Fusion dynamics in reactions forming heavy elements

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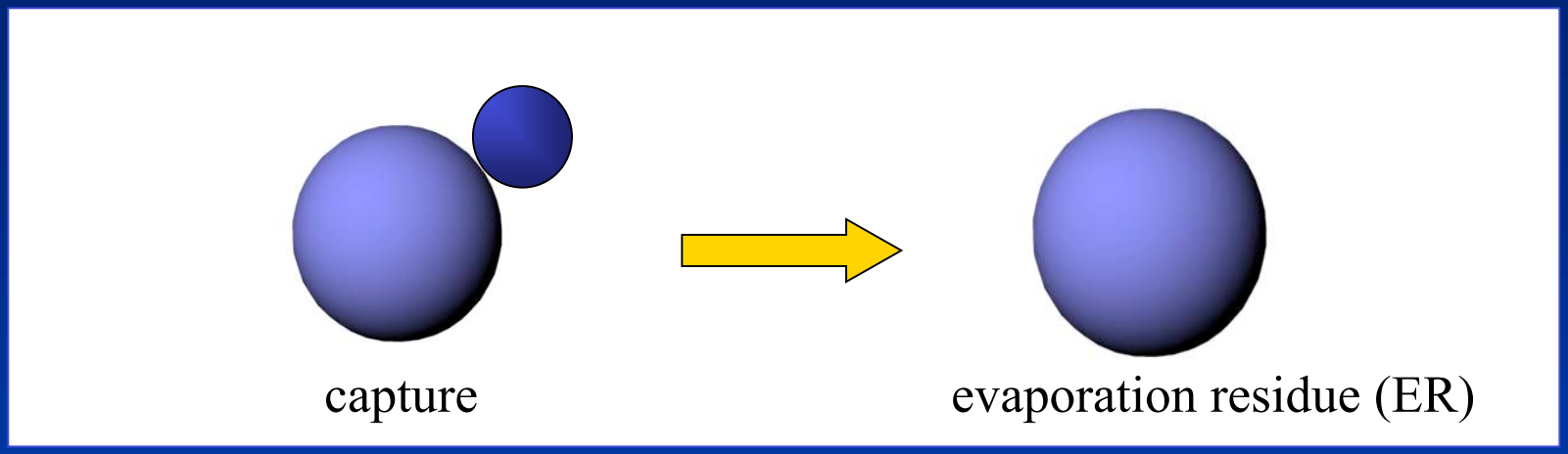


Yield of ER $\propto$ $P_{capture} \times P_{compact\ nucleus} \times P_{survival}$

capture probability

× probability of compact nucleus formation (quasi fission competition)

× survival of ER against fission competition

(Compact = well inside unconditional fission saddle-point elongation)

Study of dynamics of evolution to compact C.N.

- Experimental method: “cross-bombardments”
  - same C.N., different projectile/target
  - match C.N. properties: E*, l
  - look for differences in ER yields associated with different entrance channels -- P_{CN}

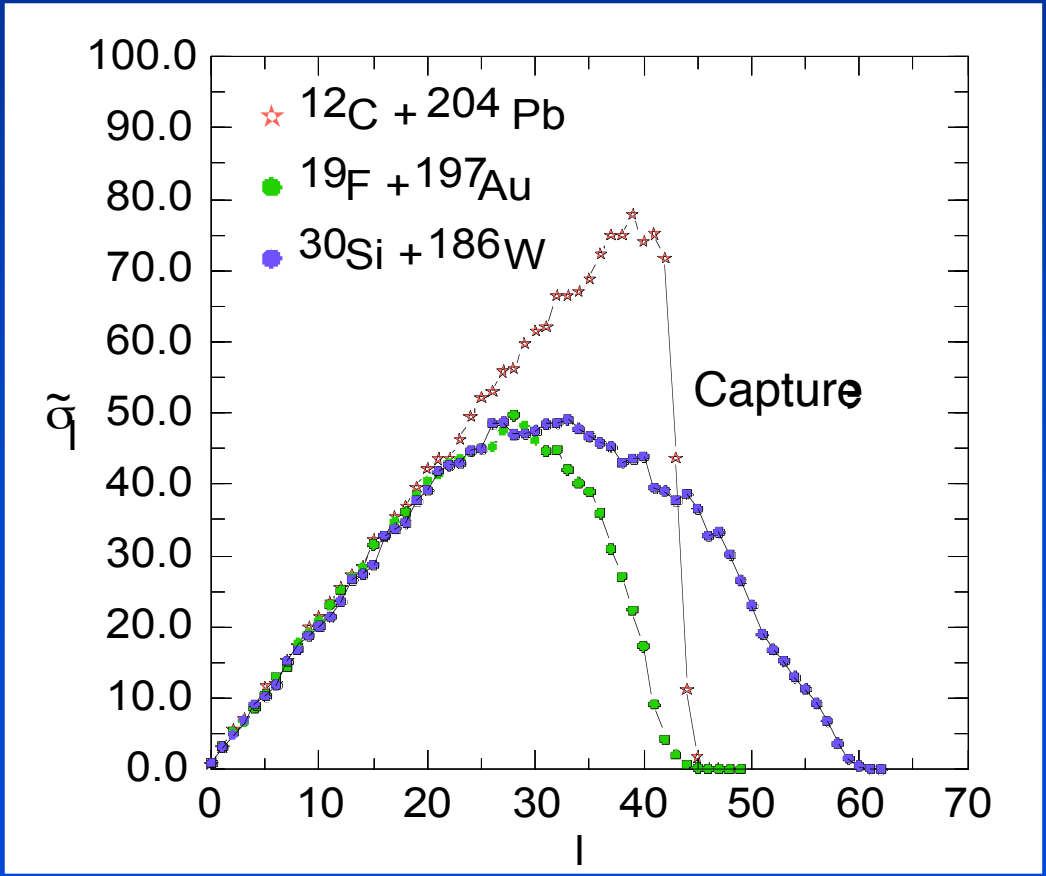
$$\sigma_{Capture}(E) = \pi \lambda^2 \sum_{l=0}^{\infty} (2l+1) T_l(E)$$

$$\tilde{\sigma}_{Capture}(E) = \sum_{l=0}^{\infty} (2l+1) T_l(E)$$

$\tilde{\sigma}$: reduced cross-section

(dimensionless)

Matching E*

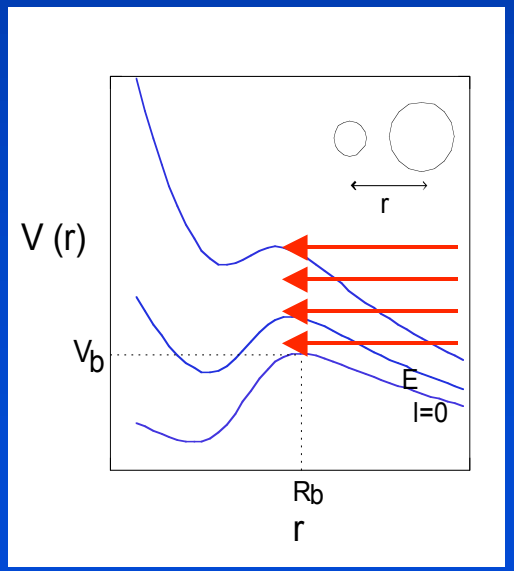


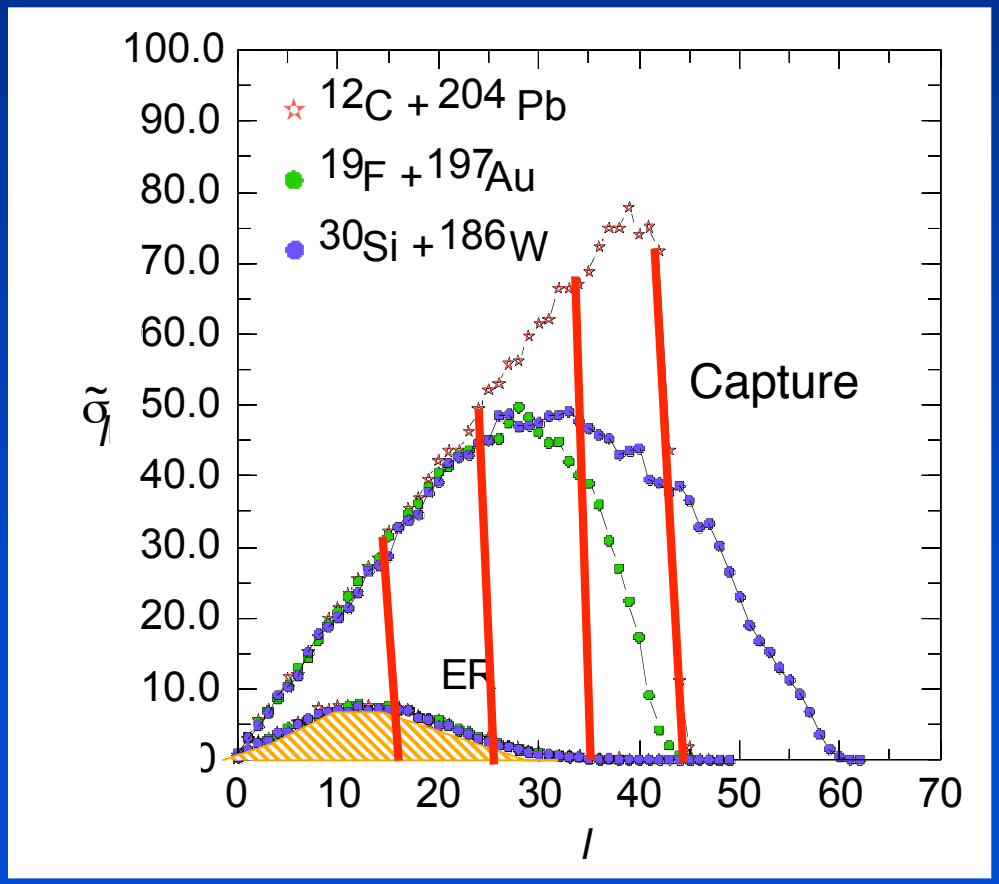
$$\sigma_{ER}(E) = \pi \lambda\!\!\!^{-2} \sum_{l=0}^{\infty} (2l+1) T_l(E)(1 - P_f(l, E^*))$$

$$\tilde{\sigma}_{ER}(E) = \sum_{l=0}^{\infty} (2l+1)(1 - P_f(l, E^*))$$

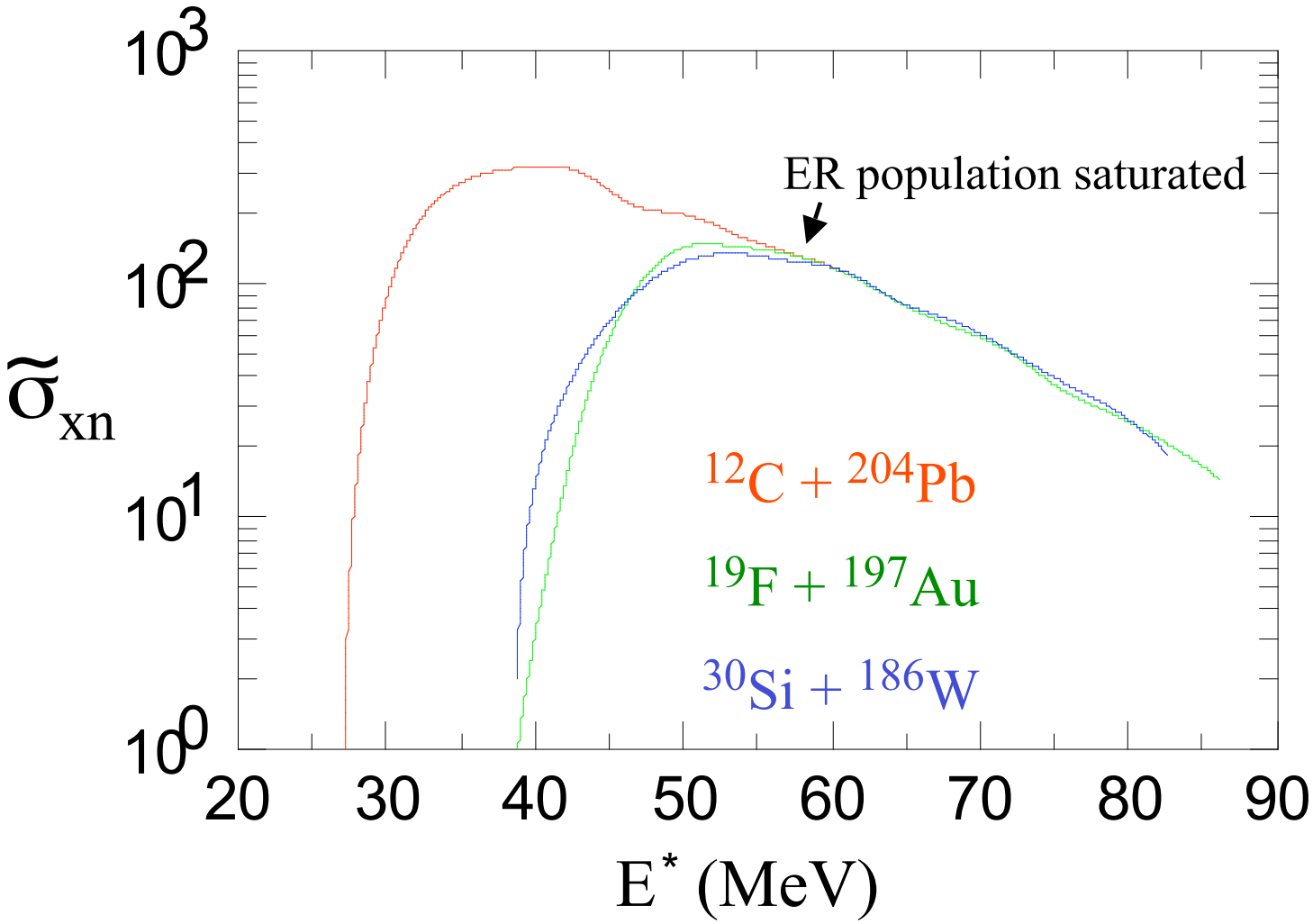
P_f: statistical fission probability

$P_f \Rightarrow 1$ for high ang. mom.



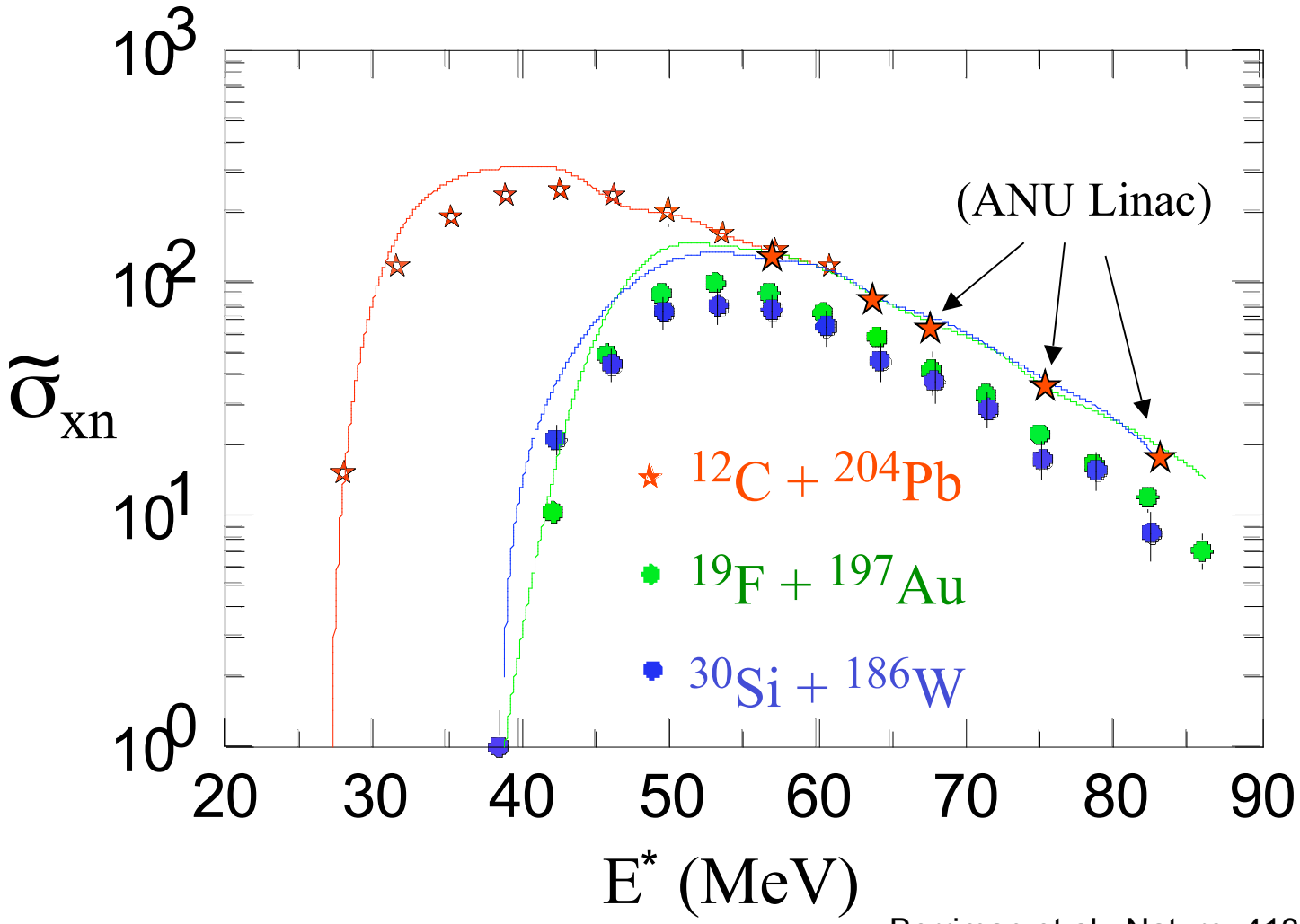


Statistical model predictions – Bohr independence hypothesis



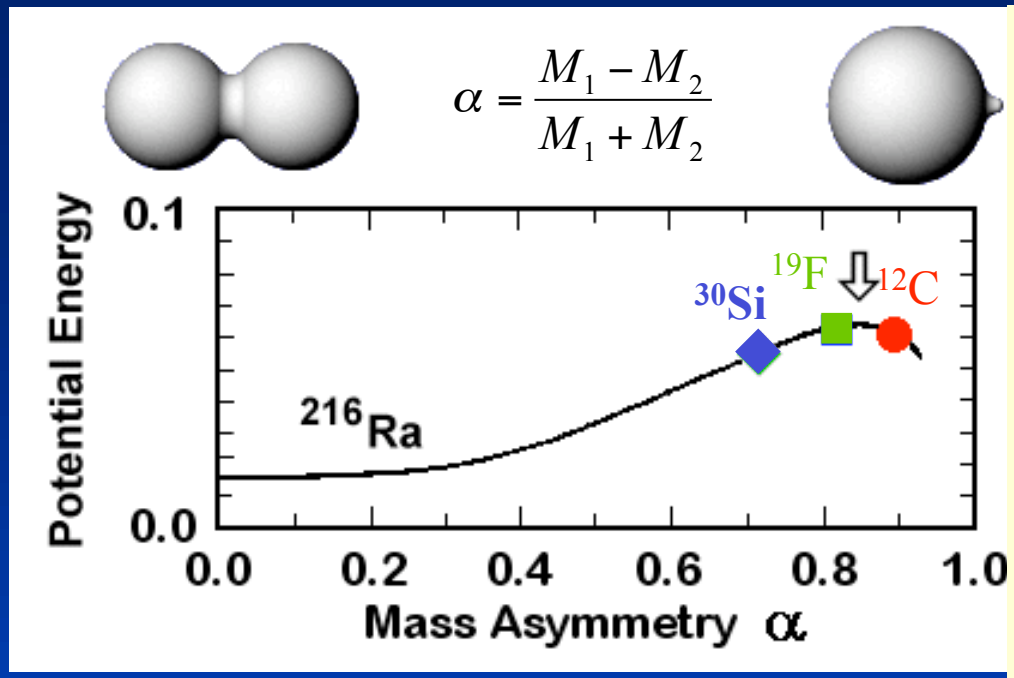
Experimental results - σ_{ER} from g.s. α-decay

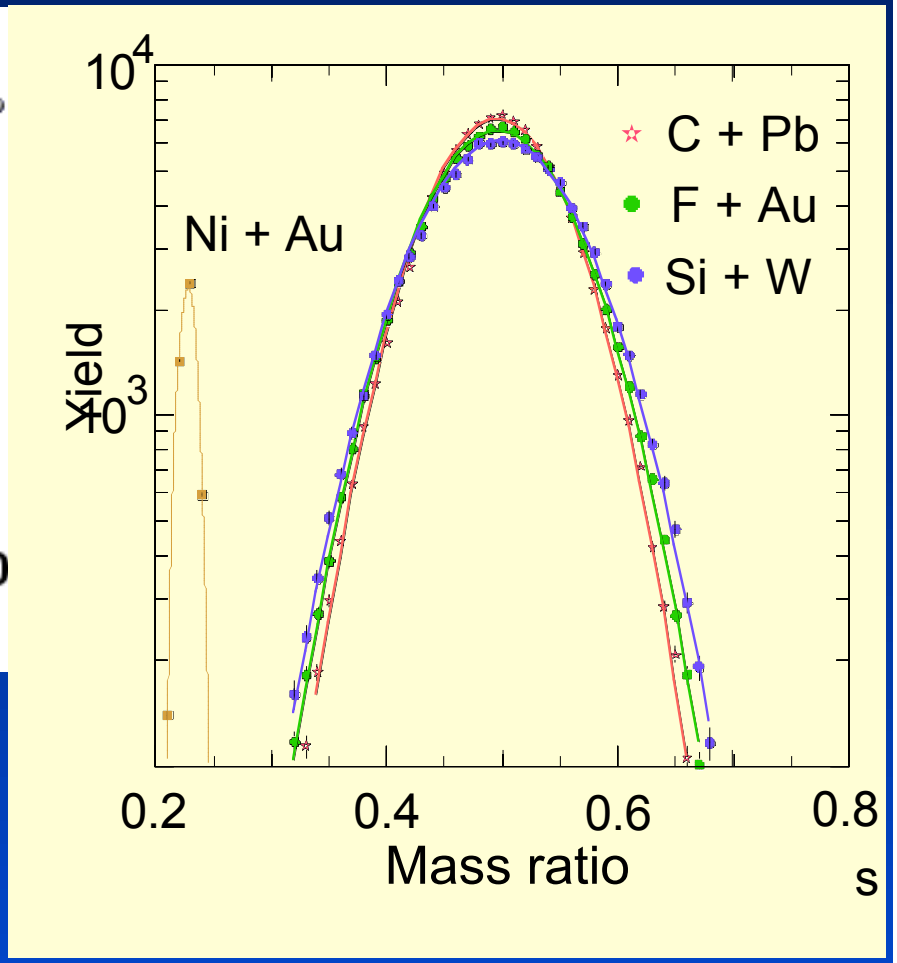
Z=88



Berriman et al., Nature 413 (2001) 144

Systematic difference - largest saturated ER yield for the lightest projectile





Evidence for:

- inhibition of ER formation – correlated with:
- presence of quasi-fission (seen in mass-distributions).
- dependence on entrance channel mass-asymmetry
- mass-asymmetry w.r.t. Businaro-Gallone peak?

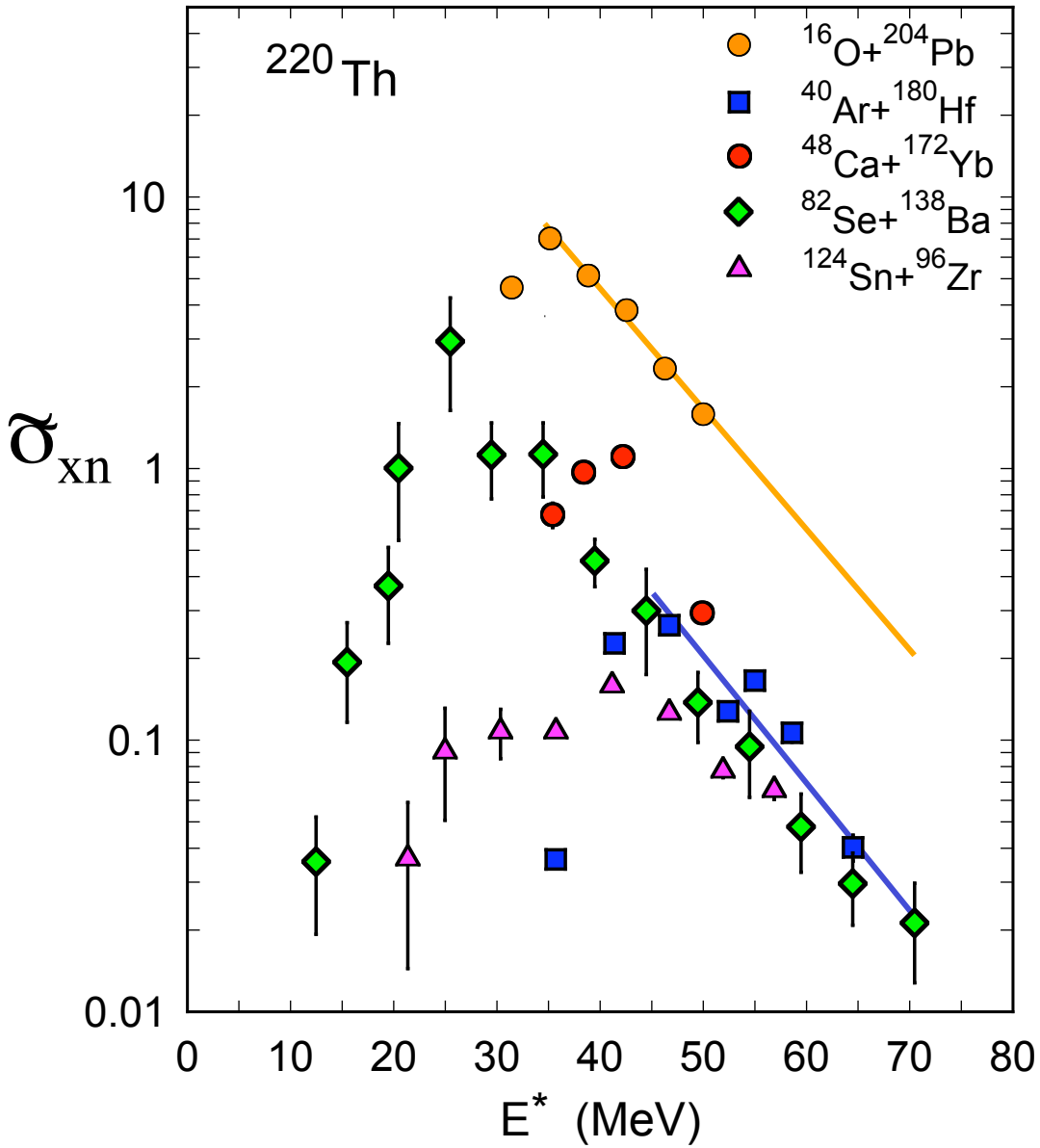
V.S. Ramamurthy and S.S. Kapoor, PRL **54** (1985) 178

Heavier, more fissile element Th – new data (ANU)

existing data

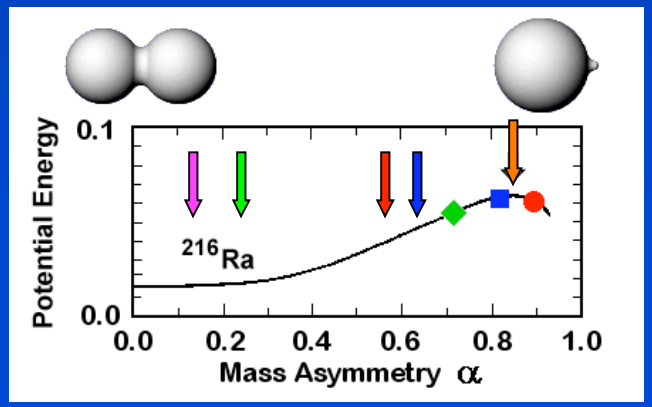
$^{16}O + ^{204}Pb$	^{220}Th (Z=90)	Hinde et al., Phys. Rev. Lett 89(2002)272701
$^{40}Ar + ^{180}Hf$		Vermeulen et al. Z.Phys. A 318 (1984)157
$^{48}Ca + ^{172}Yb$		Sahm et al., Nucl.Phys. A441(1985)316
$^{82}Se + ^{138}Ba$		Satou et al., Phys. Rev. C 65(2002)054602
$^{124}Sn + ^{96}Zr$		Sahm et al., Nucl.Phys. A441(1985)316

Z=90

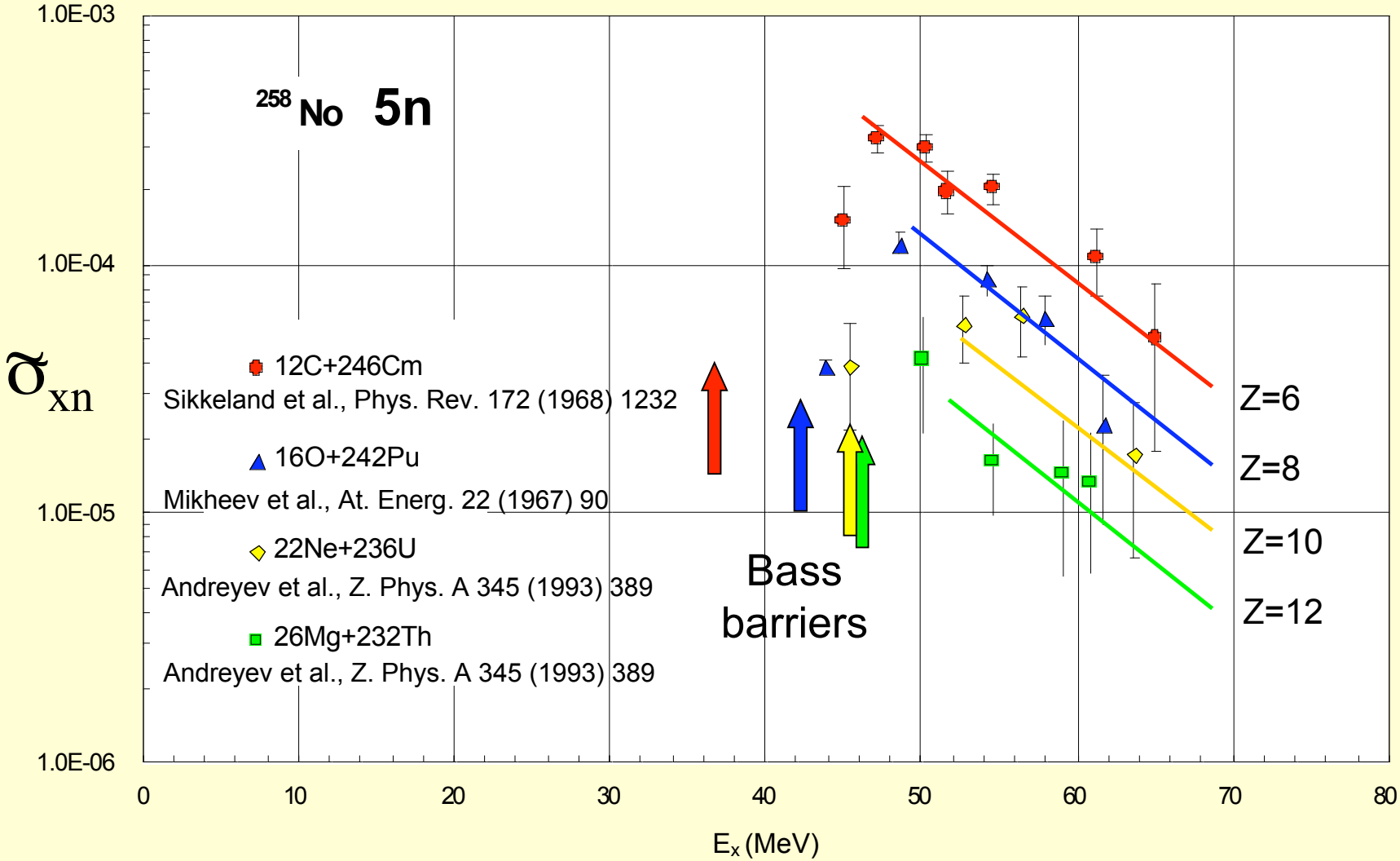


Hinde, Dasgupta, Mukherjee Phys. Rev. Lett. 89 (2002) 272701

- Remarkably, heavy projectile fusion probability only ~10% of light projectile
- Fusion inhibition already strong for A=40 projectile
- Weak dependence on mass-asymmetry once past B-G peak
- Th gives larger variation of P_{CN} as a function of mass-asymmetry



Z=102

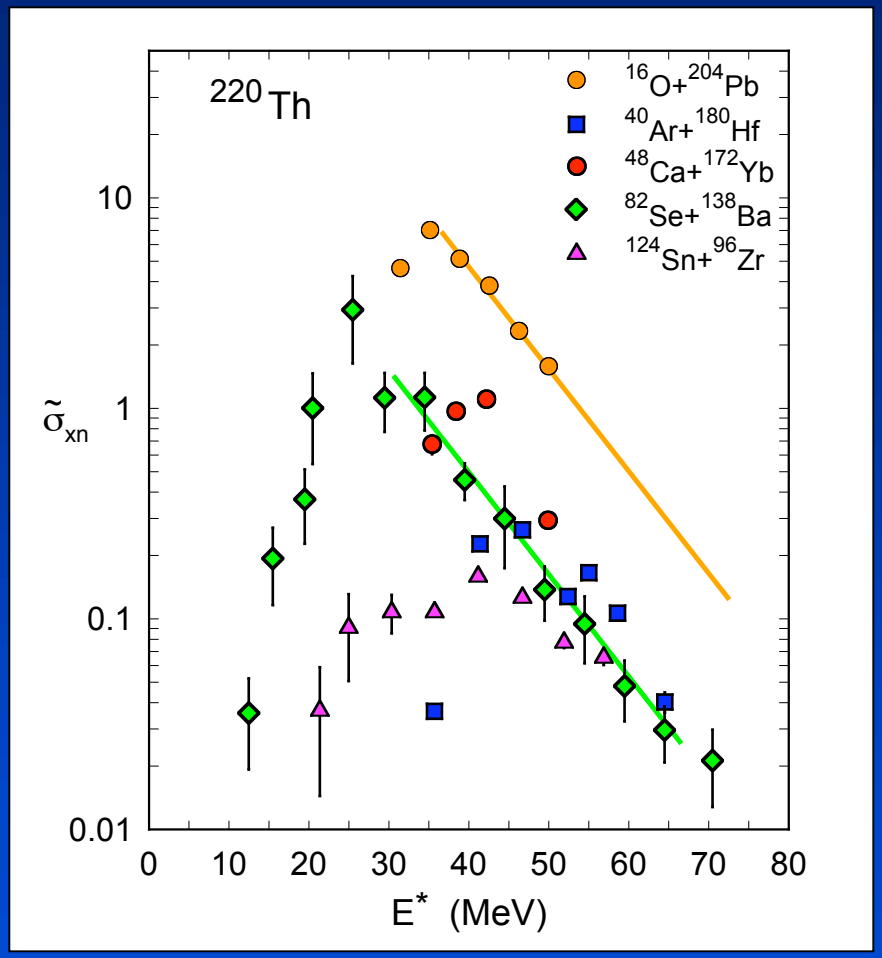

^{258}No 5n
1.0E-03
1.0E-04
1.0E-05
1.0E-06
σ_{xn}
12C+246Cm
Sikkeland et al., Phys. Rev. 172 (1968) 1232
16O+242Pu
Mikheev et al., At. Energ. 22 (1967) 90
22Ne+236U
Andreyev et al., Z. Phys. A 345 (1993) 389
26Mg+232Th
Andreyev et al., Z. Phys. A 345 (1993) 389
Bass barriers
Z=6
Z=8
Z=10
Z=12
0
10
20
30
40
50
60
70
80
E_x (MeV)

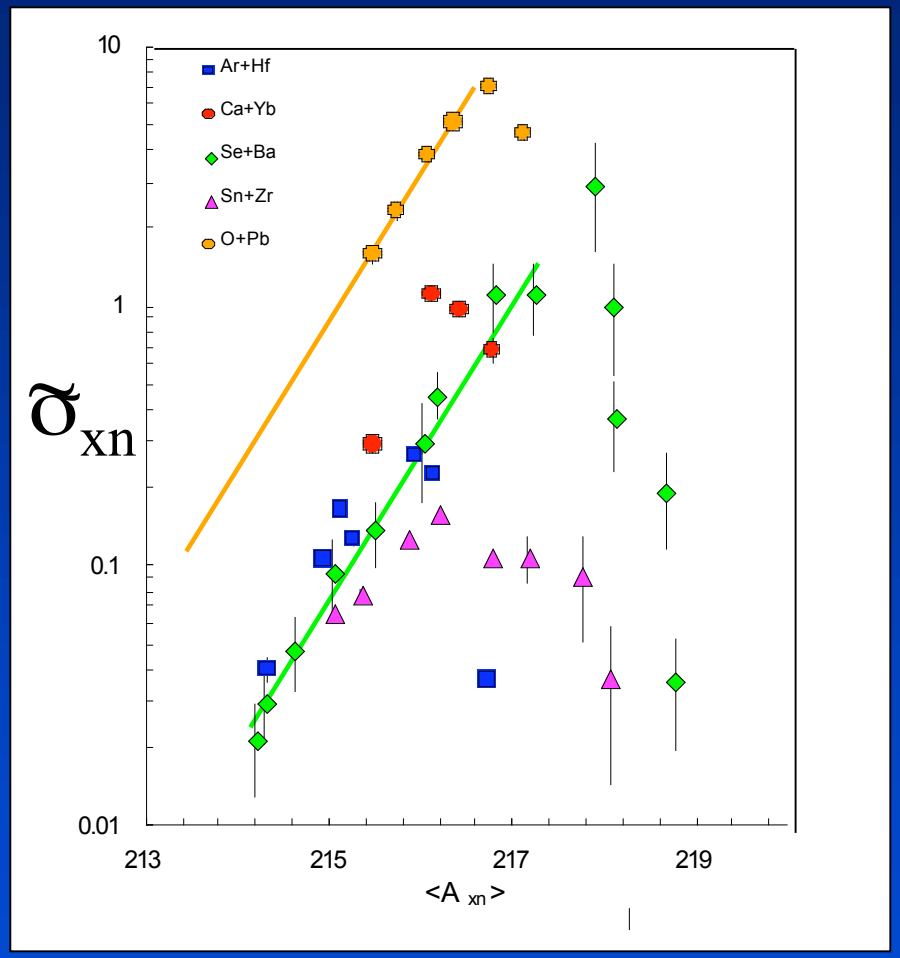
Neutron richness

Z=90

Reactions forming C.N. ^{220}Th:

<A> of xn products: $\langle A_{xn} \rangle = A_{CN} - N_{xn}$



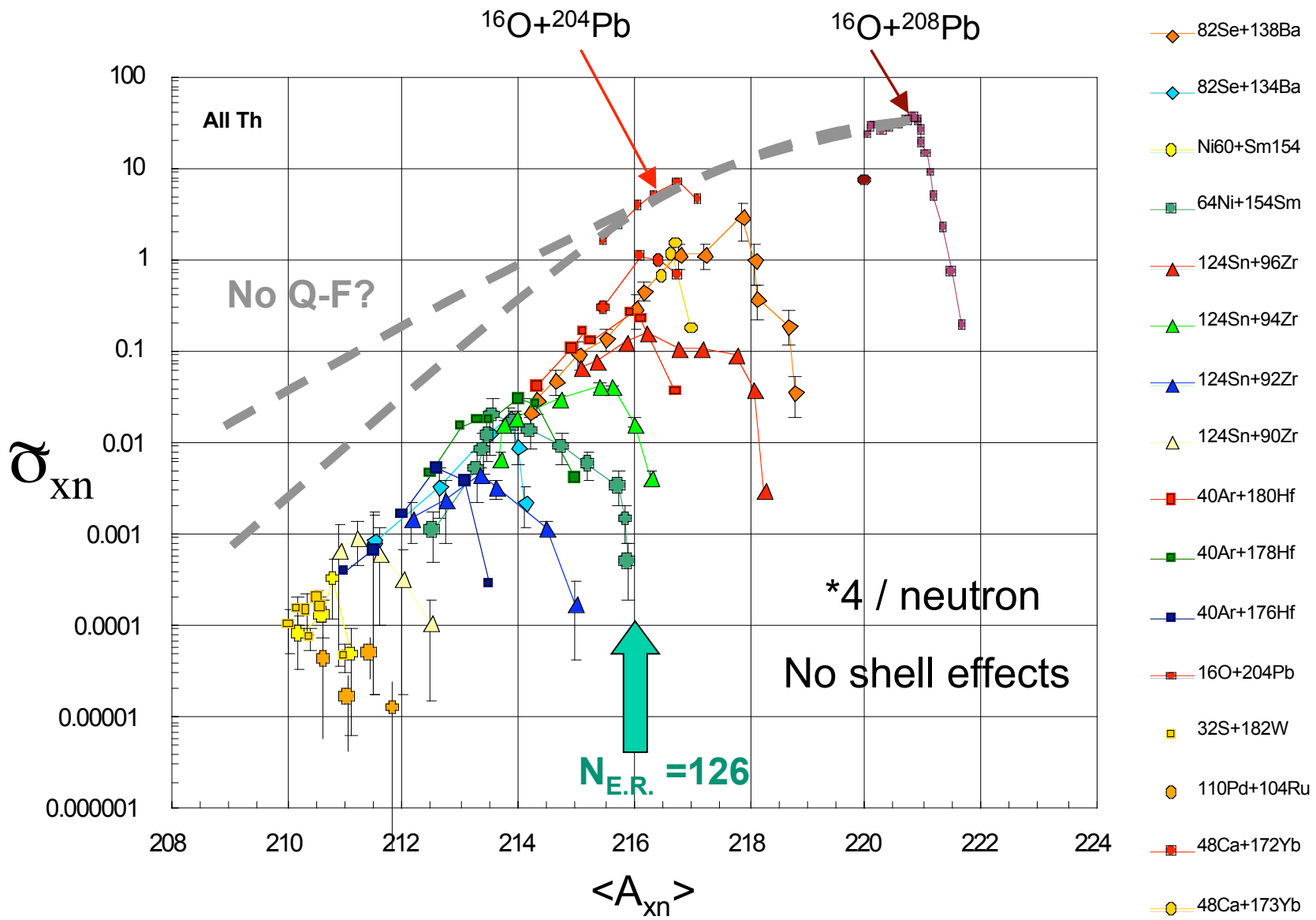


Transformation of abscissa $E^* \rightarrow \langle A_{xn} \rangle$

Both ordinate and abscissa now are determined only by expt. data

New way of representing ER yields

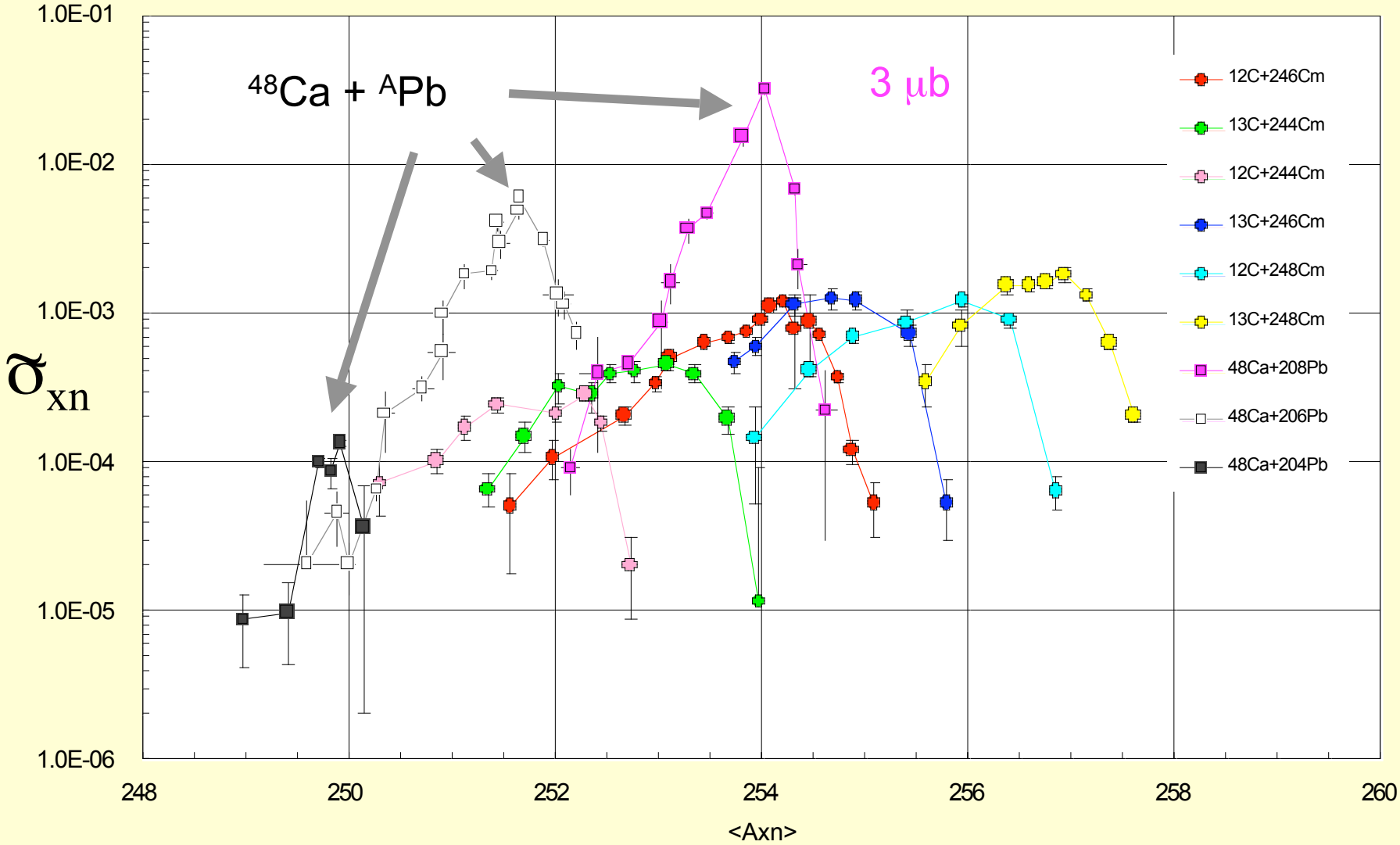
Z=90

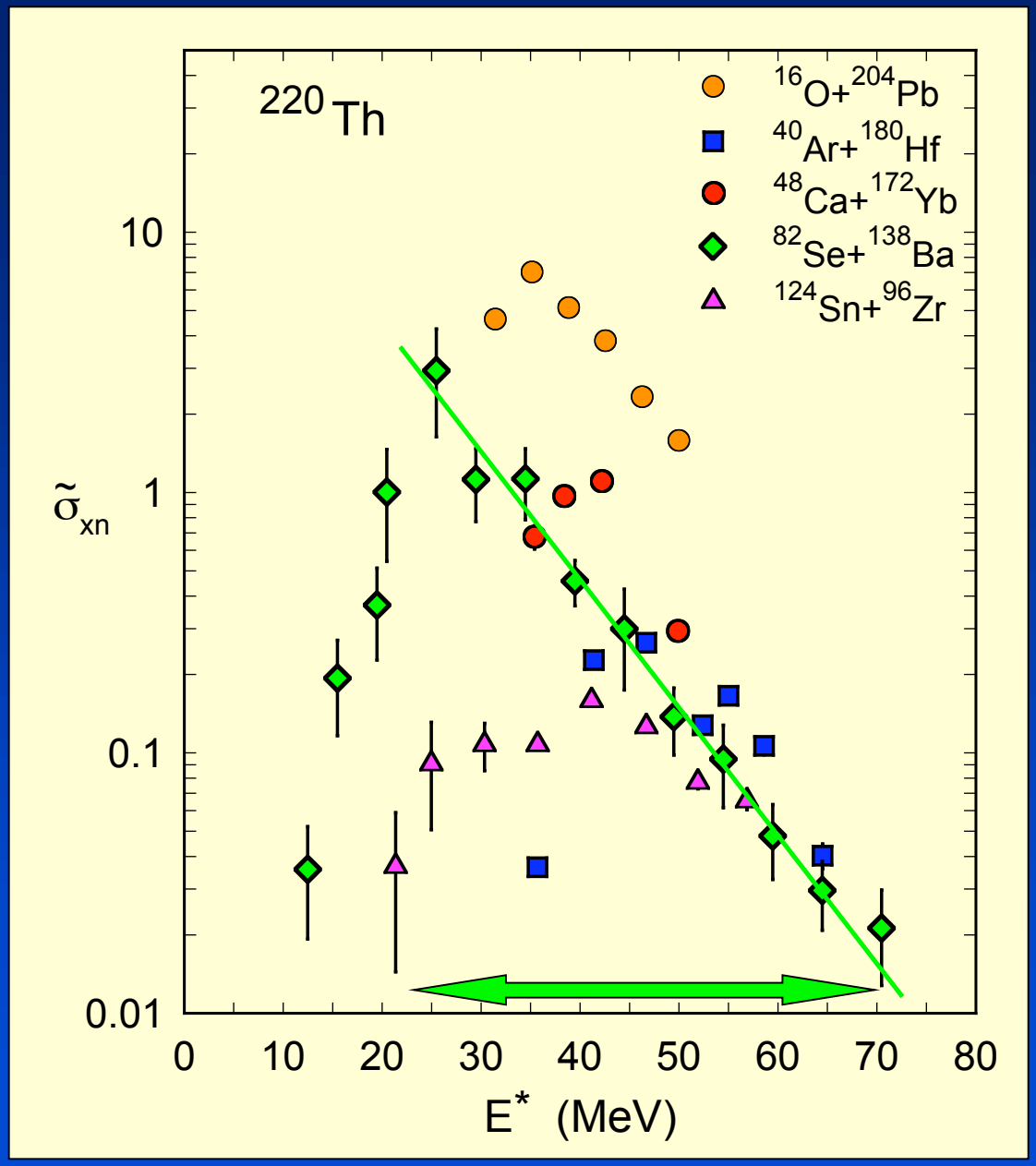


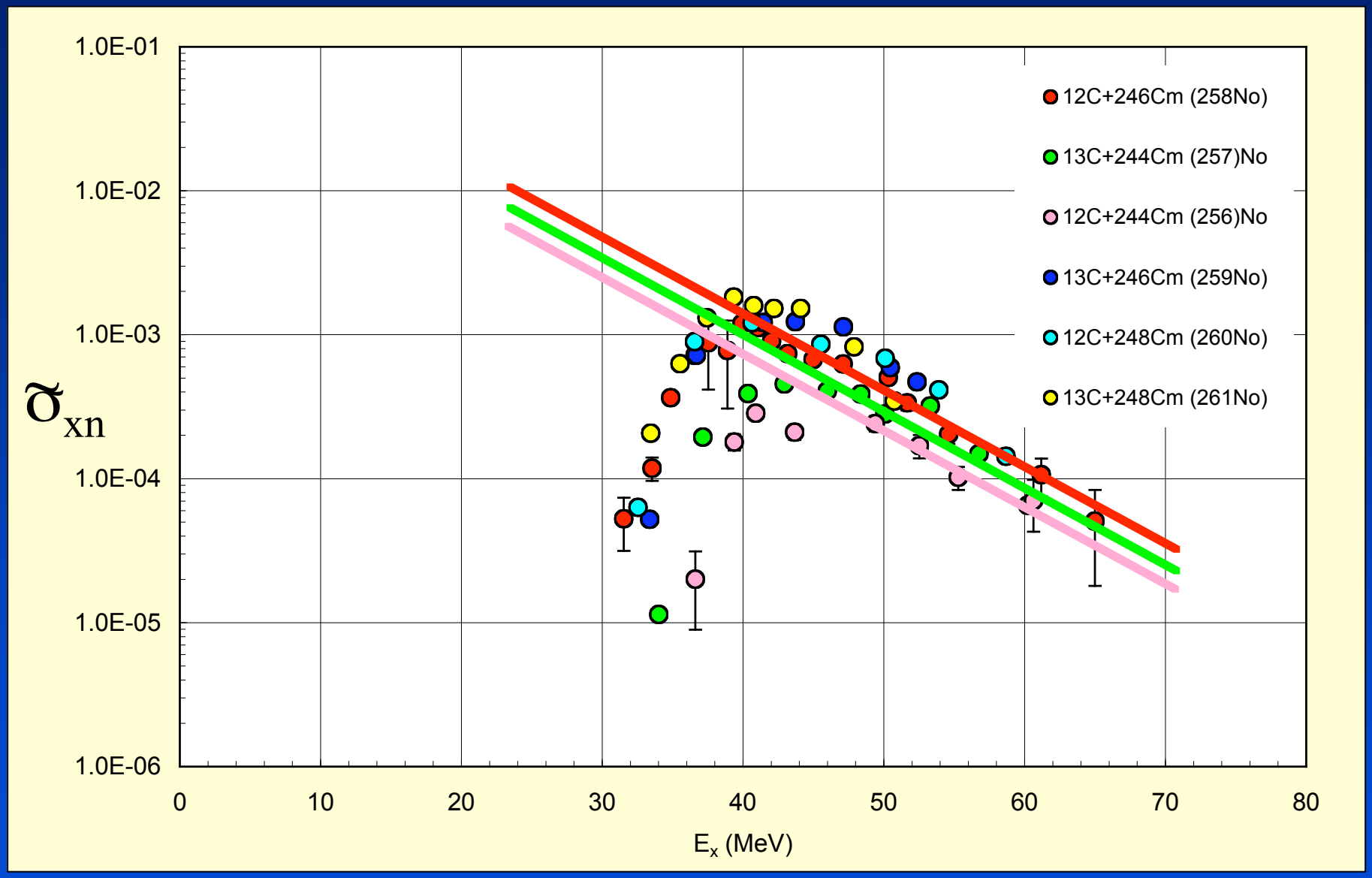
Hinde, Dasgupta Physics Letters B 622 (2005) 23-28

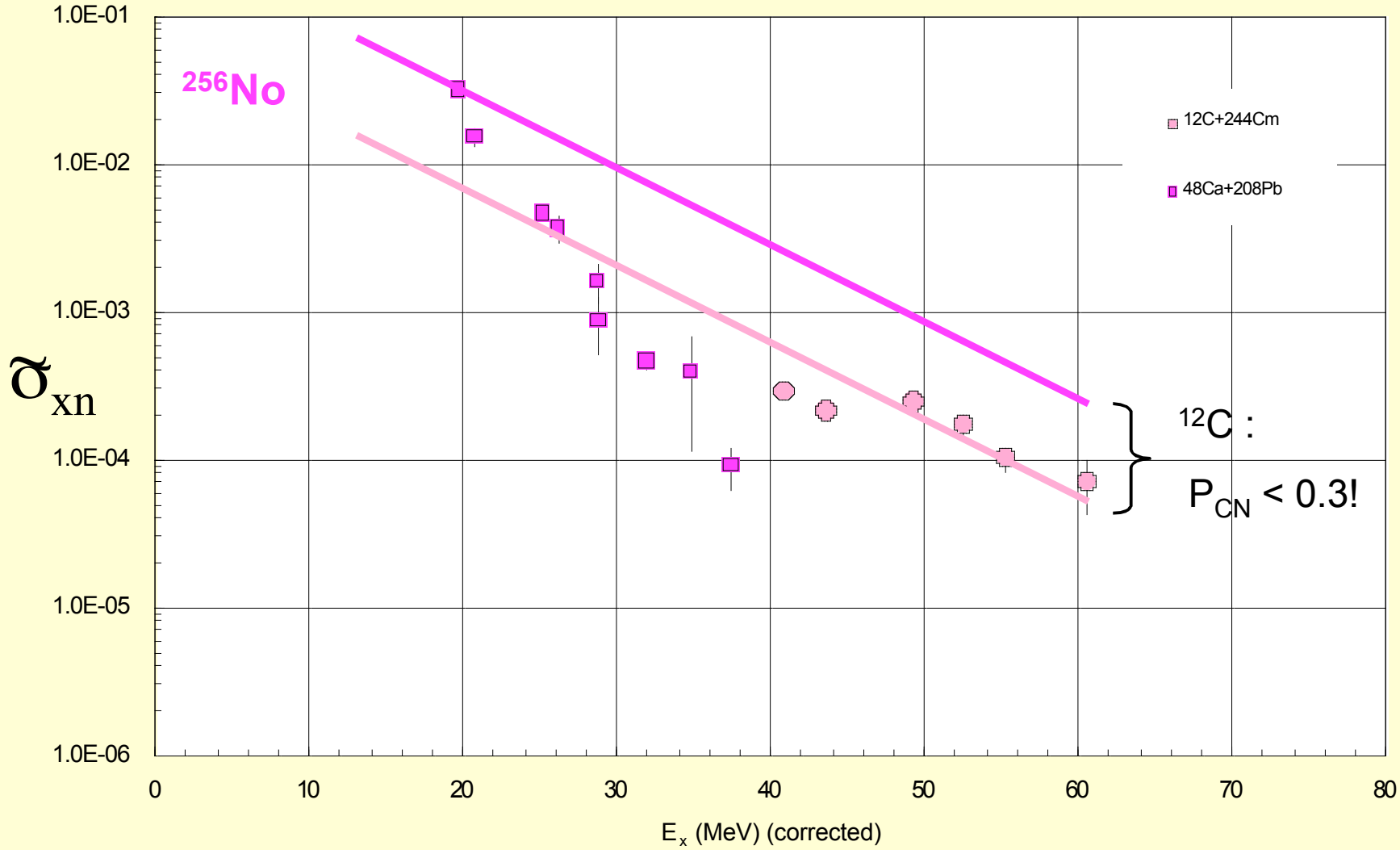
Z=102

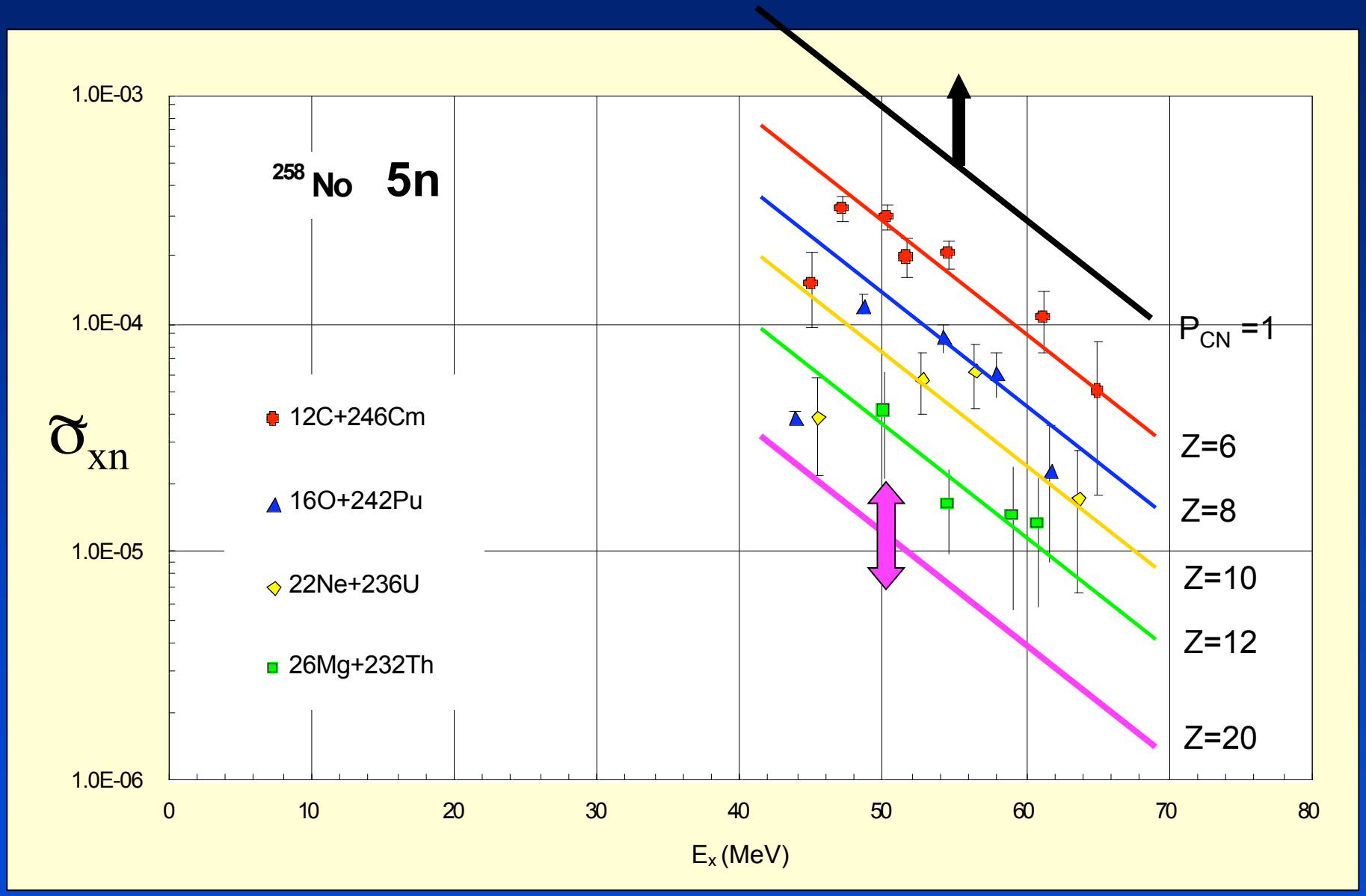
Special behaviour of $^{48}Ca+^{208}Pb$? – doubly-magic nuclei, or just low E*?

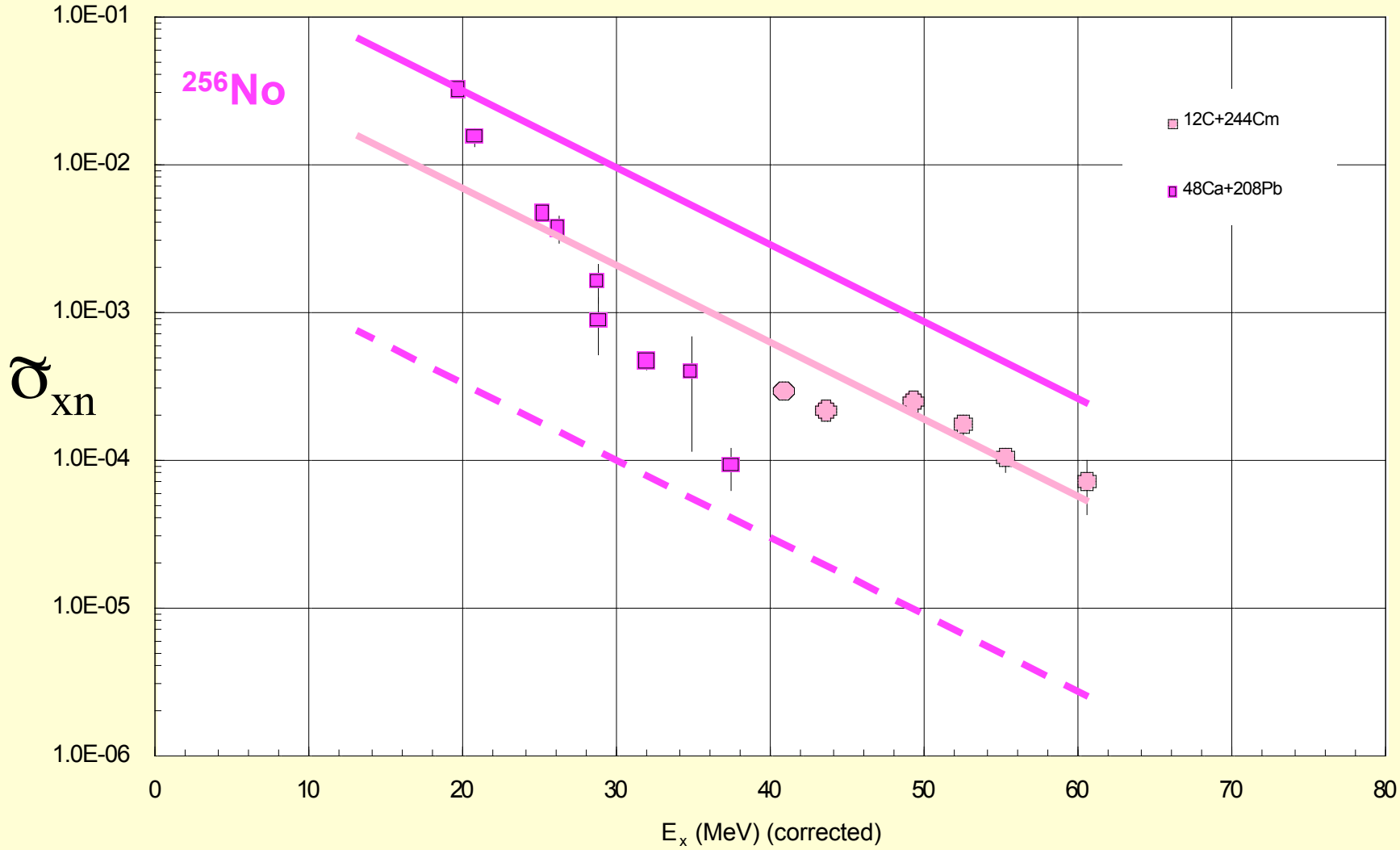



220Th
16O+204Pb
40Ar+180Hf
48Ca+172Yb
82Se+138Ba
124Sn+96Zr
10
1
0.1
0.01
σ̃xn
0
10
20
30
40
50
60
70
80
E* (MeV)

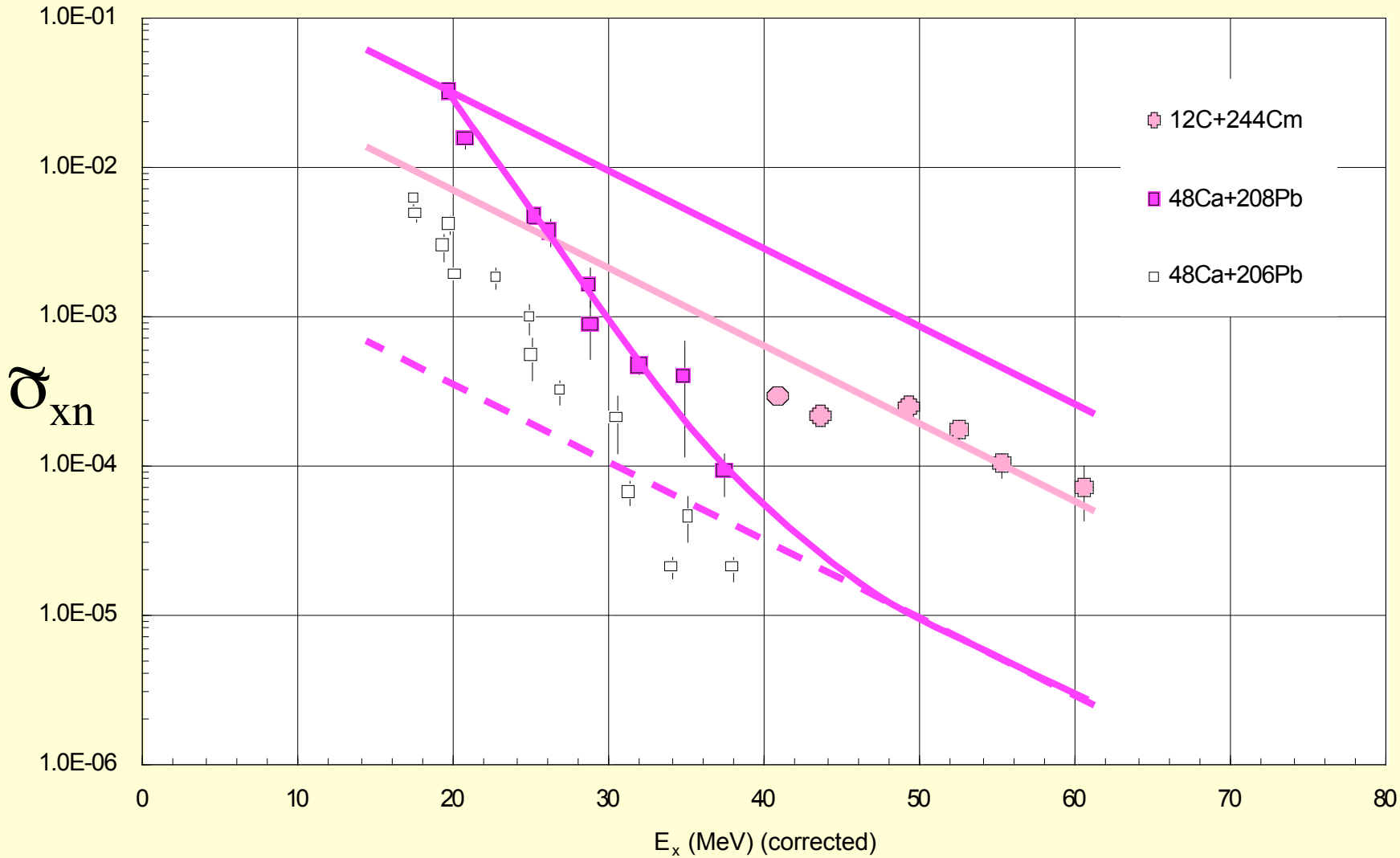

1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
σxn
0
10
20
30
40
50
60
70
80
Ex (MeV)
12C+246Cm (258No)
13C+244Cm (257)No
12C+244Cm (256)No
13C+246Cm (259No)
12C+248Cm (260No)
13C+248Cm (261No)

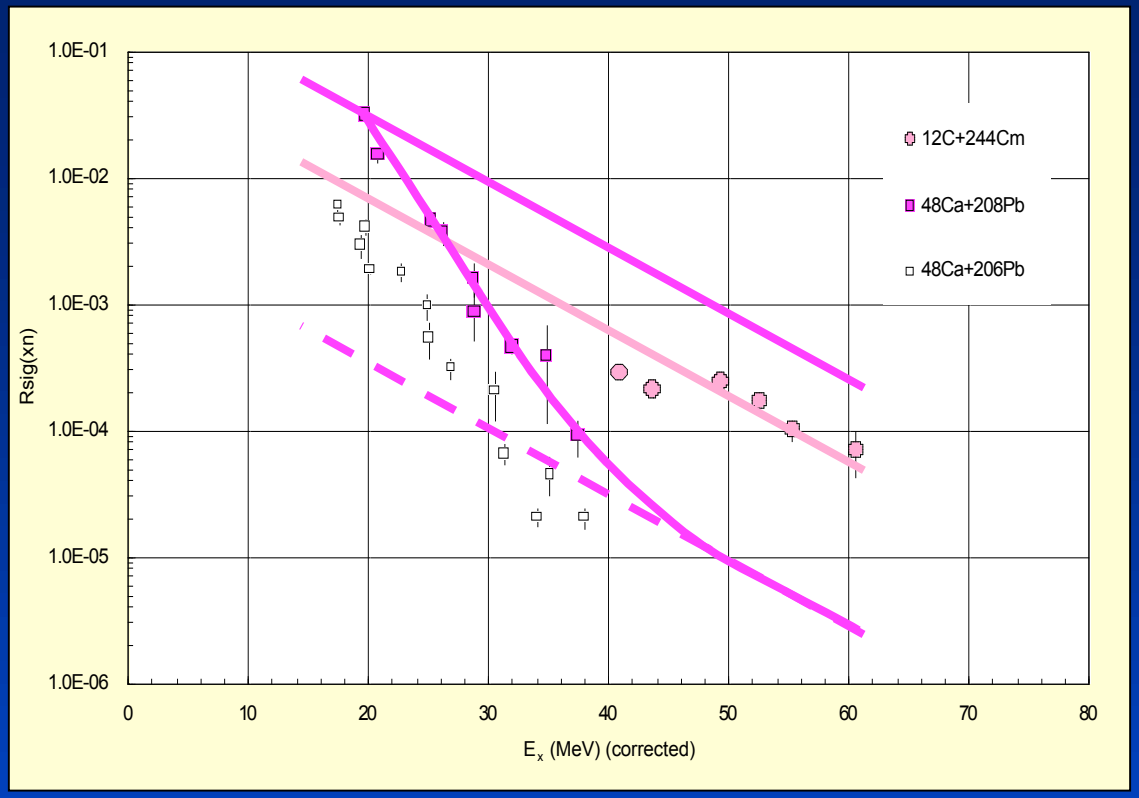

256No
12C+244Cm
48Ca+208Pb
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
σxn
0
10
20
30
40
50
60
70
80
Ex (MeV) (corrected)
12C :
PCN < 0.3!


258 No 5n
1.0E-03
1.0E-04
1.0E-05
1.0E-06
σxn
12C+246Cm
16O+242Pu
22Ne+236U
26Mg+232Th
PCN =1
Z=6
Z=8
Z=10
Z=12
Z=20
0
10
20
30
40
50
60
70
80
Ex (MeV)


256No
12C+244Cm
48Ca+208Pb
σxn
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
0
10
20
30
40
50
60
70
80
Ex (MeV) (corrected)

$^{48}Ca+^{206}Pb$ data are consistent with $^{48}Ca+^{208}Pb$ data





Reaction of two doubly-magic nuclei:

- enhancement of P_{CN} by ~ 100 at low E*
- enhancement falls exponentially: $e^{-E^*/6\ \mathrm{MeV}}$
- P_{CN} extremely sensitive to E*

CONCLUSIONS

Entrance channel conditions dramatically affect evolution to compact CN (quasi-fission competition), and thus heavy element yields

- See inhibition of ER yields even for quite mass-asymmetric reactions
- Mass-asymmetry larger than B-G peak is favourable
- Neutron-richness of composite system can be very important
- Special cases show large enhancement in yield due to closed shells
- We need more data and models describing the quasi-fission products
- We need a complete picture to predict possibilities for neutron-rich super- and very heavy isotope formation with radioactive beams