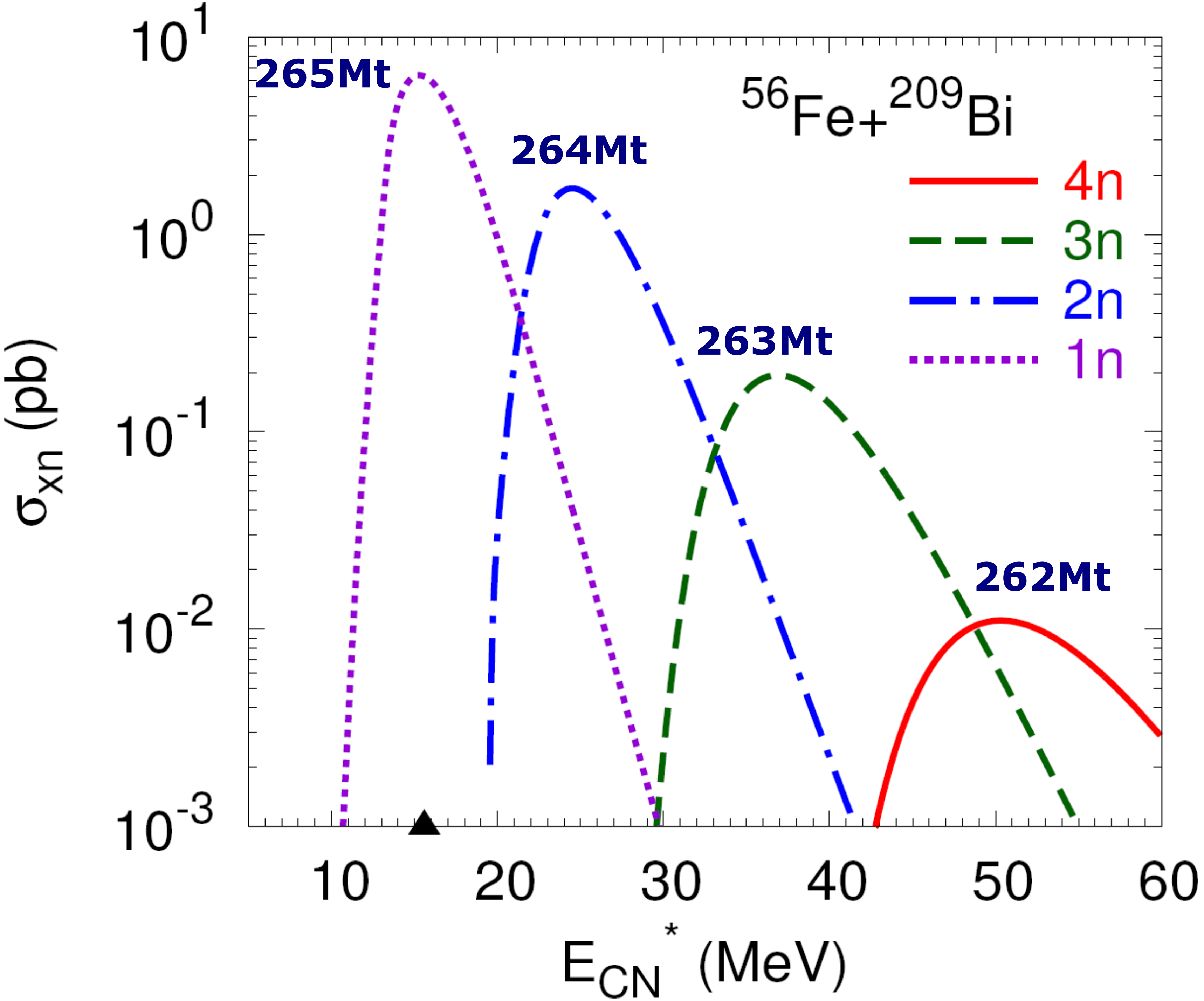

^{58}Fe+^{208}Pb
4n
3n
2n
1n
263Hs
262Hs
σ_{xn} (pb)
E_{CN}^* (MeV)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10
20
30
40
50
60

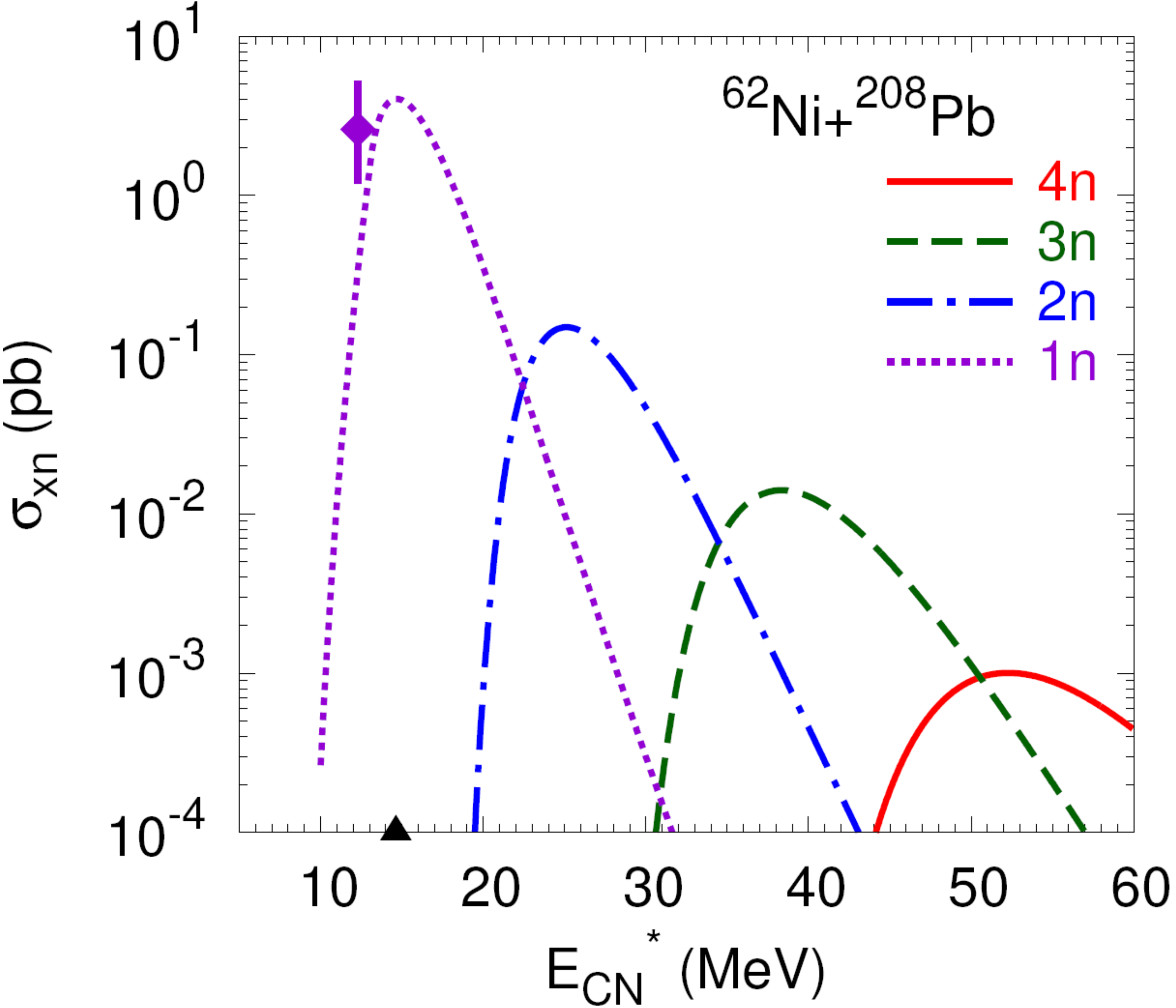

10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^{*} (MeV)
^{58}Fe+^{206}Pb
4n
3n
2n
1n
263Hs
262Hs
261Hs
260Hs

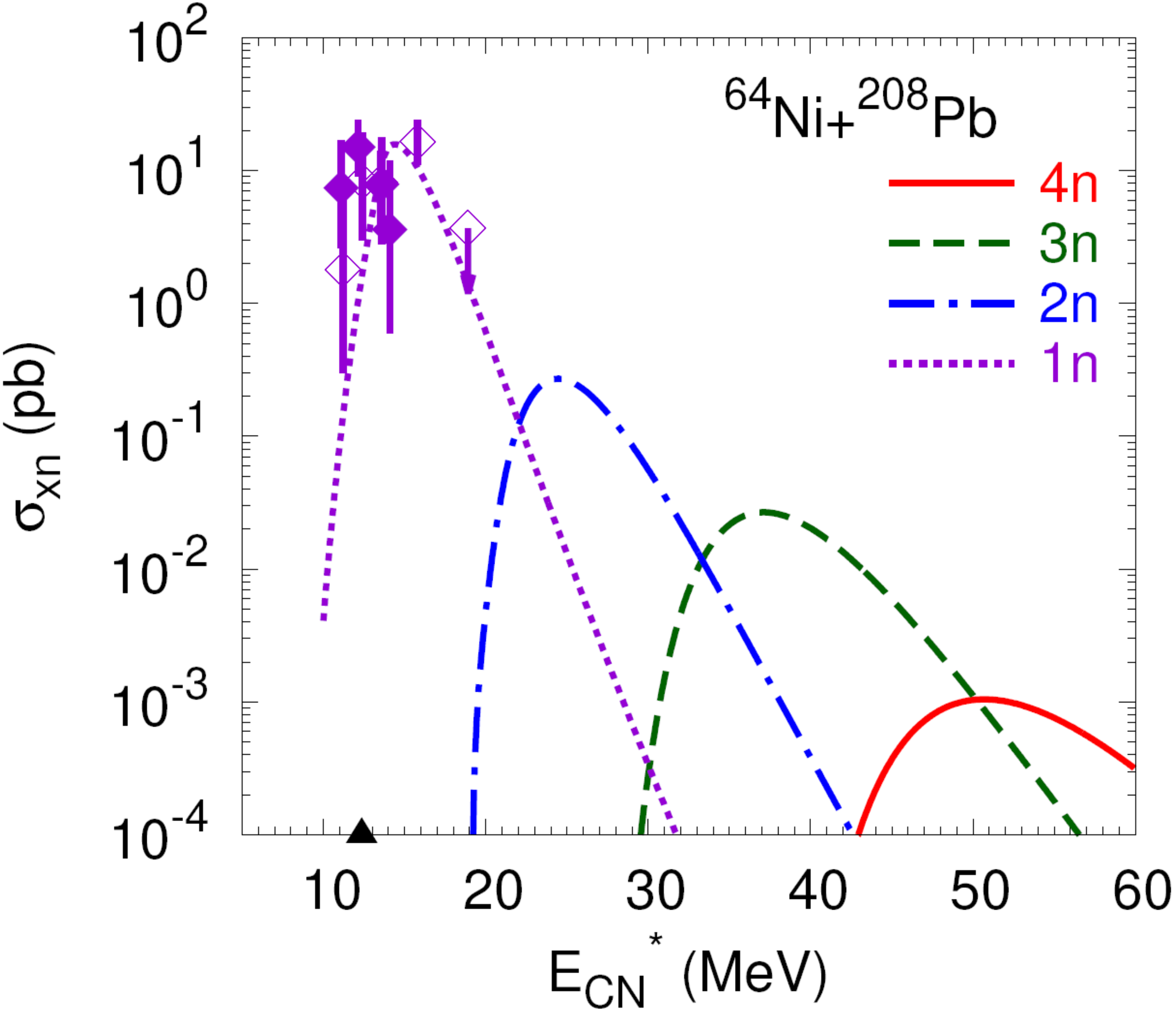

^{56}Fe+^{208}Pb
4n
3n
2n
1n
263Hs
262Hs
261Hs
260Hs
σ_{xn} (pb)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

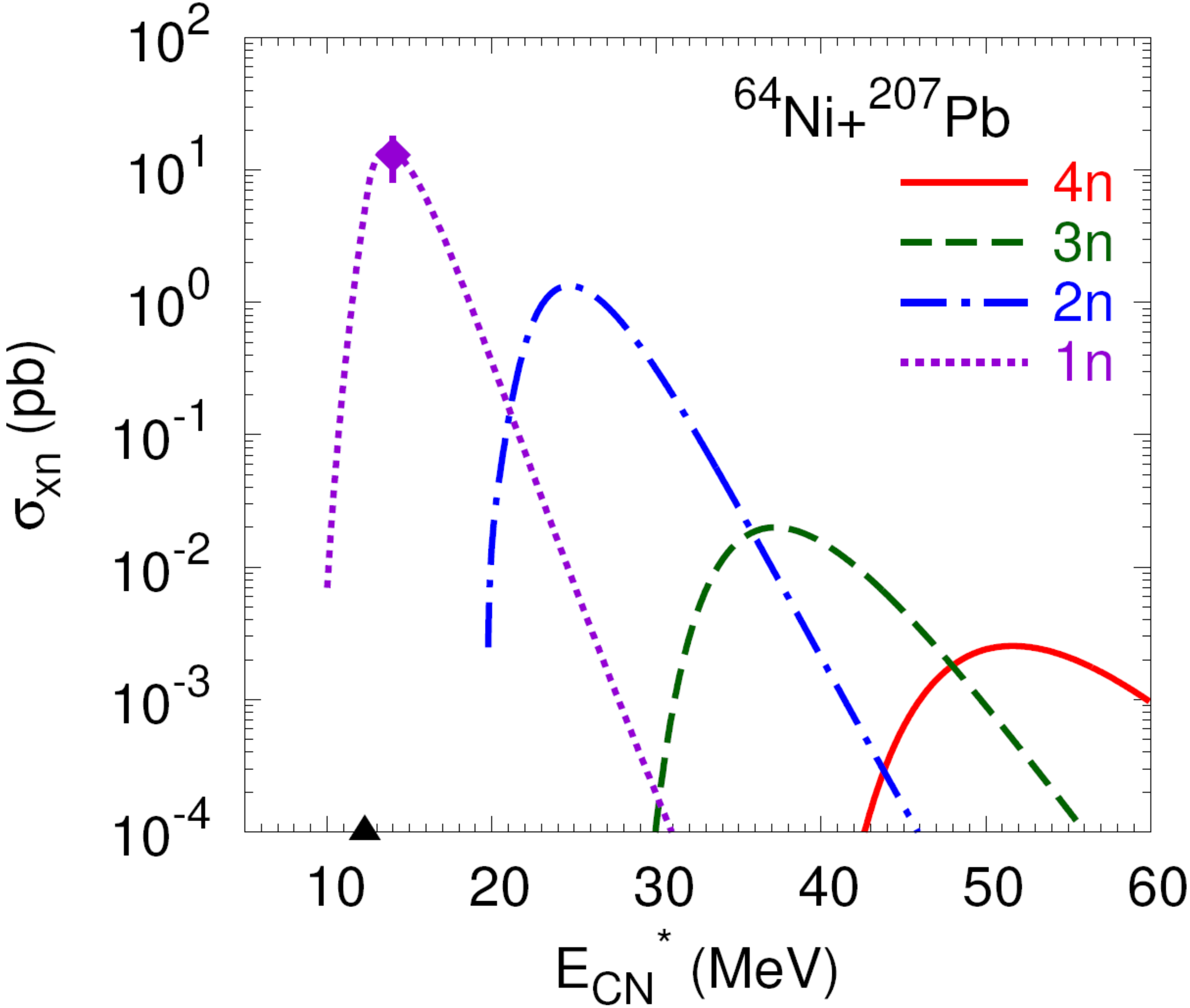

^{58}Fe+^{209}Bi
4n
3n
2n
1n
265Mt
264Mt
263Mt
σ_{xn} (pb)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

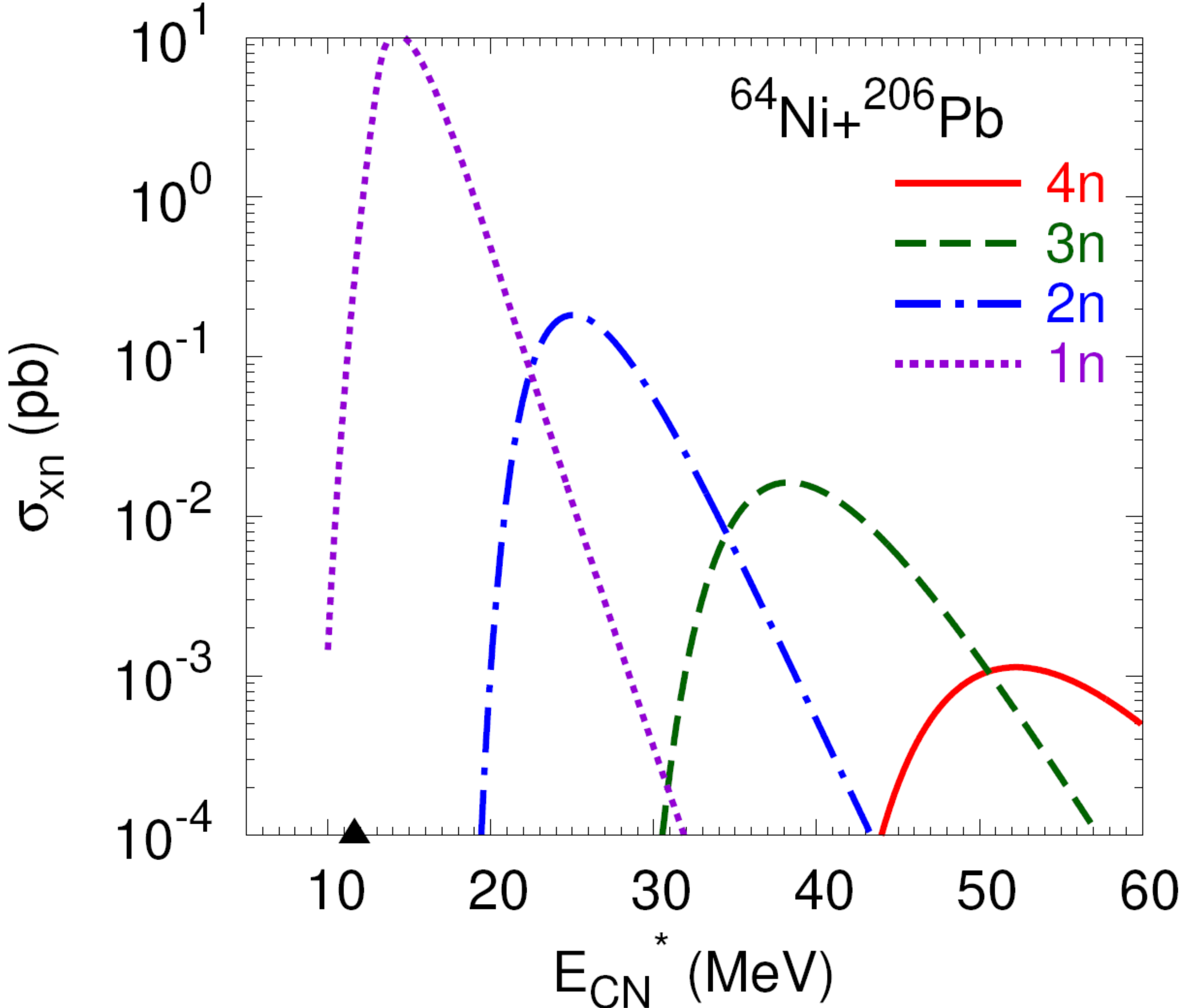

^{59}Co+^{208}Pb
4n
3n
2n
1n
265Mt
264Mt
σ_{xn} (pb)
E_{CN}^{*} (MeV)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10
20
30
40
50
60


265Mt
264Mt
263Mt
262Mt
^{56}Fe+^{209}Bi
4n
3n
2n
1n
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^{*} (MeV)

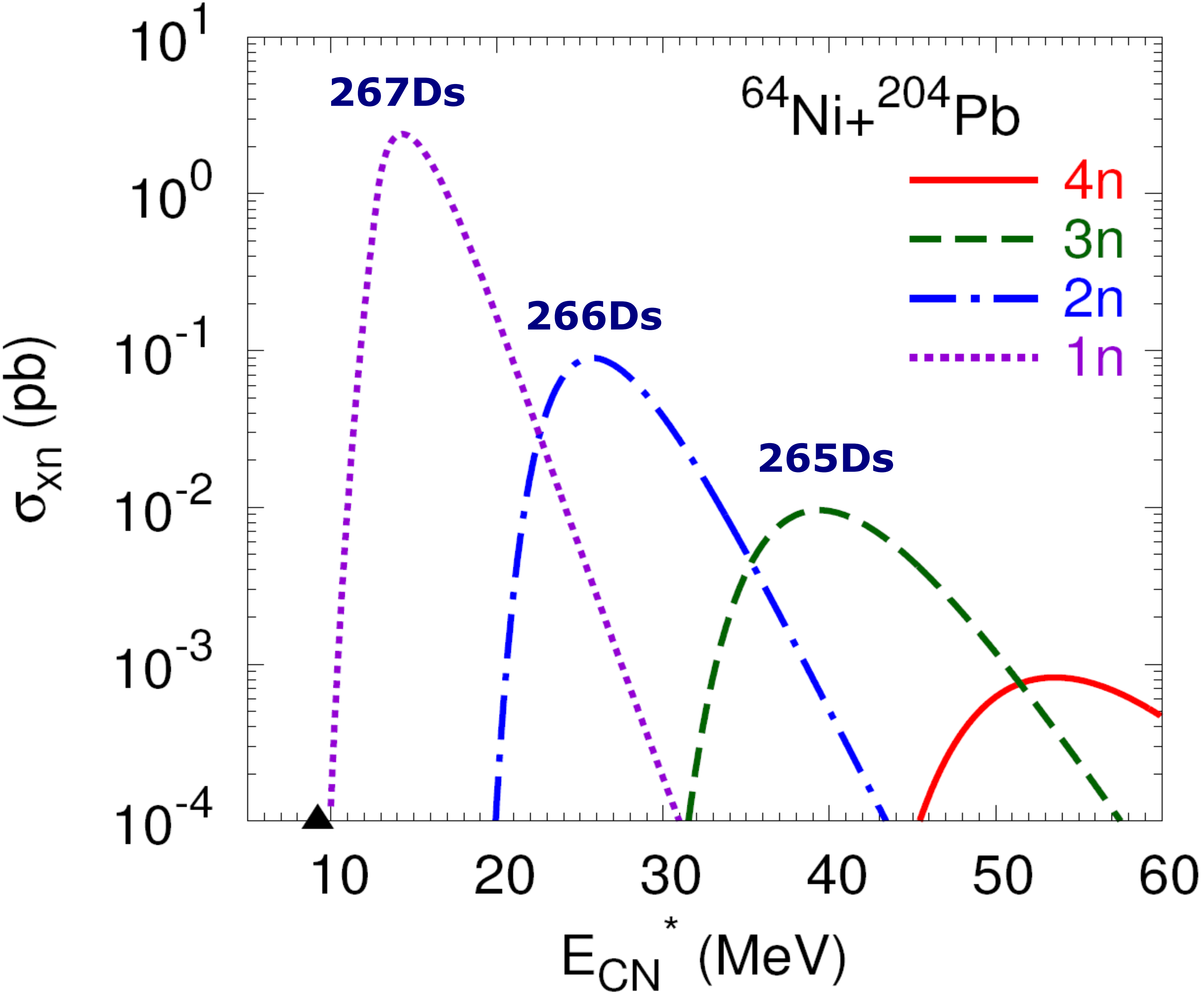

^{62}Ni+^{208}Pb
4n
3n
2n
1n
σ_{xn} (pb)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

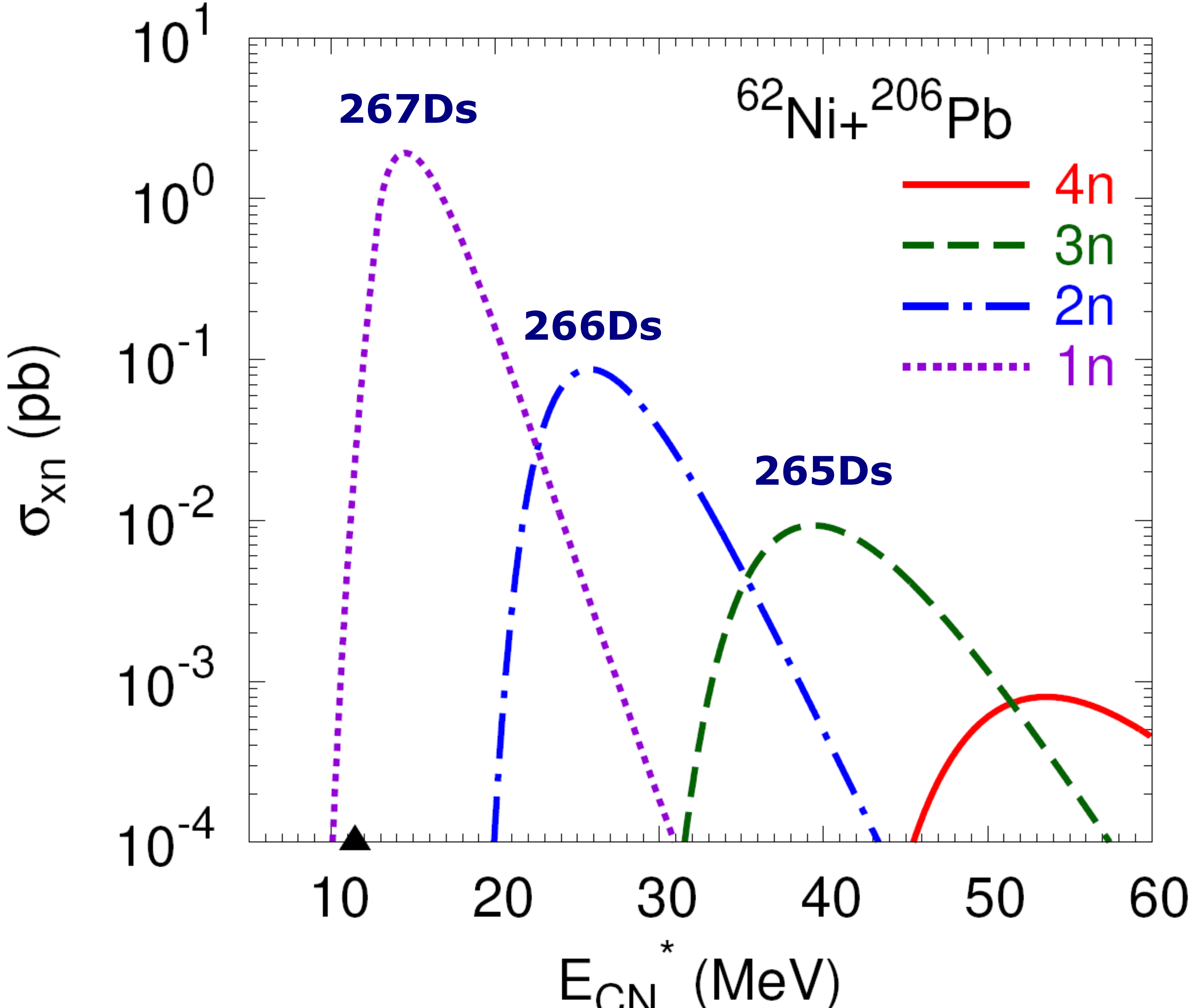

^{64}Ni+^{208}Pb
4n
3n
2n
1n
σ_{xn} (pb)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

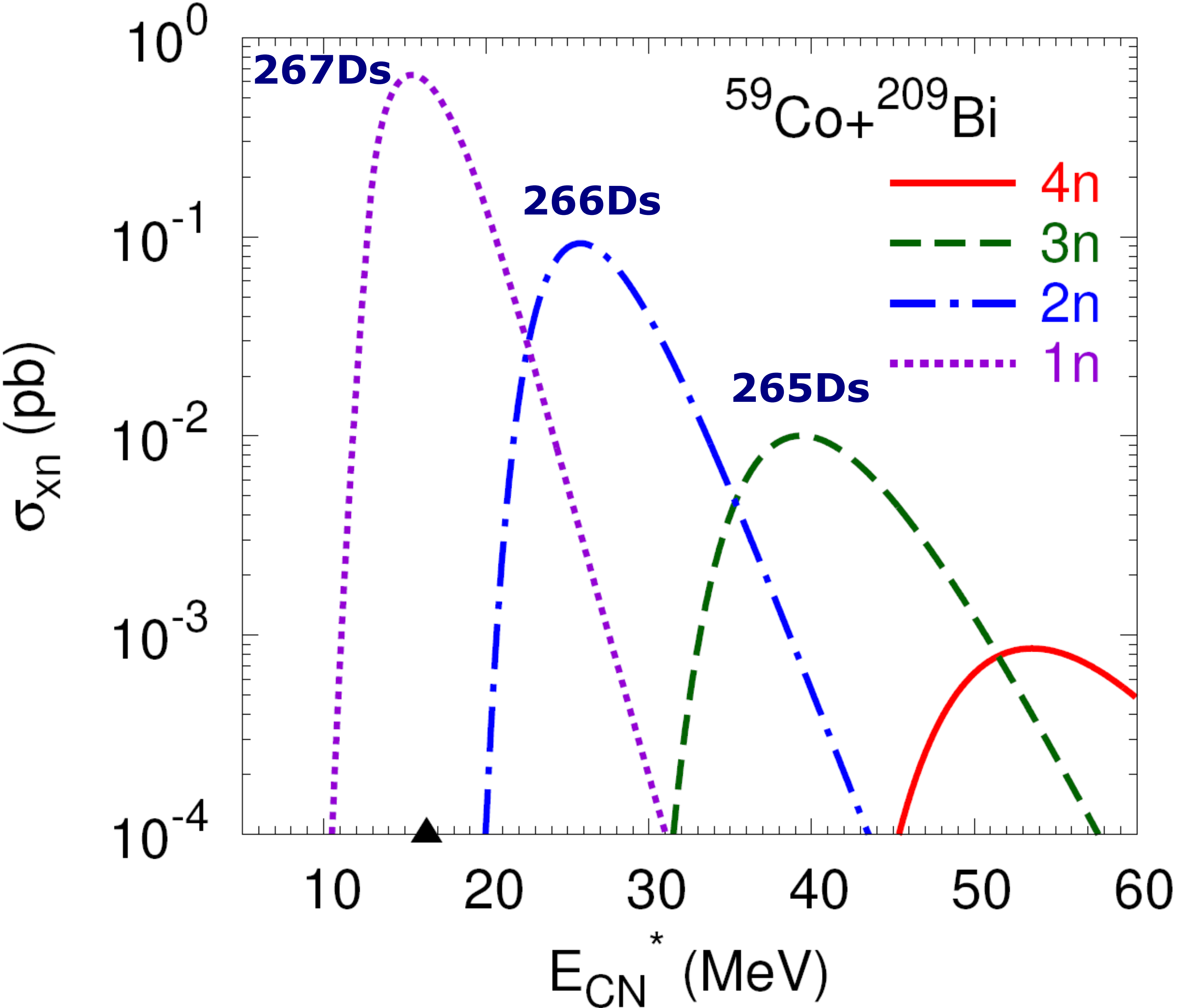

^{64}Ni+^{207}Pb
4n
3n
2n
1n
σ_{xn} (pb)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

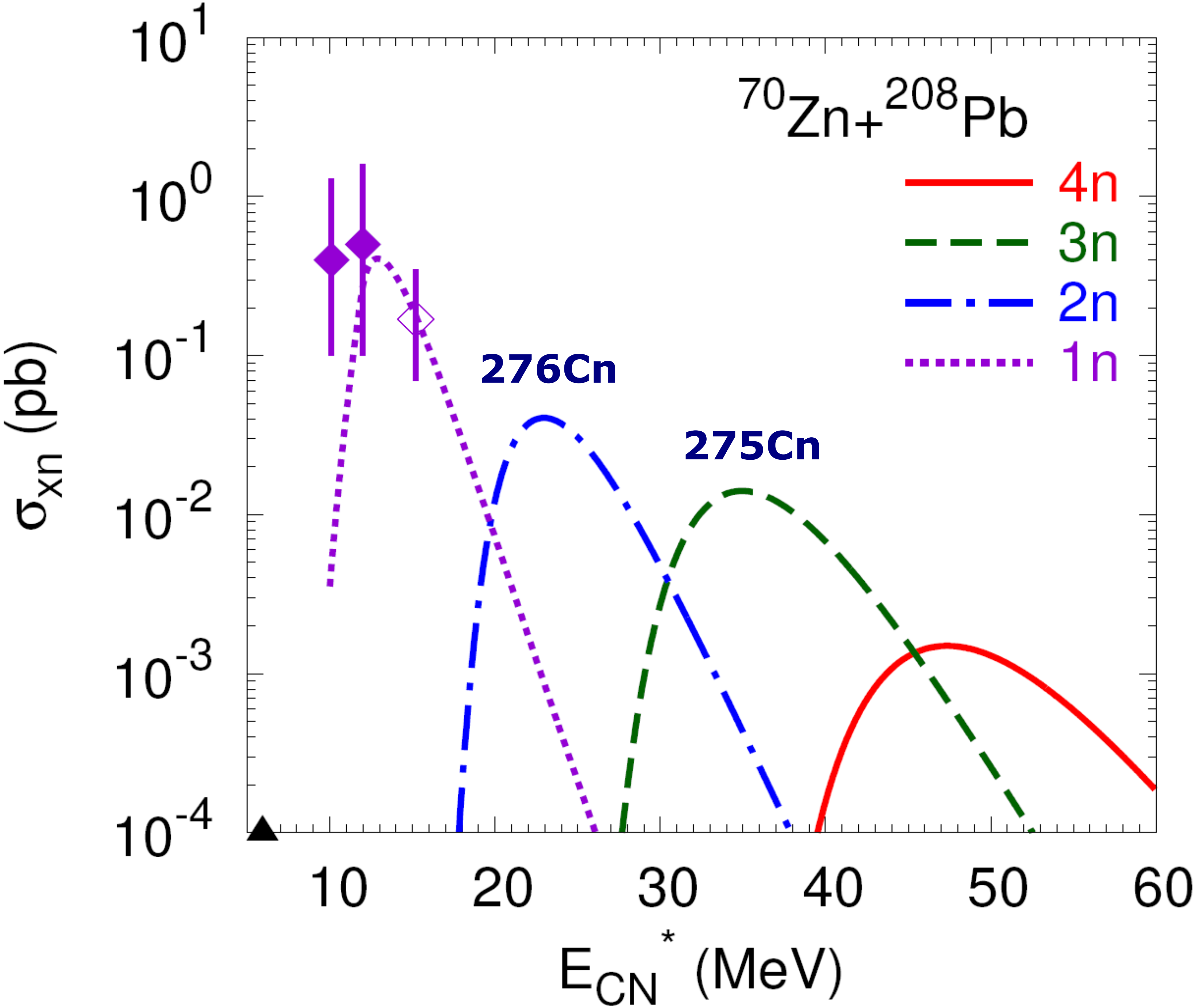


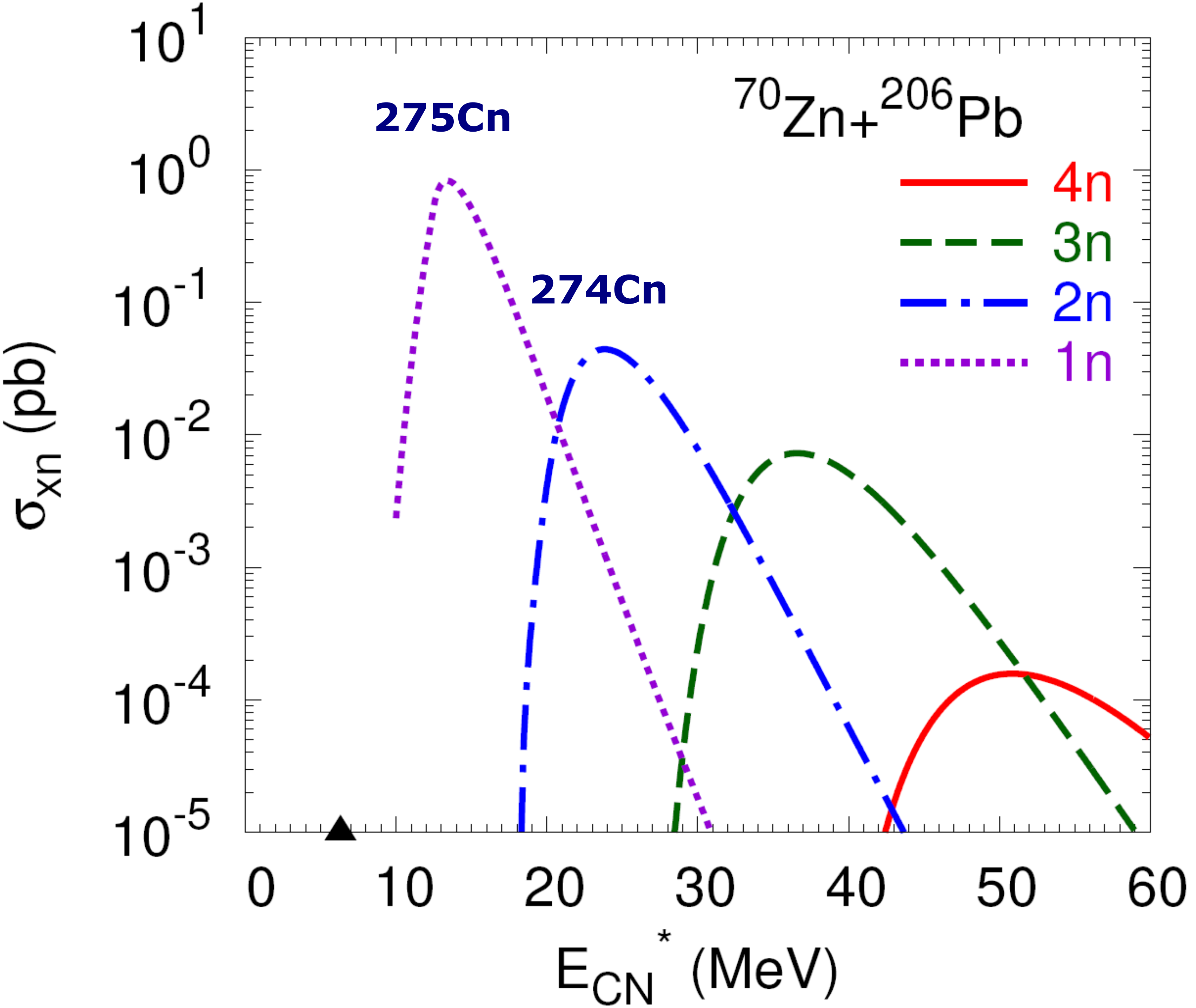
^{64}Ni+^{206}Pb
4n
3n
2n
1n
σ_{xn} (pb)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
E_{CN}^{*} (MeV)


267Ds
266Ds
265Ds
^{64}Ni+^{204}Pb
4n
3n
2n
1n
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^{*} (MeV)

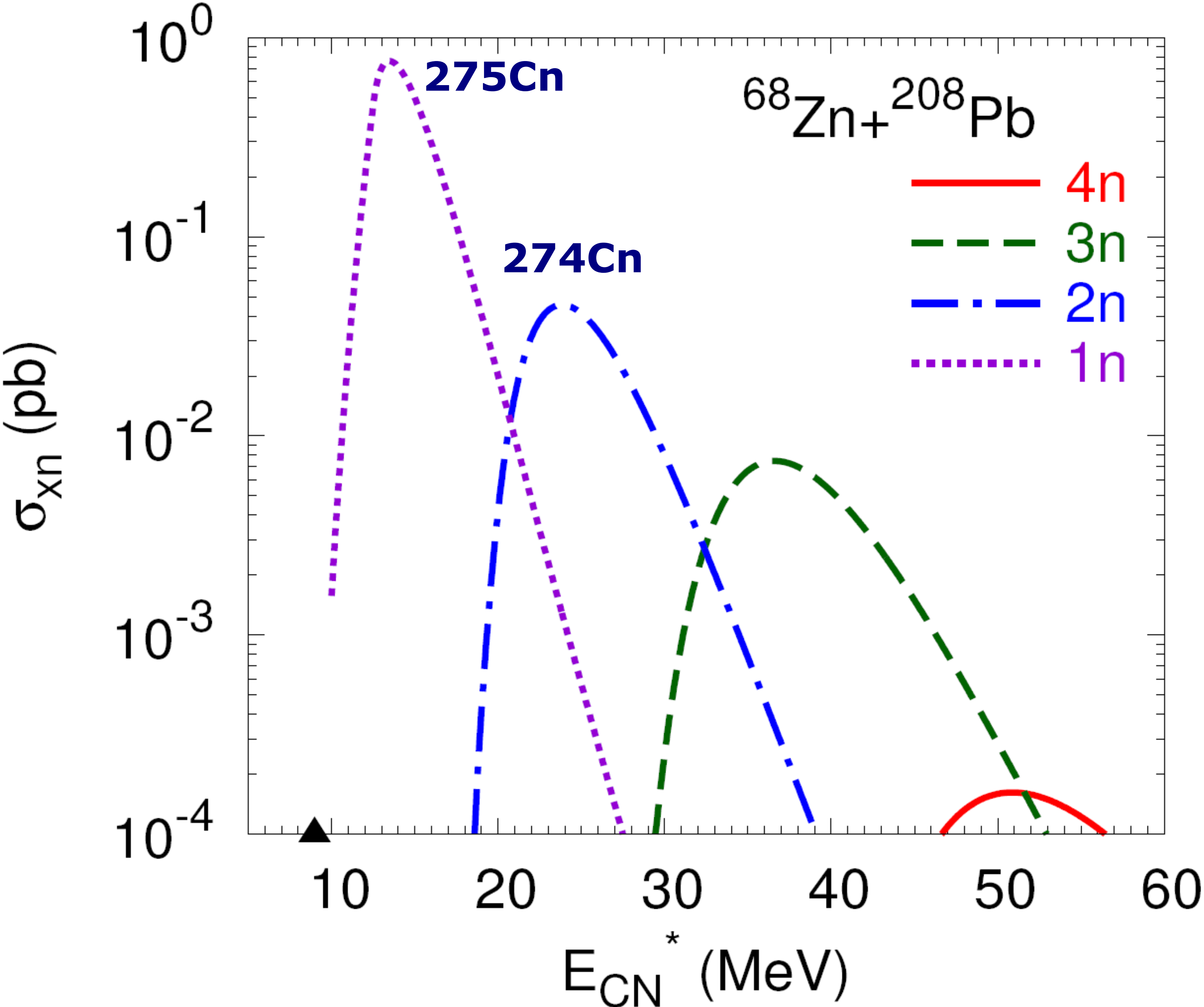

10^1
10^0
10^-1
10^-2
10^-3
10^-4
σ_xn (pb)
10
20
30
40
50
60
E_CN* (MeV)
62Ni+206Pb
4n
3n
2n
1n
267Ds
266Ds
265Ds

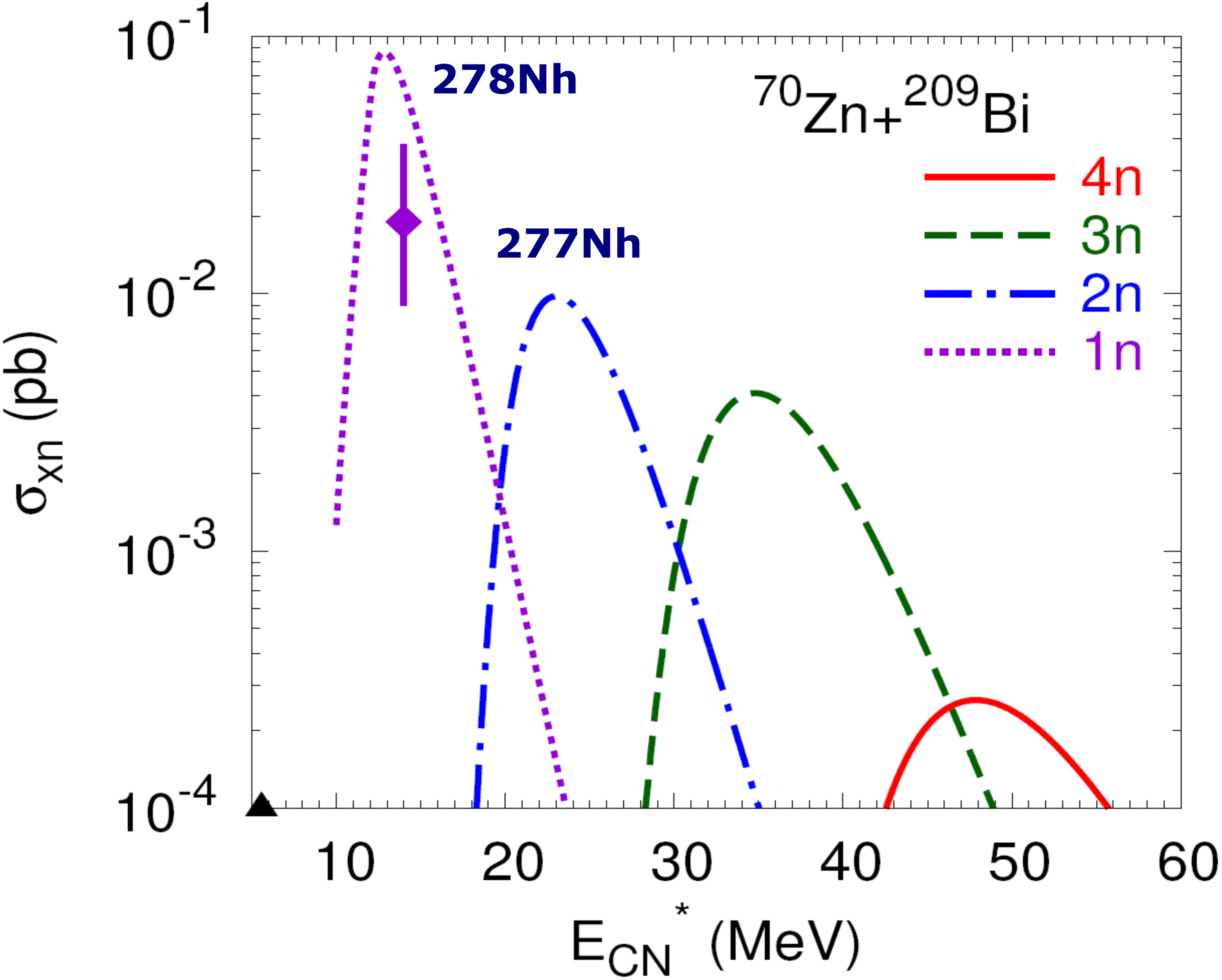

267Ds
266Ds
265Ds
^{59}Co+^{209}Bi
4n
3n
2n
1n
σ_{xn} (pb)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
E_{CN}^{*} (MeV)

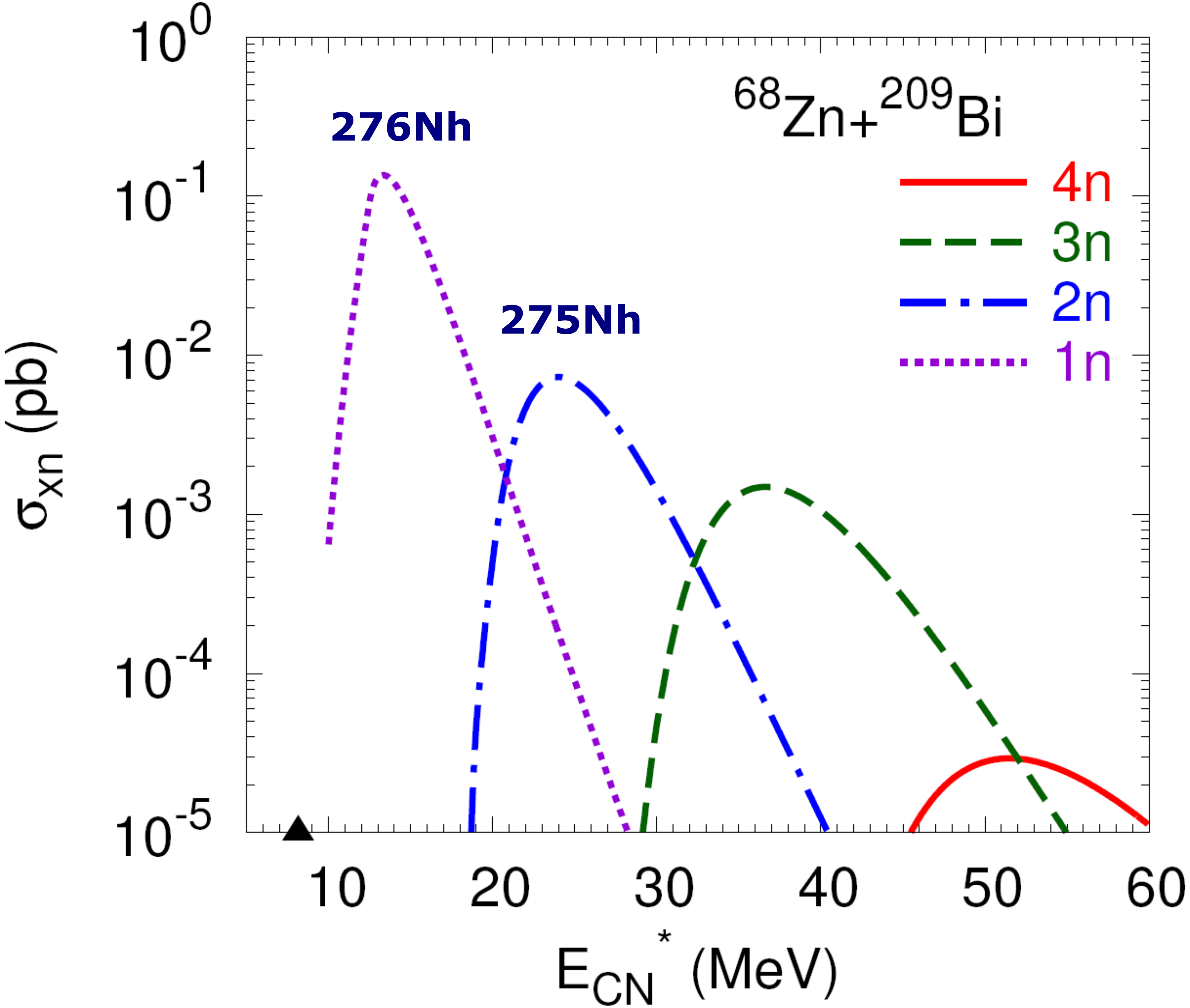

^{70}Zn+^{208}Pb
4n
3n
2n
1n
276Cn
275Cn
σ_{xn} (pb)
E_{CN}^* (MeV)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60

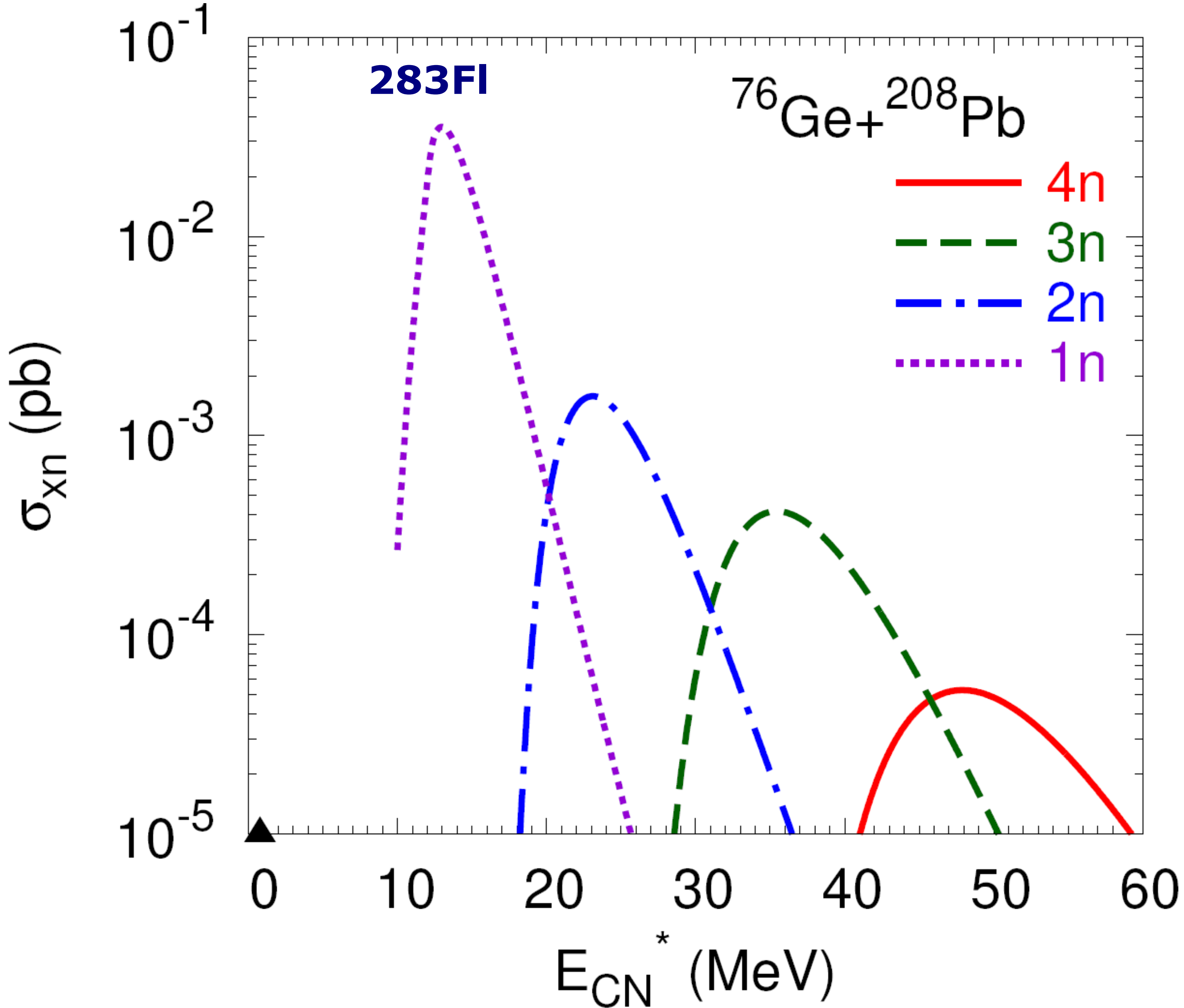


$^{70}Zn+^{206}Pb$
275Cn
274Cn
4n
3n
2n
1n
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
σ_{xn} (pb)
0
10
20
30
40
50
60
E_{CN}^{*} (MeV)


^{68}Zn+^{208}Pb
4n
3n
2n
1n
275Cn
274Cn
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^{*} (MeV)


^{70}Zn+^{209}Bi
278Nh
277Nh
4n
3n
2n
1n
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
σ_{xn} (pb)
E_{CN}^{*} (MeV)


^{68}Zn+^{209}Bi
276Nh
275Nh
4n
3n
2n
1n
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
σ_{xn} (pb)
10
20
30
40
50
60
E_{CN}^{*} (MeV)


283Fl
^{76}Ge+^{208}Pb
4n
3n
2n
1n
σ_{xn} (pb)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
50
60
E_{CN}^* (MeV)

$^{48}Ca+^{239}Pu \rightarrow ^{283}Fl+4n$

$^{76}Ge+^{208}Pb \rightarrow ^{283}Fl+1n$

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

$^{48}Ca+^{233}U \rightarrow ^{277}Cn+4n$

$^{70}Zn+^{208}Pb \rightarrow ^{277}Cn+1n$

Summary

1. **Using the cold fusion reactions in xn-channels, one can directly produce and study the neutron-deficient SHN in Factory**

2. **For future, population of the yrast rotational band of SHN produced in cold fusion** ($^{50}Ti+^{208}Pb \rightarrow ^{256}Rf+2n$)

Dependence of fission barrier on spin

$$B_f(E^*_{CN}, J) = B_f^{LD}(J) + B_f^{M}(E^*_{CN} = 0)$$

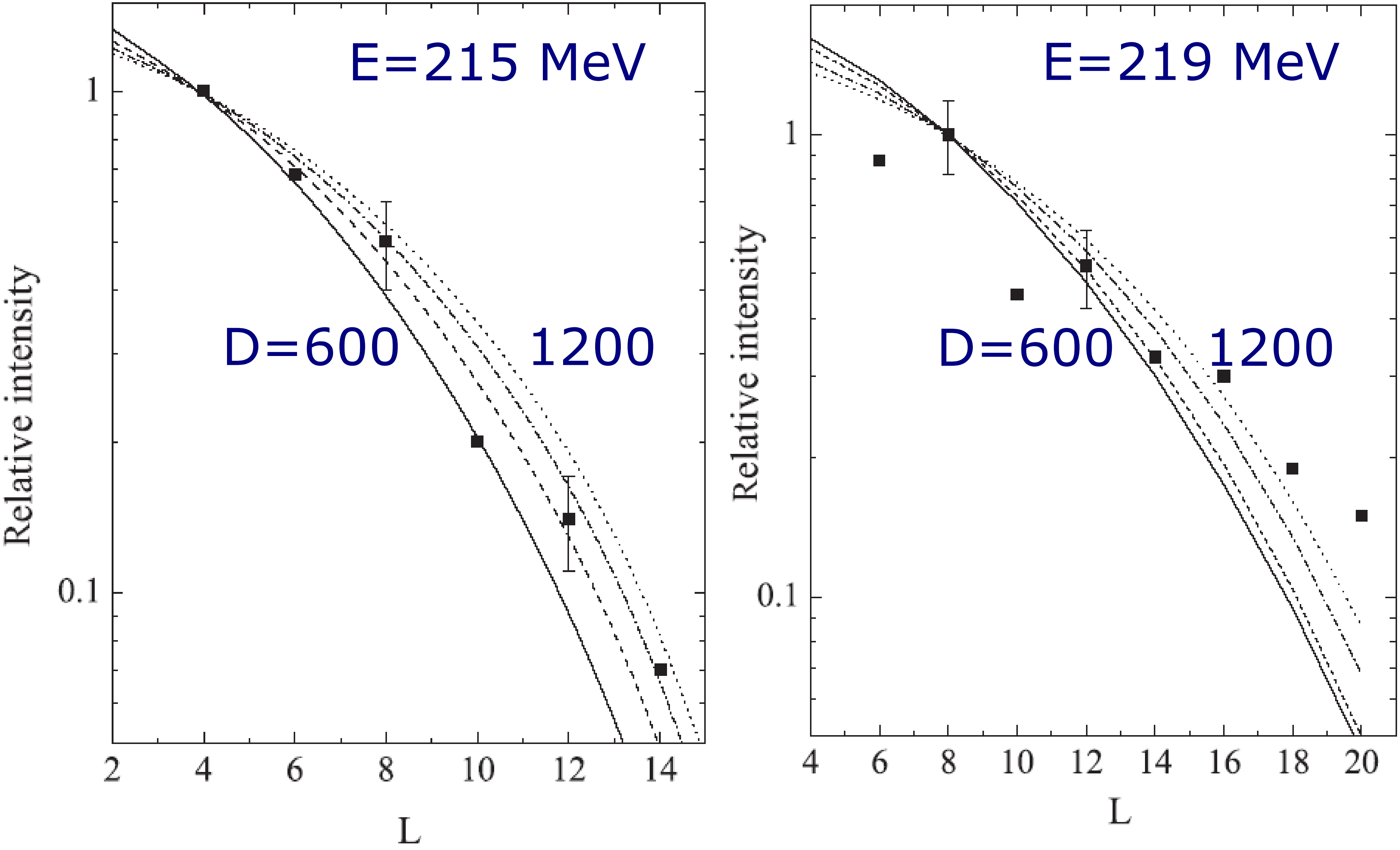
$$\mathrm{x}\ \exp[-E^*_{CN}(J)/E_D]\exp[-J(J+1)/D]$$

Damping parameter D from exper. data

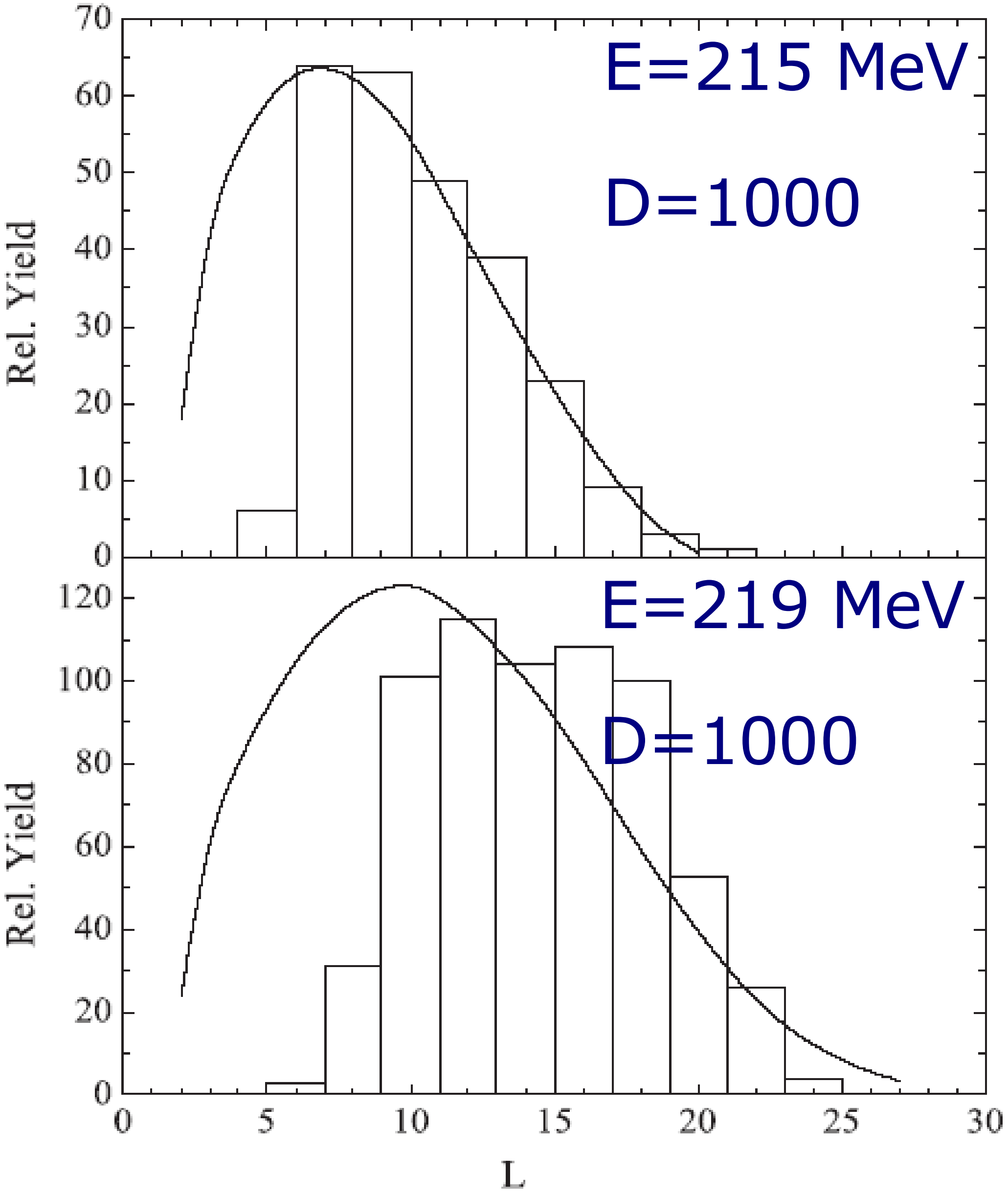
$$E_D = \alpha_0 A^{4/3}/a,$$

where $\alpha_0 = 0.4.$

$^{48}Ca+^{208}Pb \rightarrow ^{254}No+2n$

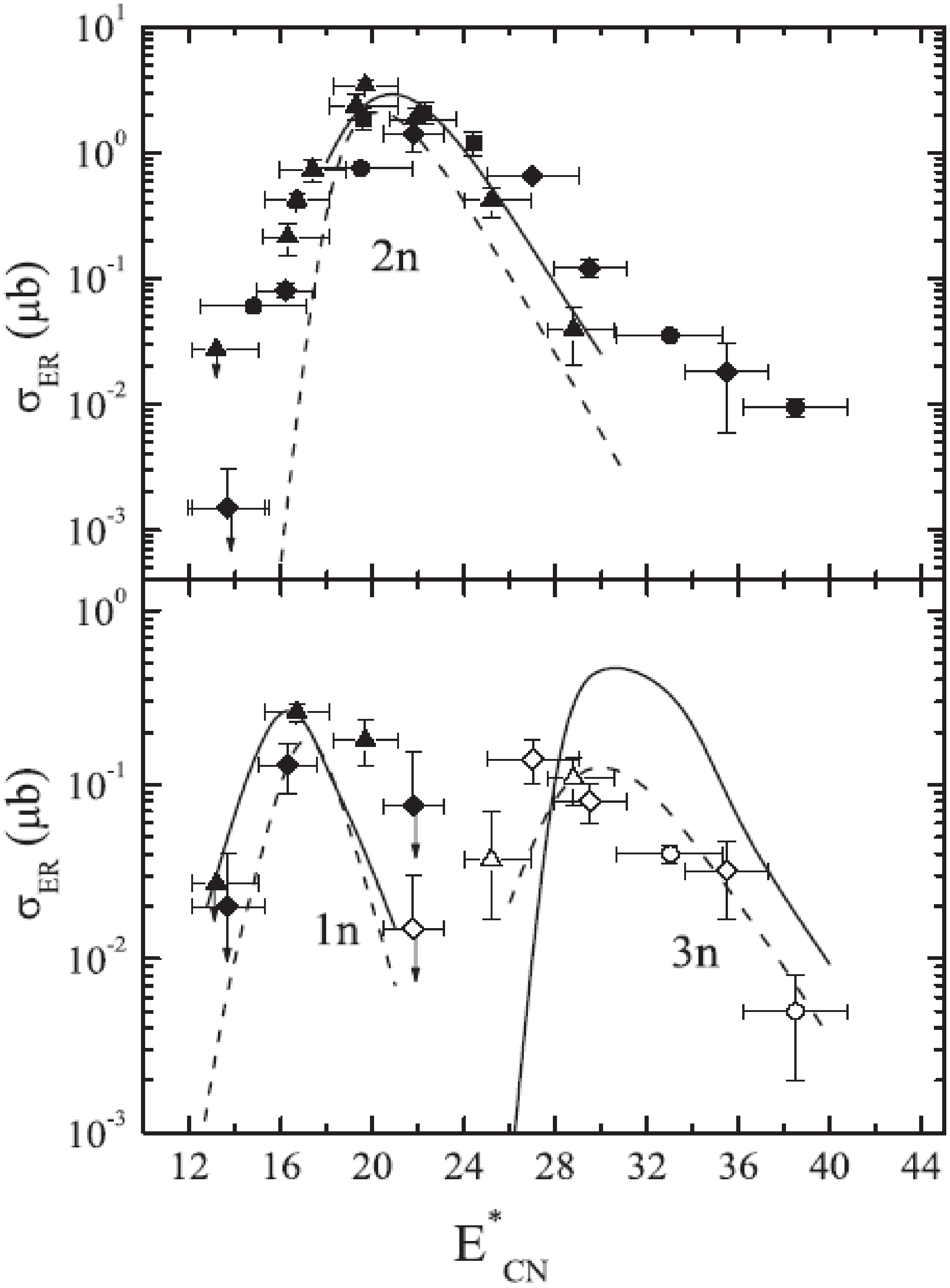


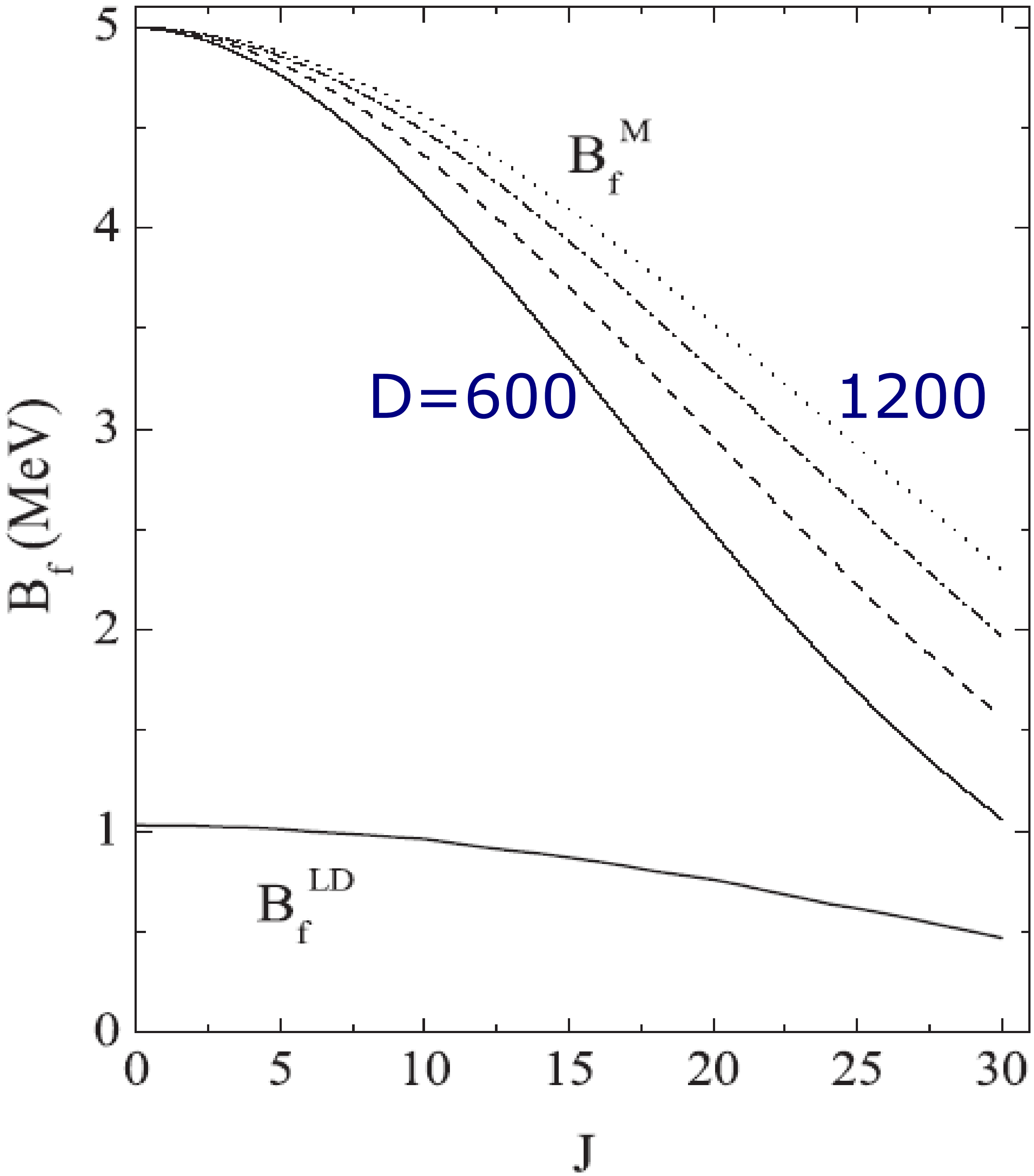
$^{48}Ca+^{208}Pb \rightarrow ^{254}No+2n$



^{48}Ca+^{208}Pb

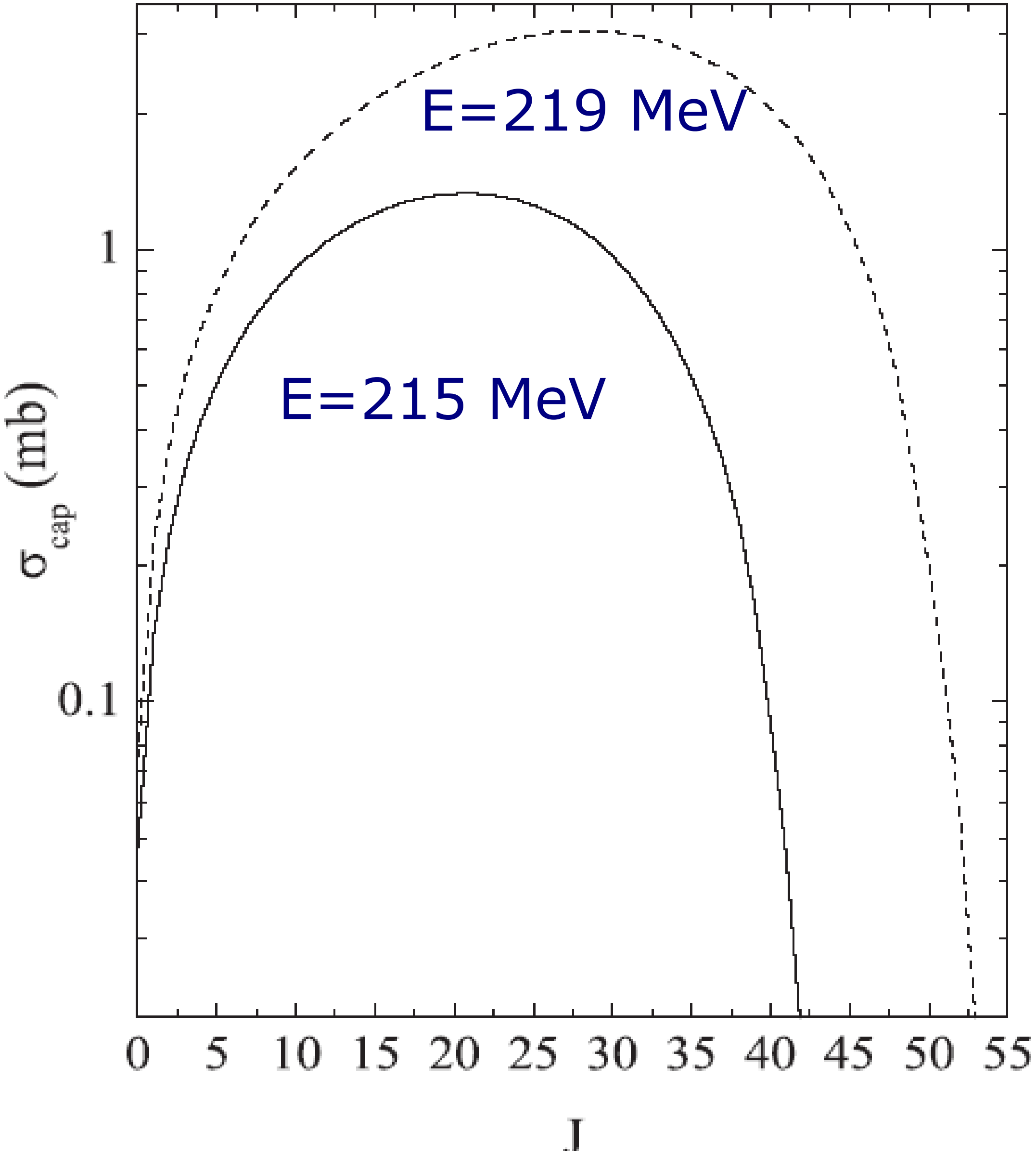
D=1000

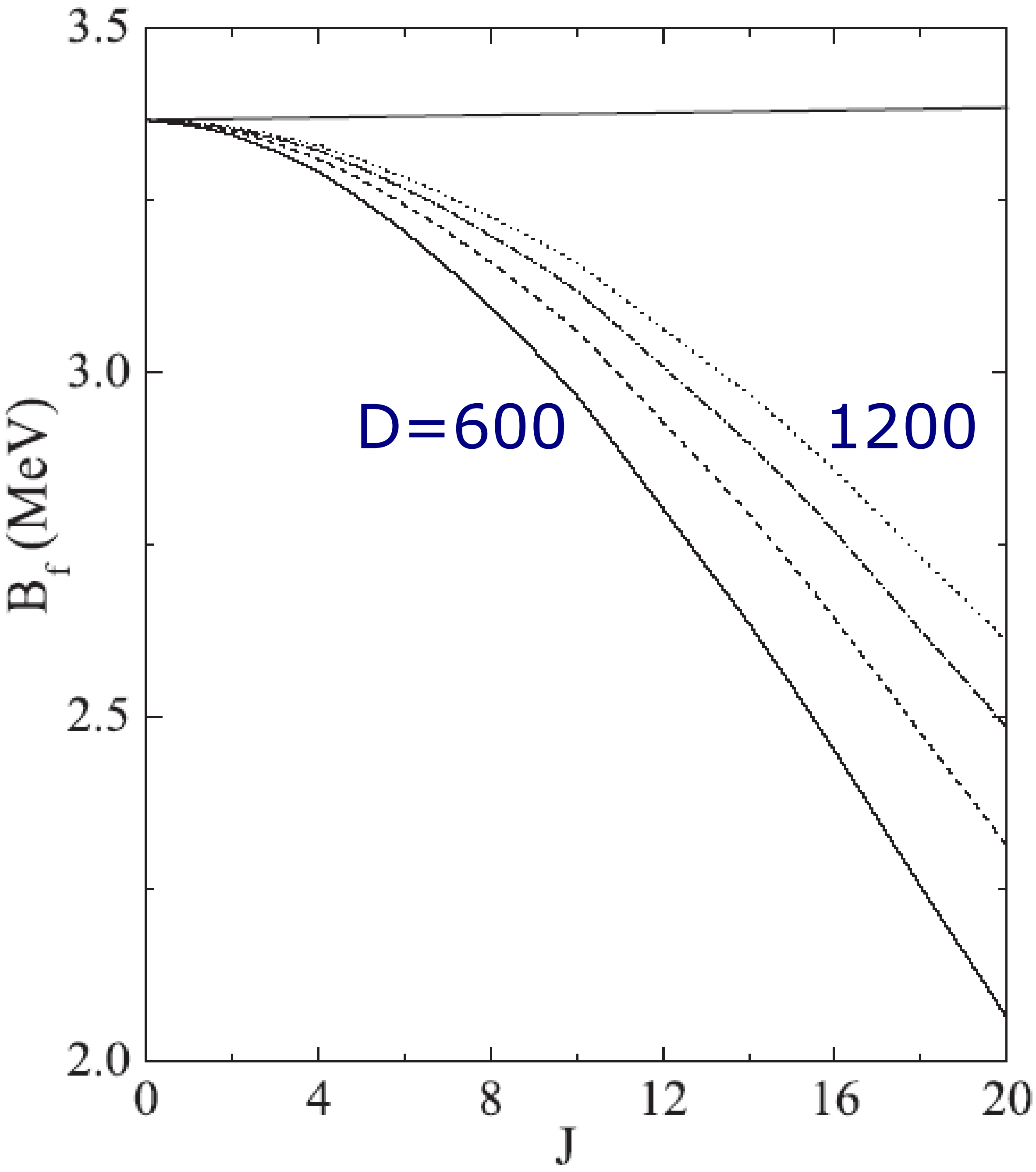




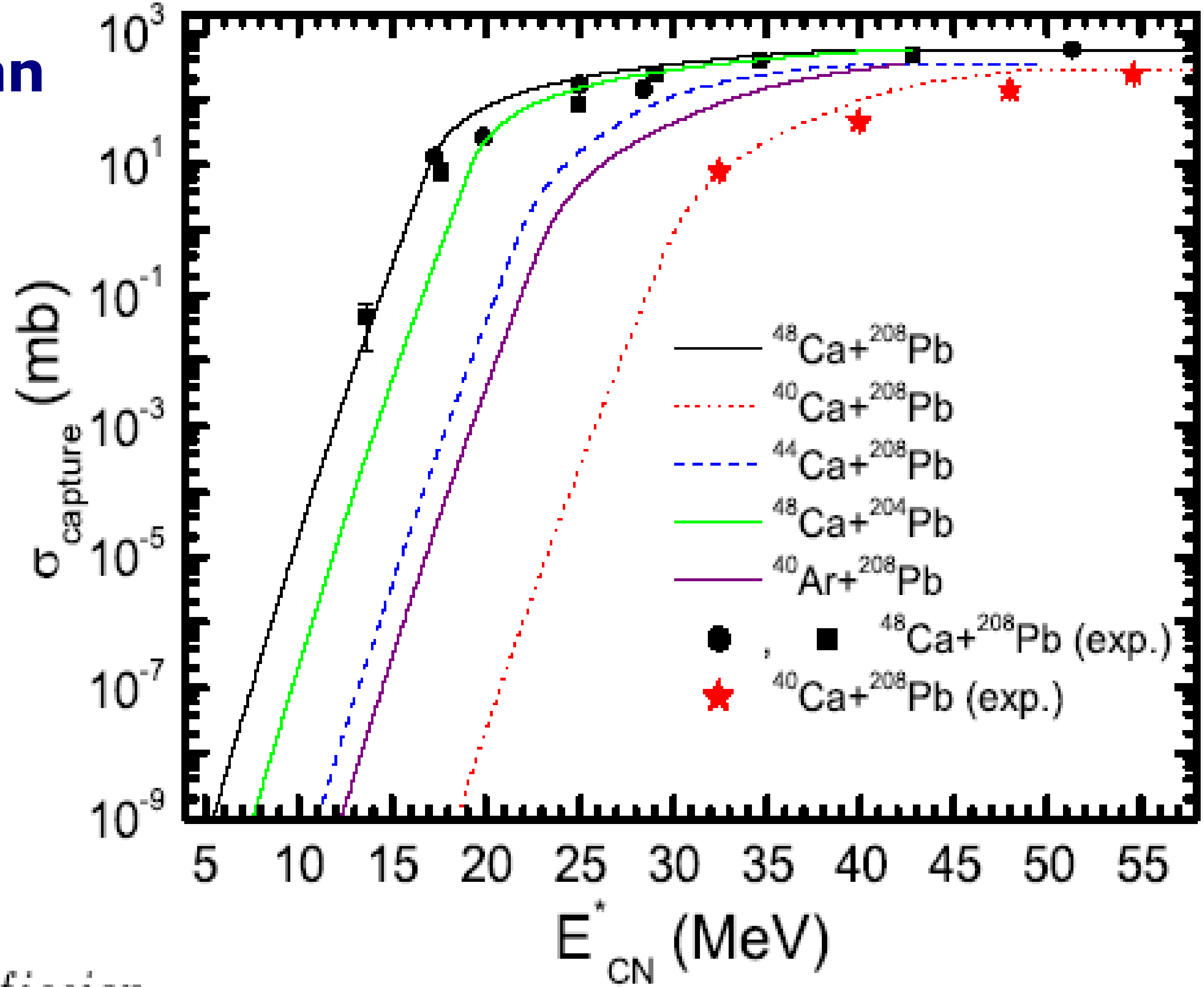
B_f^M
D=600
1200
B_f^{LD}
B_f (MeV)
J
0
1
2
3
4
5
0
5
10
15
20
25
30

^{48}Ca+^{208}Pb


E=219 MeV
E=215 MeV
1
0.1
σ_{cap} (mb)
0
5
10
15
20
25
30
35
40
45
50
55
J


3.5
3.0
2.5
2.0
B_f (MeV)
0
4
8
12
16
20
J
D=600
1200

V.V.Sargsyan



$$P_{CN} \approx \frac{\sigma_{fission}}{\sigma_{capture}}$$

This allows us to obtain an access to the isotopes which are unreachable in other reactions due to the lack of proper projectile-target combinations

A weak drop of the cross section is due to

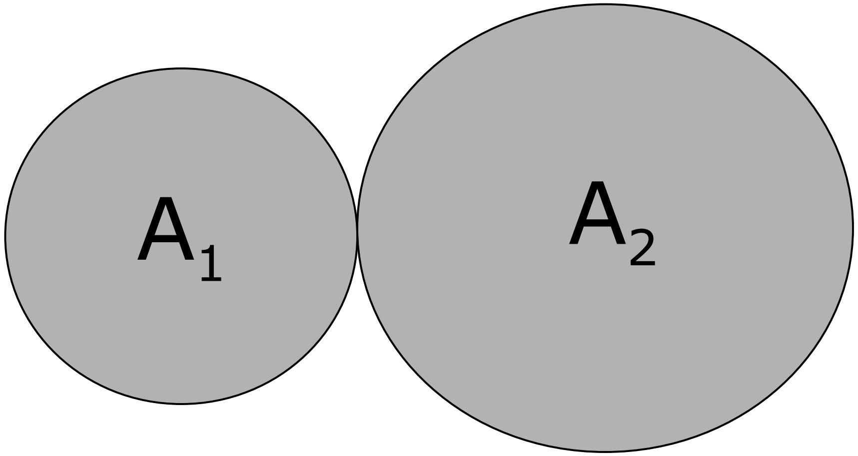
1. the interplay of fusion and survival probabilities
2. a weak change of the difference between the fission barrier height and neutron binding energy at 1-4 steps of n-evaporation

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

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 $A_2 = 0$