Actinide Production in $^{238}U + ^{238}U(^{248}Cm)$ Multi-nucleon Transfer Reactions Revisited

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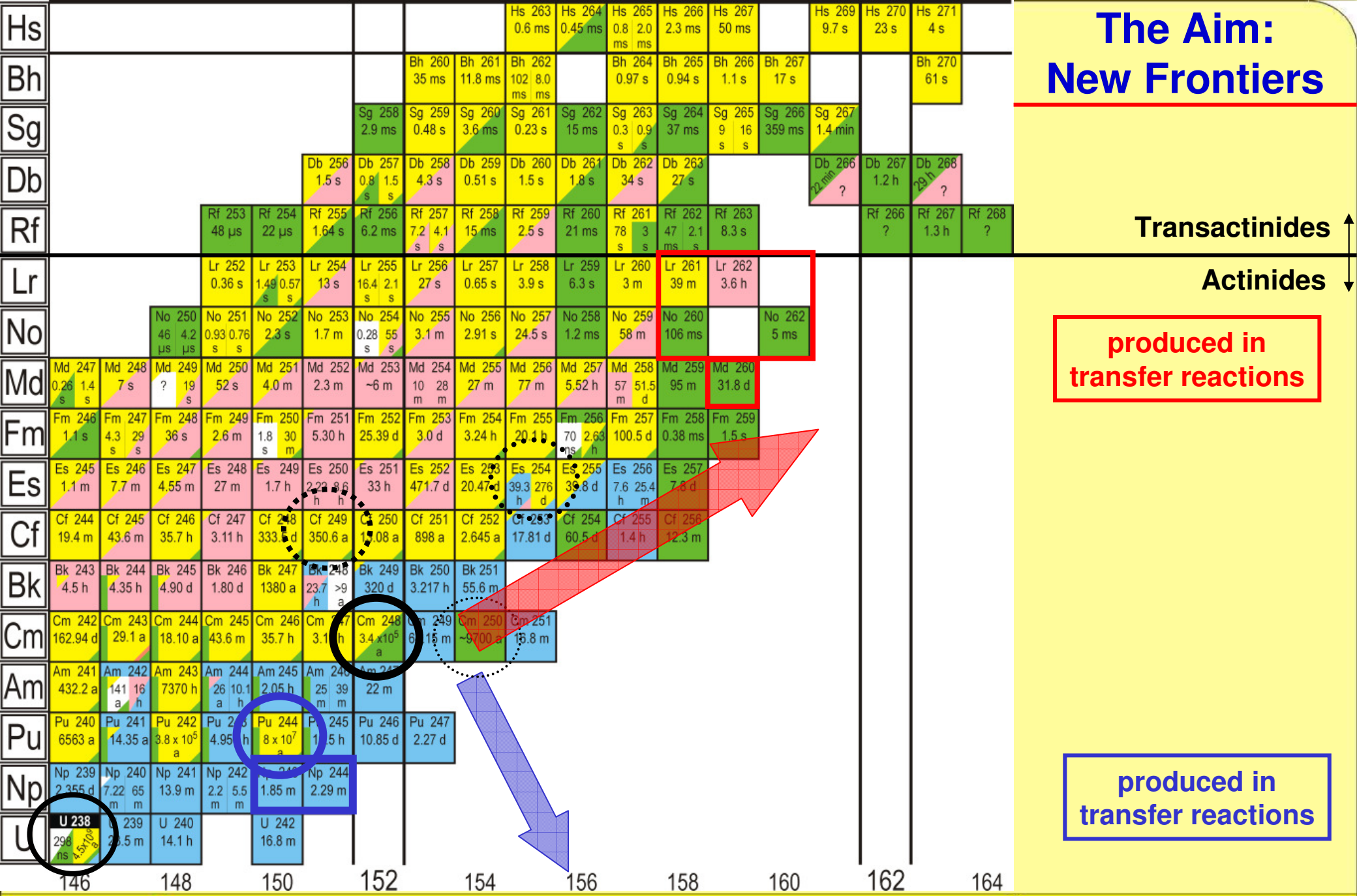
* The Aim
* A (Simplified) Multi-nucleon Transfer Picture

* The $^{238}U + ^{238}U$ Reactions
  - Experimental results (advantages + disadvantages)
  - Comparison with other projectiles
  - Comparison with other targets
  - Production mechanism
  - Kinematics


The Aim:
New Frontiers
Transactinides
Actinides
produced in transfer reactions
produced in transfer reactions
Hs
Bh
Sg
Db
Rf
Lr
No
Md
Fm
Es
Cf
Bk
Cm
Am
Pu
Np
U
146
148
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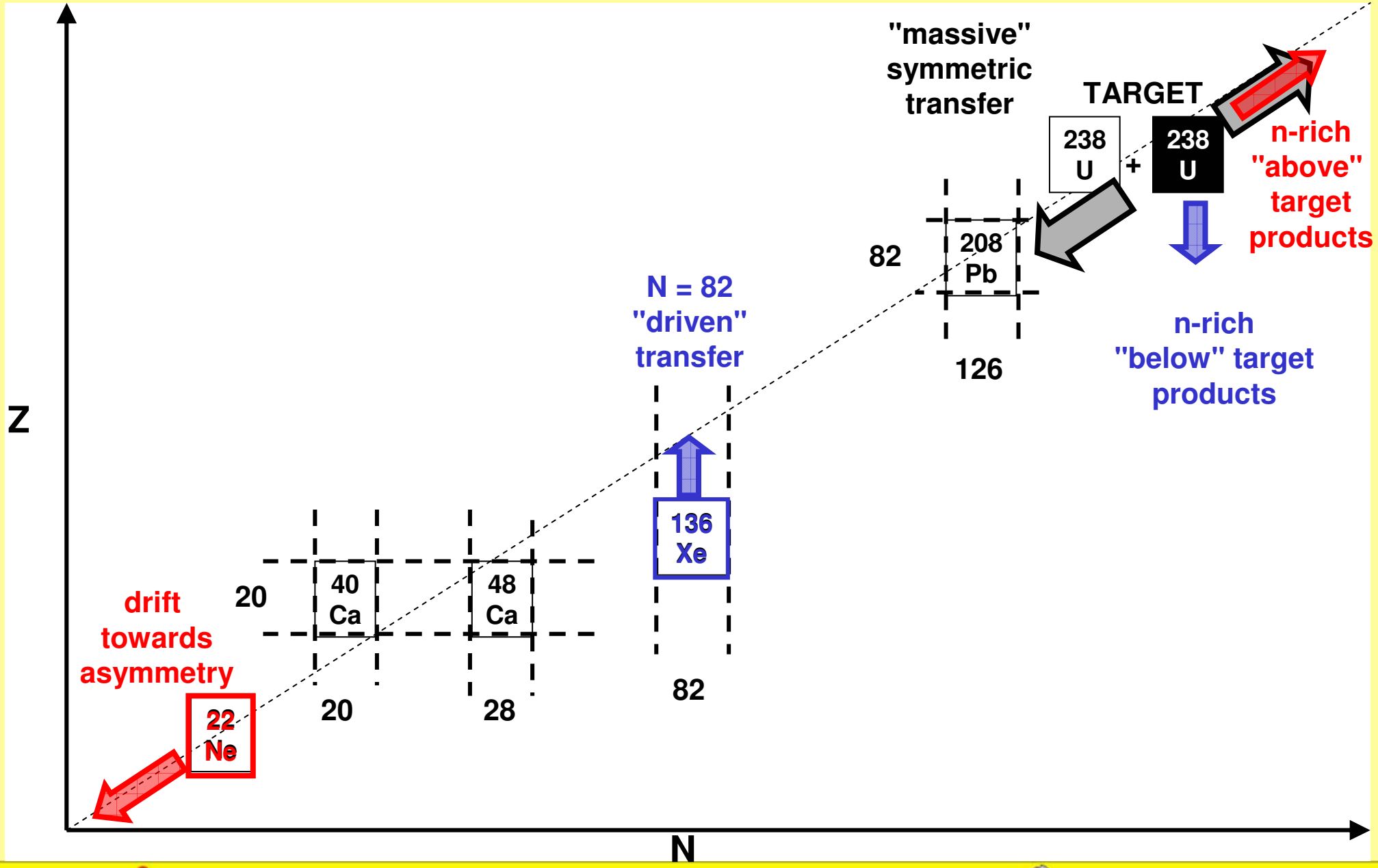
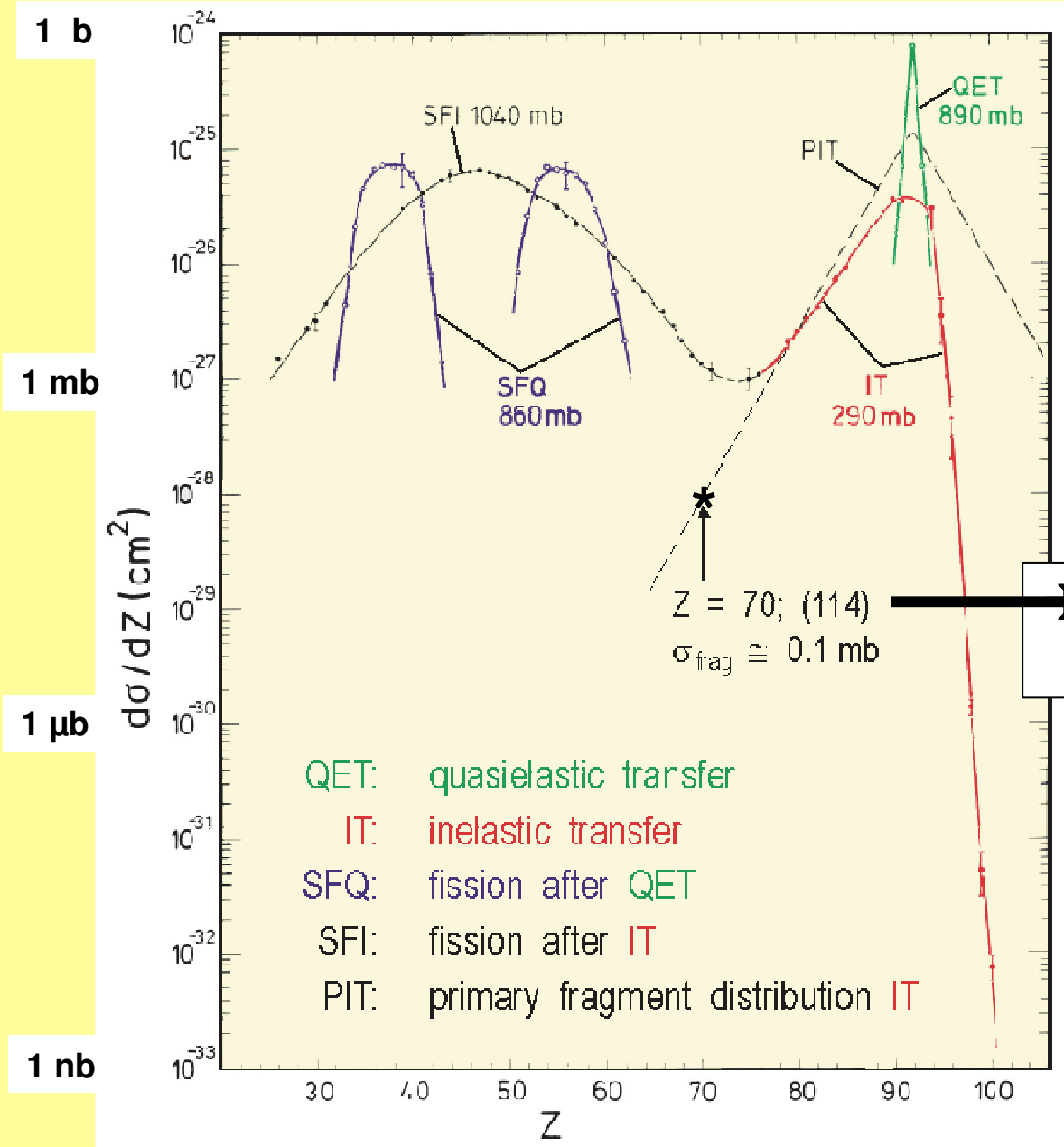
162
164

A (Simplified) Multi-nucleon Transfer Picture



$^{238}U + ^{238}U$: Z-Distribution

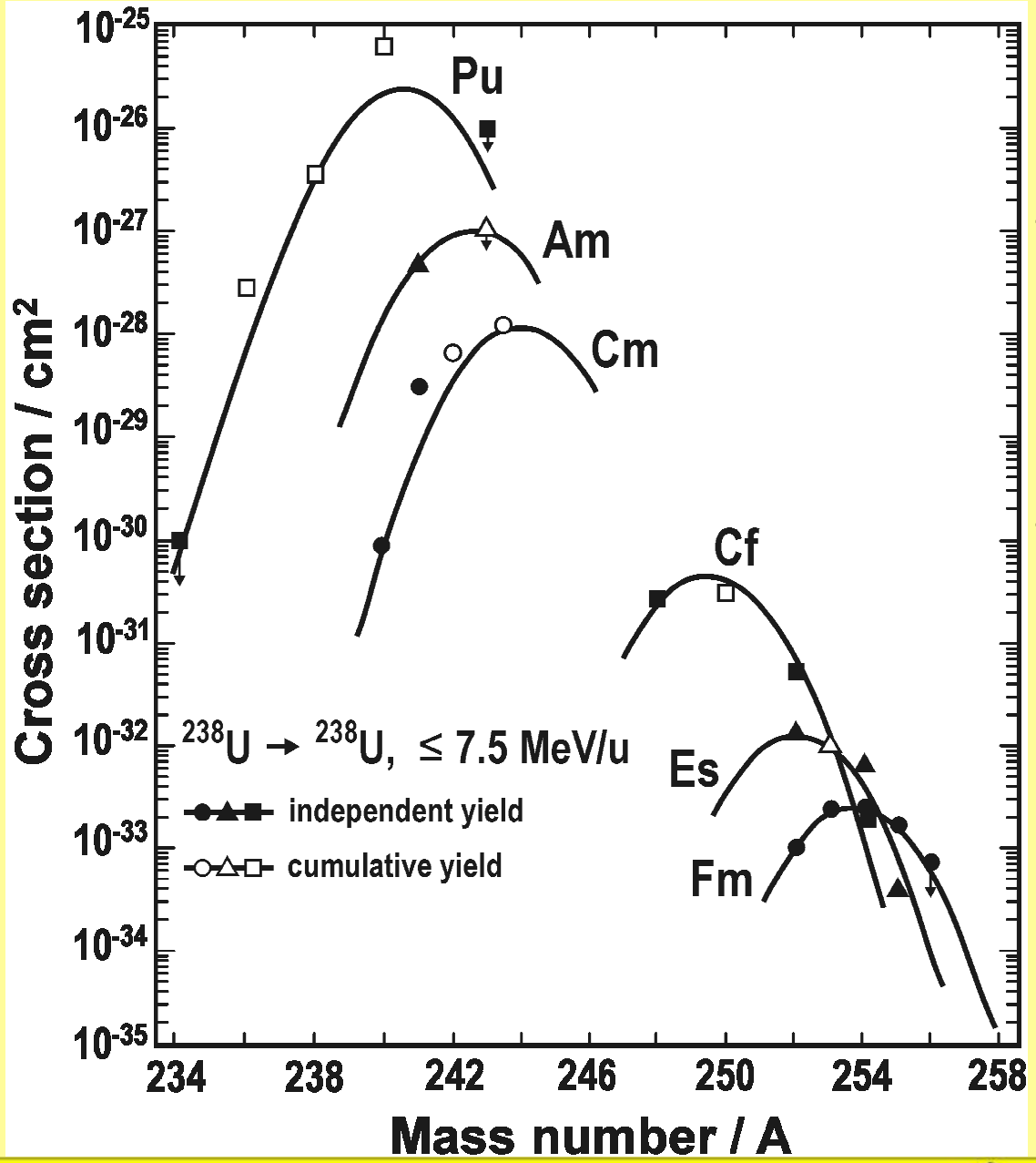


E(^{238}U) ≤ 7.5 MeV/u

σ = 0.1 mb for Z = 114 as a *primary fragment*

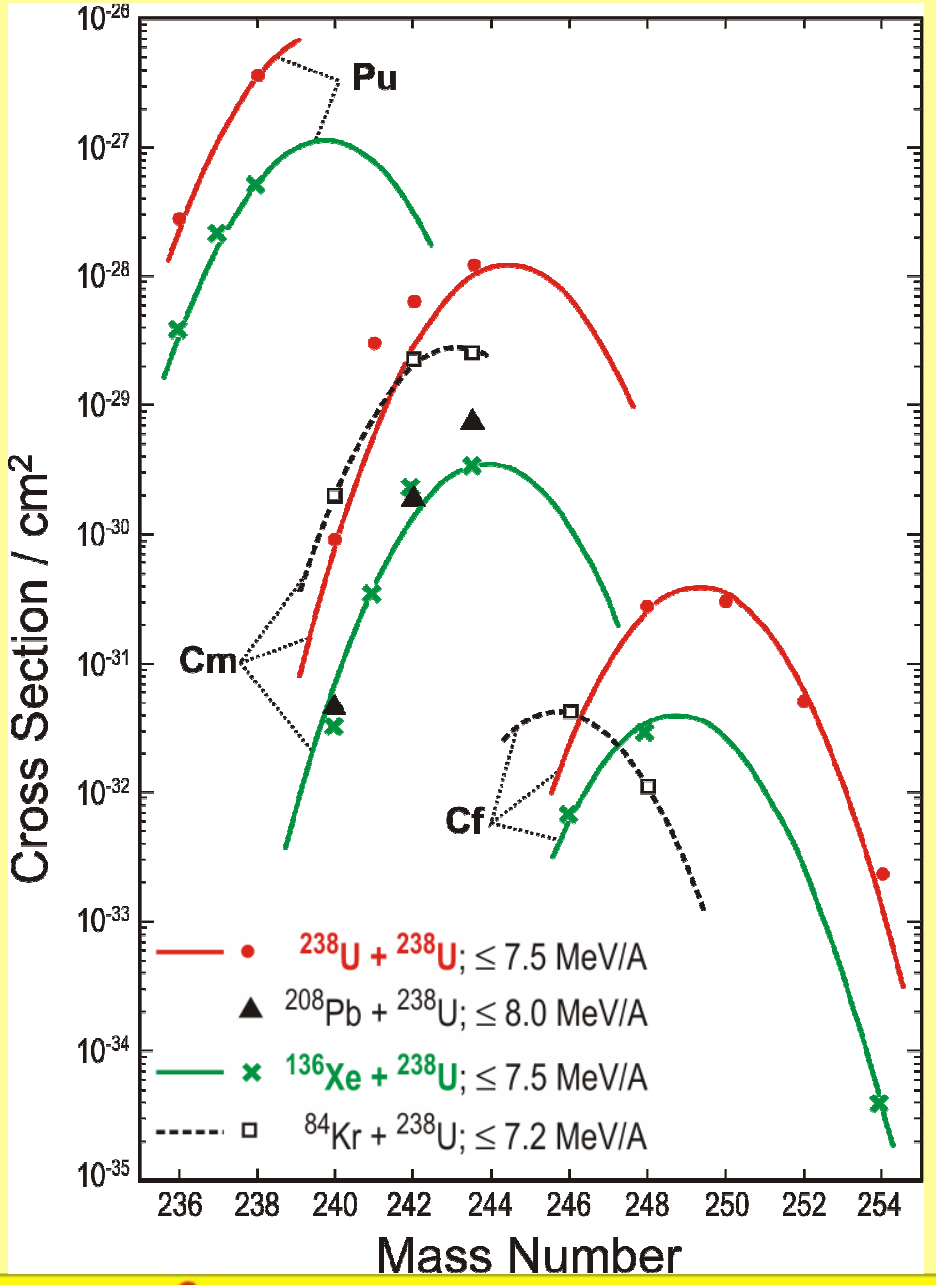
M. Schädel et al.
Phys. Rev. Lett. 41 (1978) 469
Radiochim. Acta 25 (1978) 111

$^{238}U + ^{238}U \rightarrow$ Actinides; Multi-nucleon Transfer



M. Schädel et al.
PRL 41 (1978) 469

^{86}Kr, ^{136}Xe, ^{208}Pb, ^{238}U + ^{238}U ➔ Actinides; Multi-nucleon Transfer



Heavy actinide ($Z > T_{Target}$) production w/ ^{238}U - targets:

^{238}U - best "heavy" ($A \geq 50$) projectile:

➔ highest cross section

➔ most n-rich products

But: - relatively low U-beam intensity

- serious target problems w/ U-beam

$I_{max}(^{238}U) = 2.5 \times 10^{11}\ s^{-1}$ (40 nA_{part})

$N_T\ (^{238}U) = 1.5 \times 10^{19}\ cm^{-2}$ (assumed)

(≈ 6 mg/cm² ^{238}U)

used: 300 mg/cm² U-target = catcher

U explosive-plated on Cu

today: $I_{max}(^{238}U) \approx 100\ nA_{part}$

+ frequent PIG-source changes

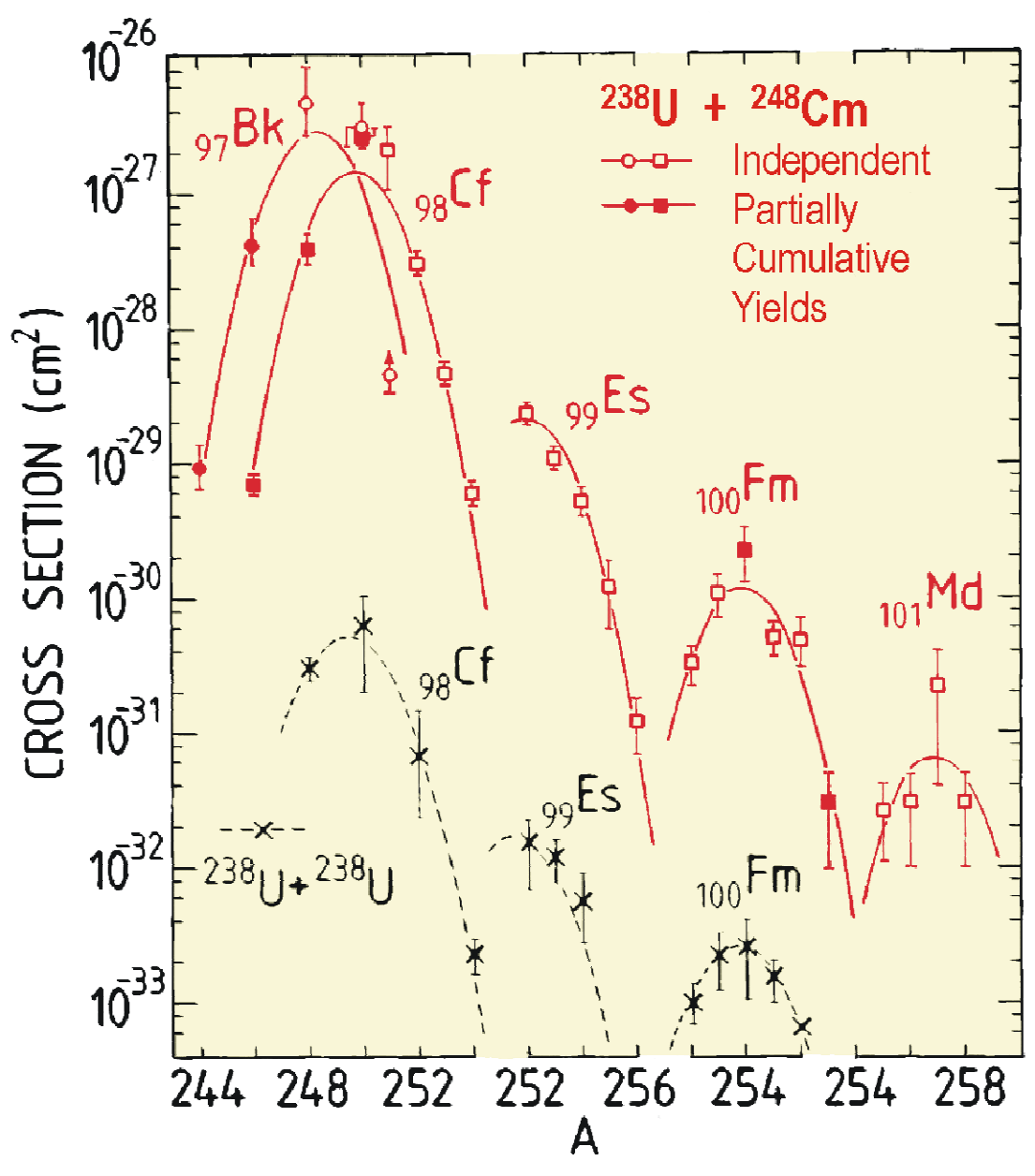
^{238}U: M. Schädel et al., PRL 41 (1978) 469

^{208}Pb: T. Lund et al., Z.Phys. A 303 (1981) 115

^{136}Xe: M. Schädel; light Z: A. Türler, K.J Moody et al.

^{84}Kr: K.L. Wolf et al., ACS Meeting Chicago 1977

(^{238}U + ^{238}U) vs (^{238}U + ^{248}Cm) ➔ Heavy Actinides



Cross section from multi-nucleon ("deep-inelastic") transfer

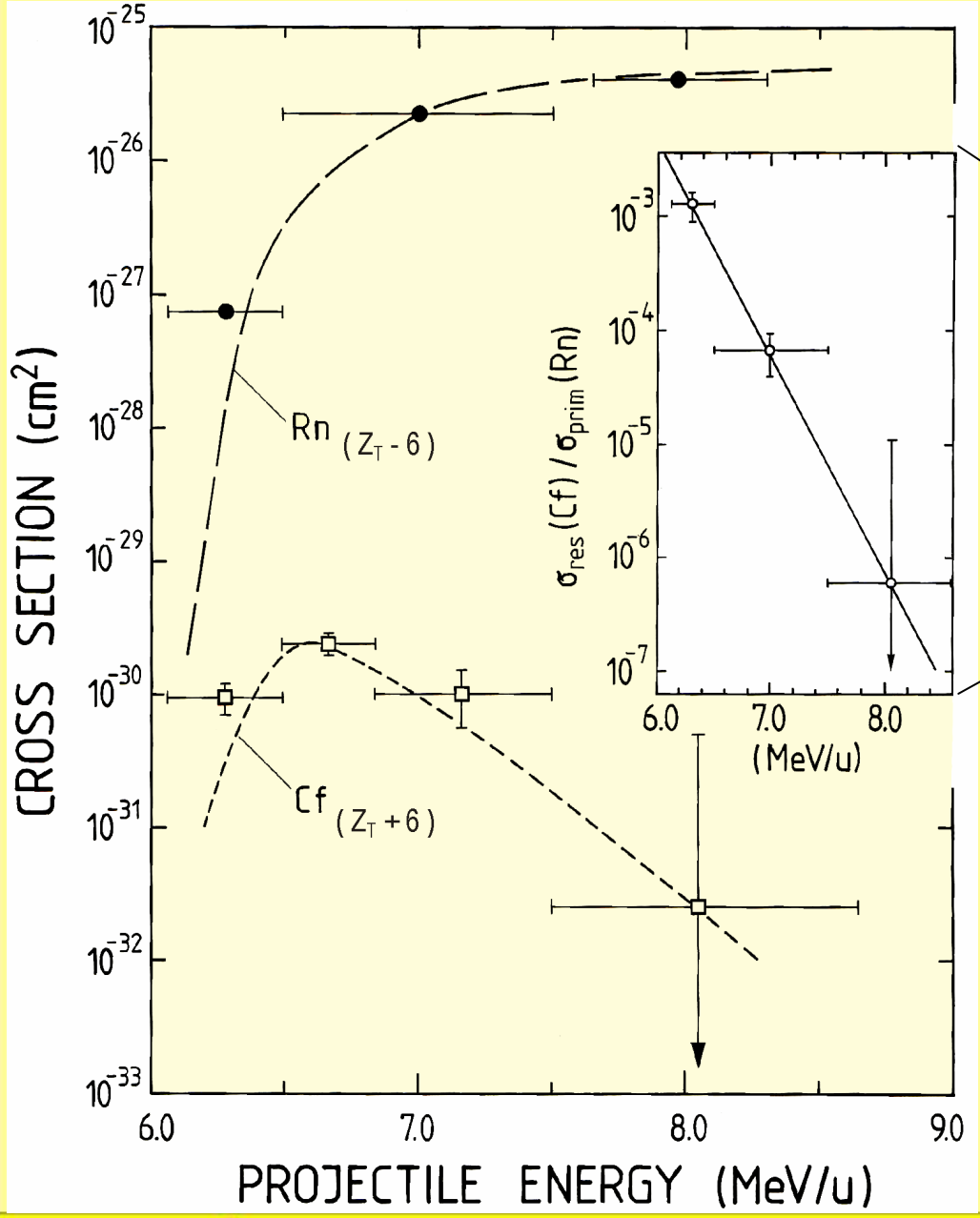
From ^{238}U + ^{238}U
to ^{238}U + ^{248}Cm

➔ ≈ 10^3 gain in σ

Isotope distributions:
- same width
- same position

M. Schädel et al.,
Phys. Rev. Lett. 48 (1982) 852

$^{238}U + ^{238}U$ ➔ Actinides; Multi-nucleon Transfer



"Excitation functions" measured ➔

$\sigma_{max} \approx 1.1 \times E_B$

Ratio between
residual Z=98 products (σ_{res})
and
primary formed Z=98 fragments (σ_{prim})
(based on the Rn (Z_{Target} - 6) data)

as a function of $E_{lab}(^{238}U)$

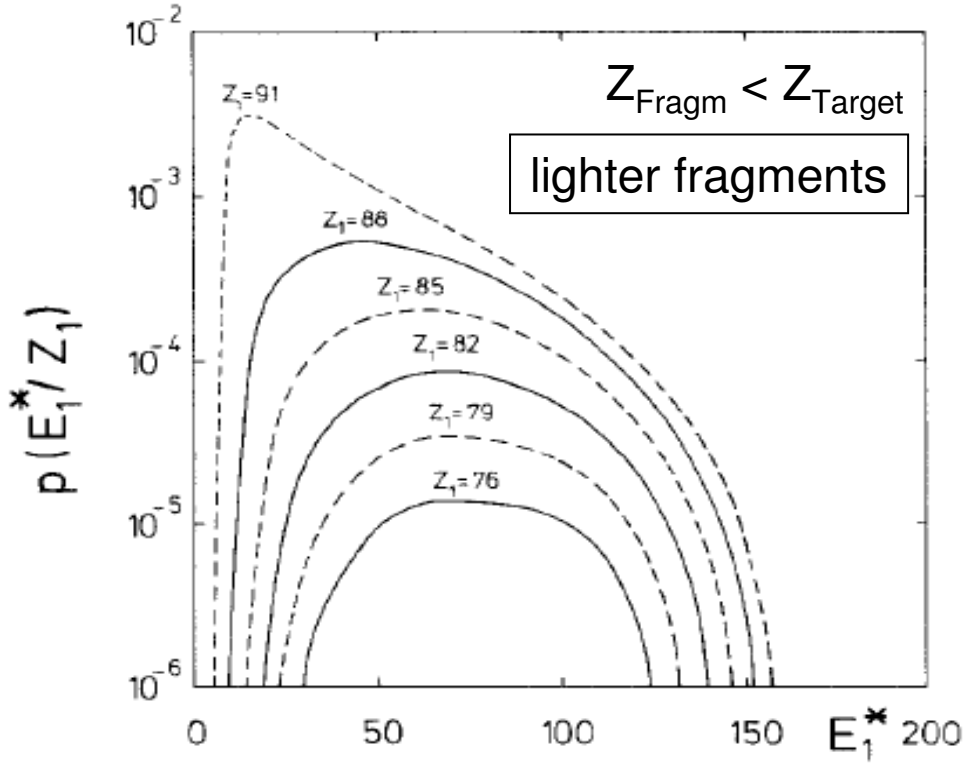
From diffusion model calc.:

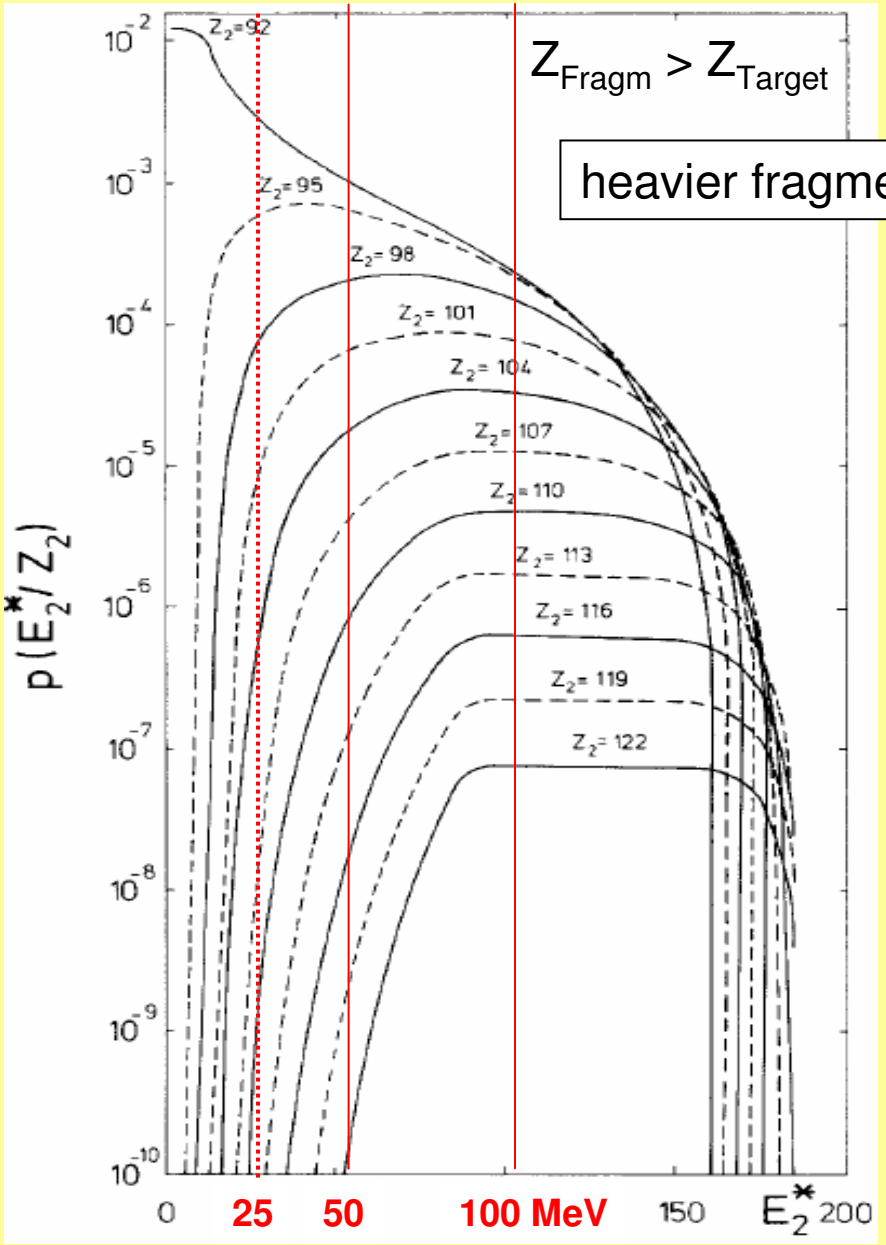
C. Riedel, W. Nörenberg Z. Phys. A 290 (1979) 385

Heavy actinides from deep-inelastic or multi-nucleon transfer reactions are formed in (3n – 4n) channels - independent of beam energy

M. Schädel et al., Phys. Rev. Lett 41 (1978) 469 and doctoral thesis

$^{238}U + ^{238}U$ ➔ Deep-inelastic Transfer; Diffusion Model

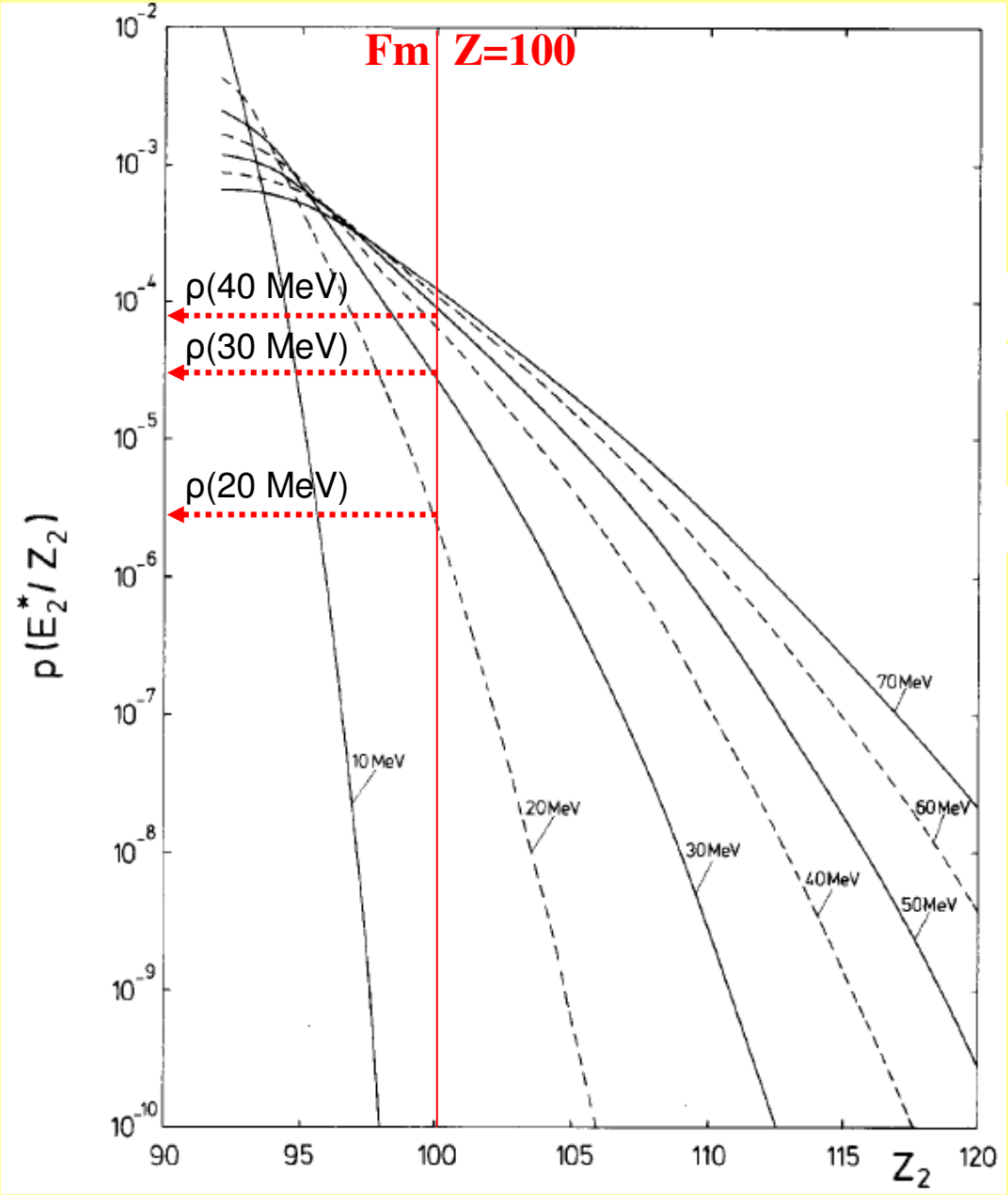




Excitation energy probabilities for different atomic numbers (Z)

C. Riedel, W. Nörenberg, Z. Phys. A 290 (1979) 385

$^{238}U + ^{238}U \rightarrow$ Fm, Deep-inelastic Transfer; Theory: Diffusion Model



Formation probabilities of heavy fragments (Z_2) for different excitation energies

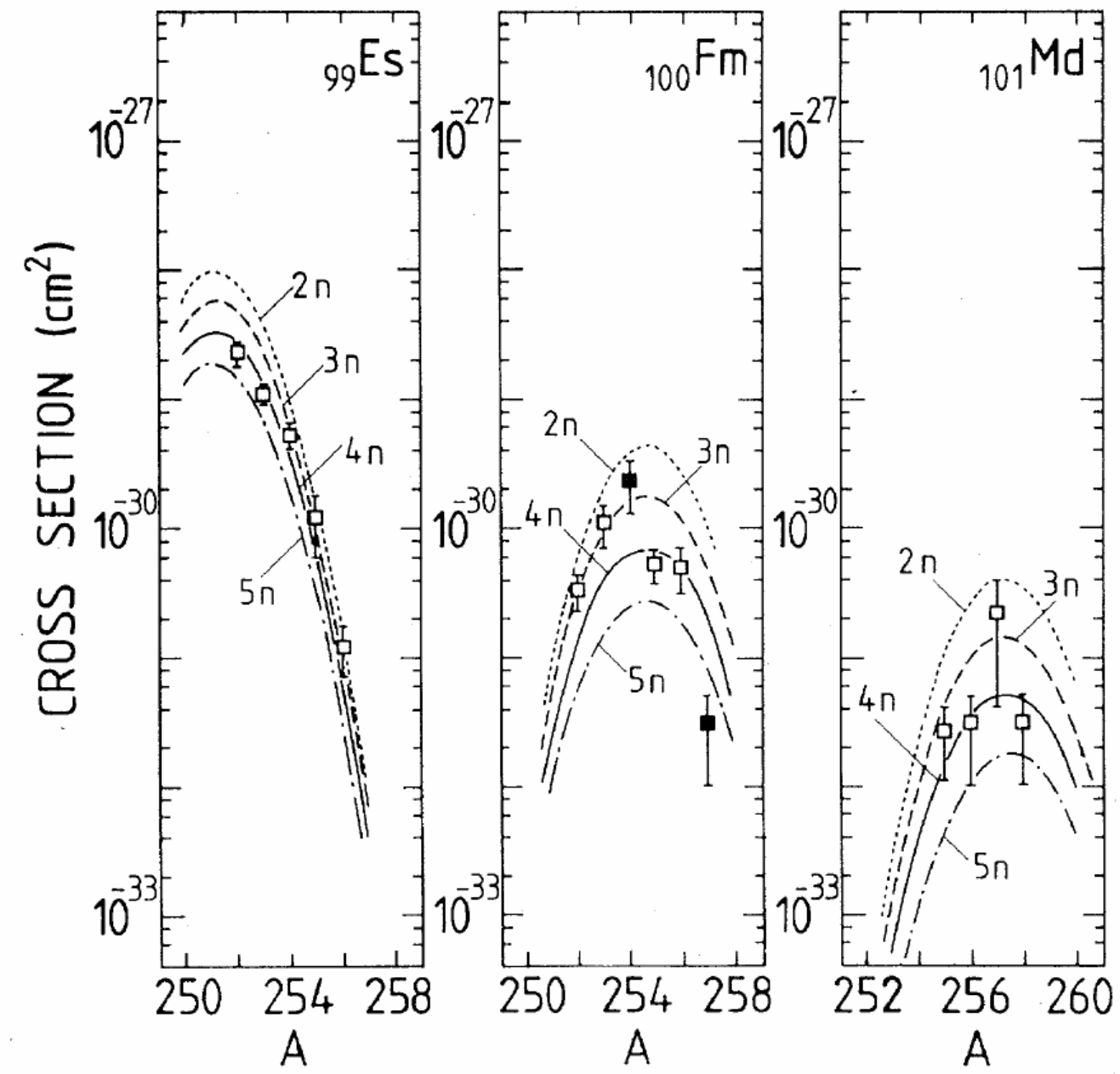
$\rho \approx 8 \times 10^{-5}$ w/ $E^* = 40$ MeV

$\rho \approx 3 \times 10^{-5}$ w/ $E^* = 30$ MeV

$\rho \approx 3 \times 10^{-6}$ w/ $E^* = 20$ MeV

C. Riedel, W. Nörenberg
Z. Phys. A 290 (1979) 385

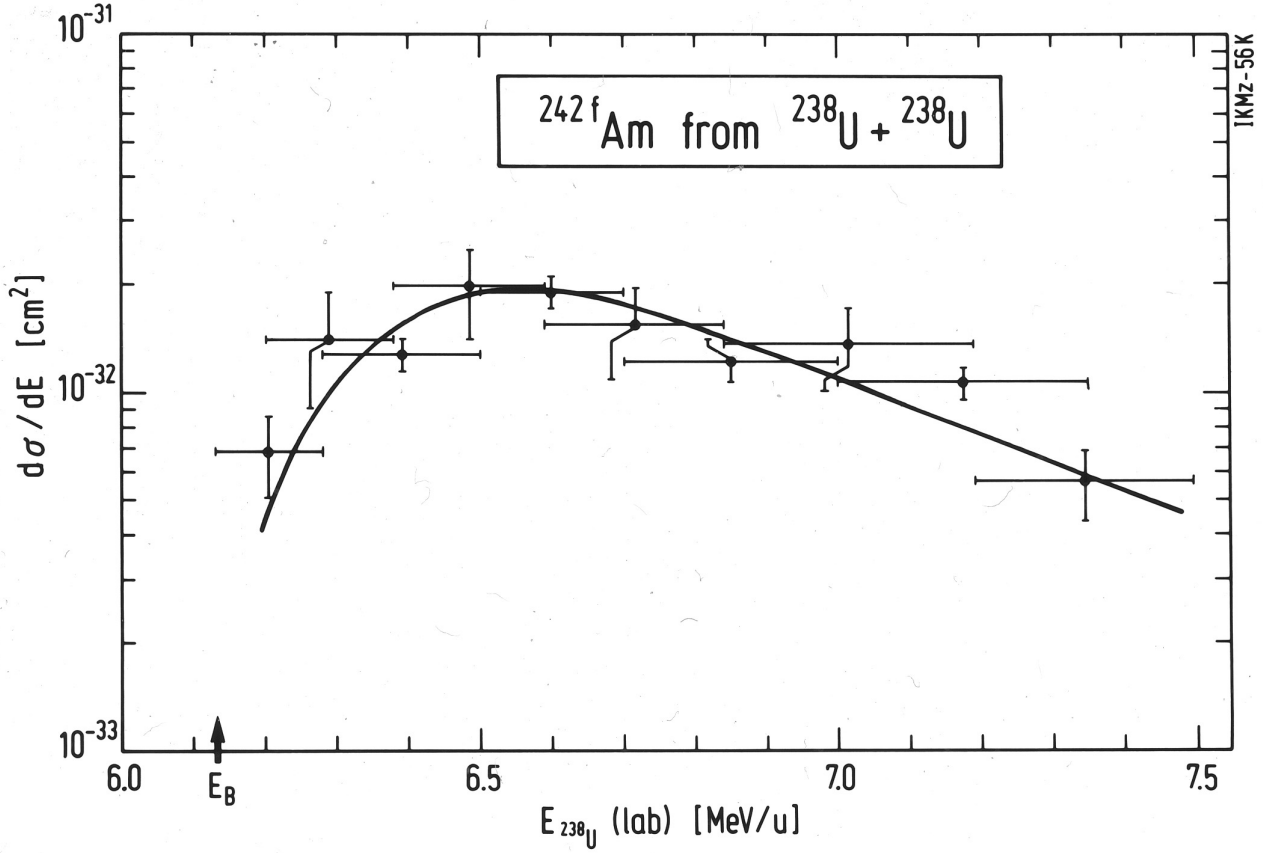
$^{238}U + ^{248}Cm$ ➔ Actinides; Multi-nucleon Transfer



Heavy actinides from multi-nucleon reactions are produced in (3n - 4n) channels

M. Schädel et al., Phys. Rev. Lett. 48 (1982) 852

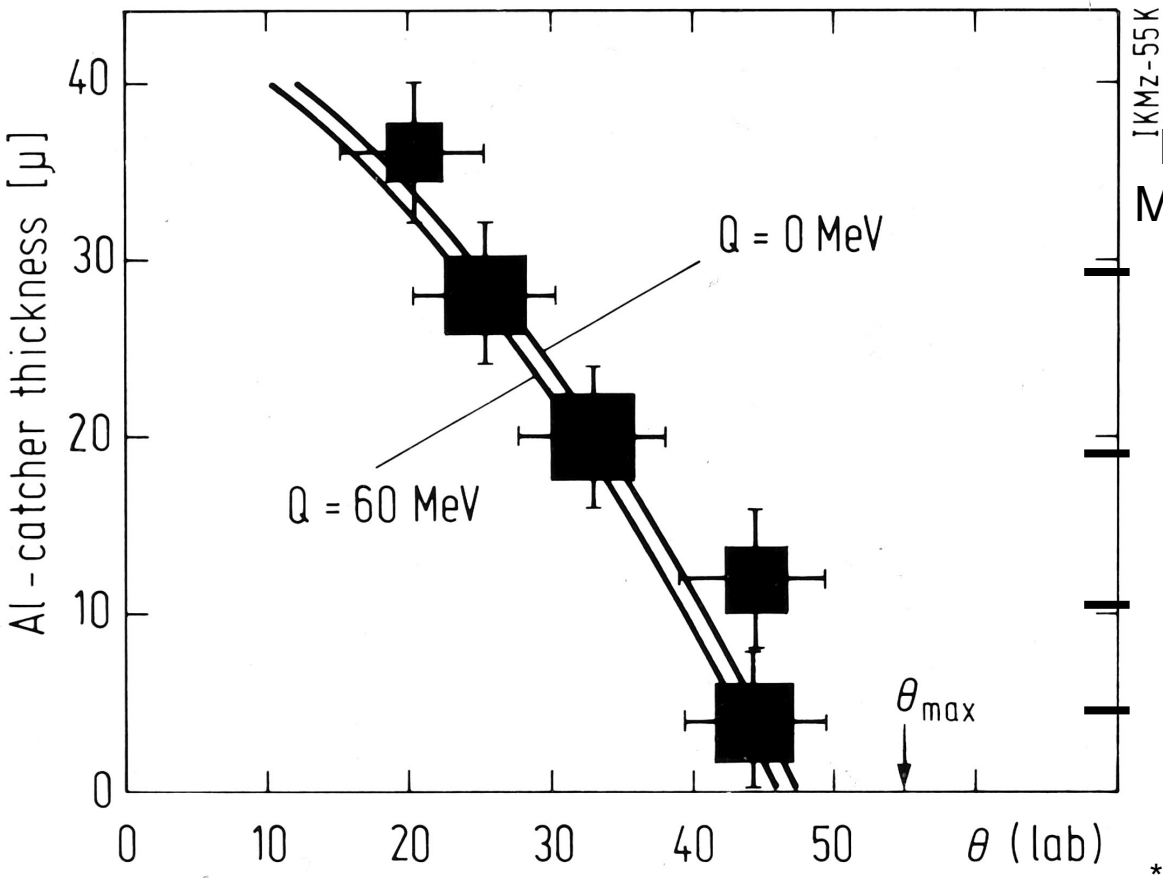
$^{238}U + ^{238}U$: $^{242mf}Am$ – Excitation Function



H.W. Gäggeler et al., NIM 188 (1981) 367

$^{238}U + ^{238}U$: $^{242mf}Am$ – Range + Angular Distribution

8.3 MeV/u (1.35 E/B) ➔ E_B, $^{238}U + ^{238}U$ - "thick" target



$^{243mf}Am^*$

E/A MeV/u	E MeV
2.0	≈ 500
1.0	≈ 250
0.4	≈ 100
0.1	≈ 25

* not corrected for projected ranges and energy loss in target

H.W. Gäggeler et al., NIM 188 (1981) 367

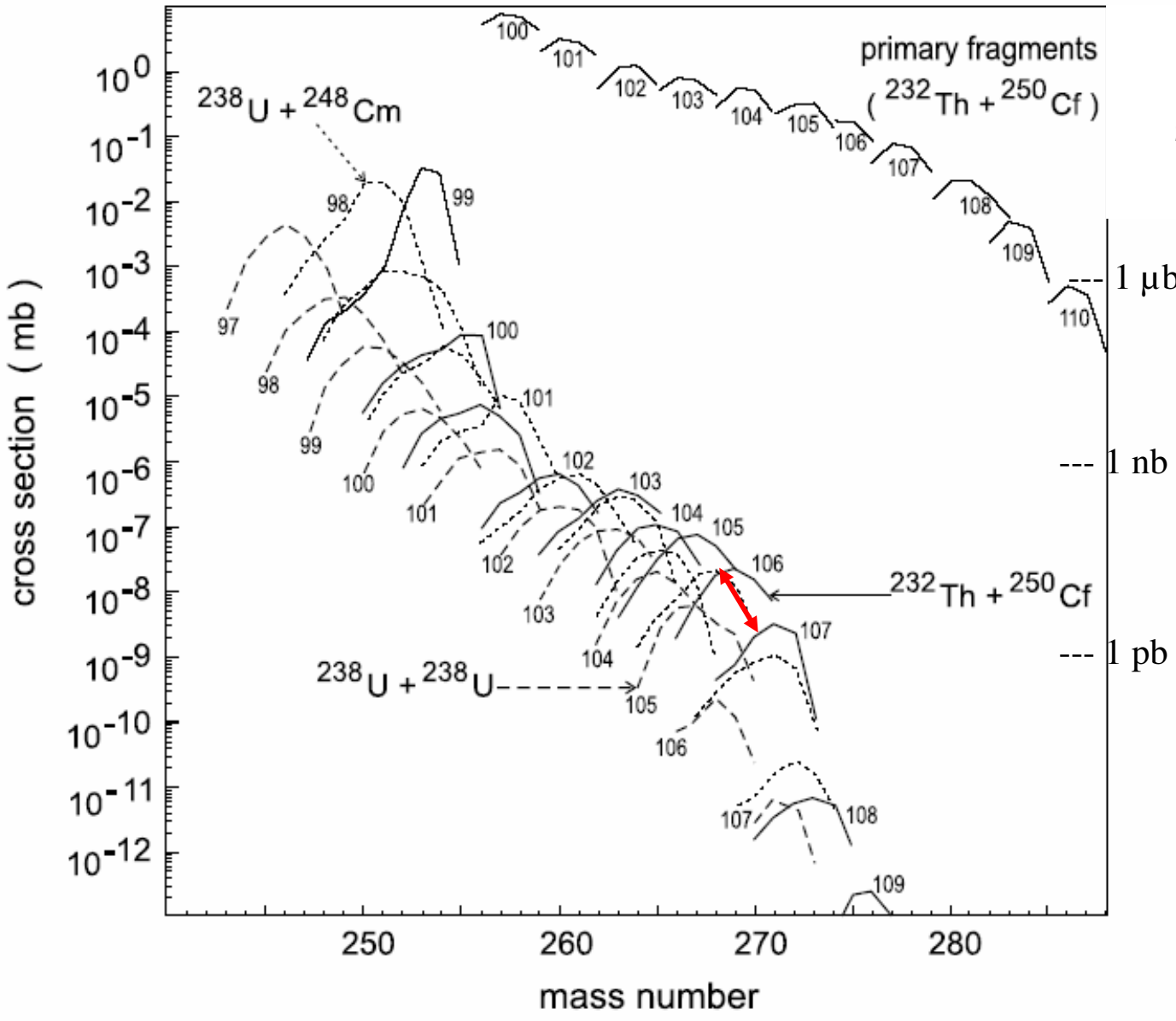
Lines:
Kinematic calculations w/
- formation at $E^* \leq 60$ MeV
- emission at grazing angle

Kinematic calculation#

^{238}U MeV/u	$^{242mf}Am$ MeV	at Θ_{lab}
6.5	1273	25
7.0	1042	38
7.5	880	46
8.0	755	51

W.W. Wilcke et al. At. Data Nucl. Data Tab. 25 (1980) 389

$^{238}U + ^{238}U$ ➔ Transactinides (SHE); Multi-nucleon Transfer

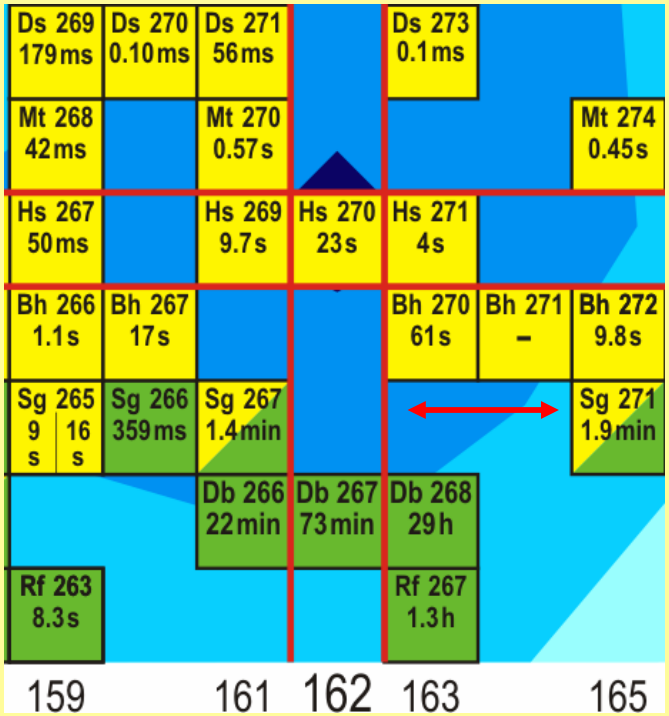


^{271}Sg cross section

Transfer ⇔ Fusion+Decay

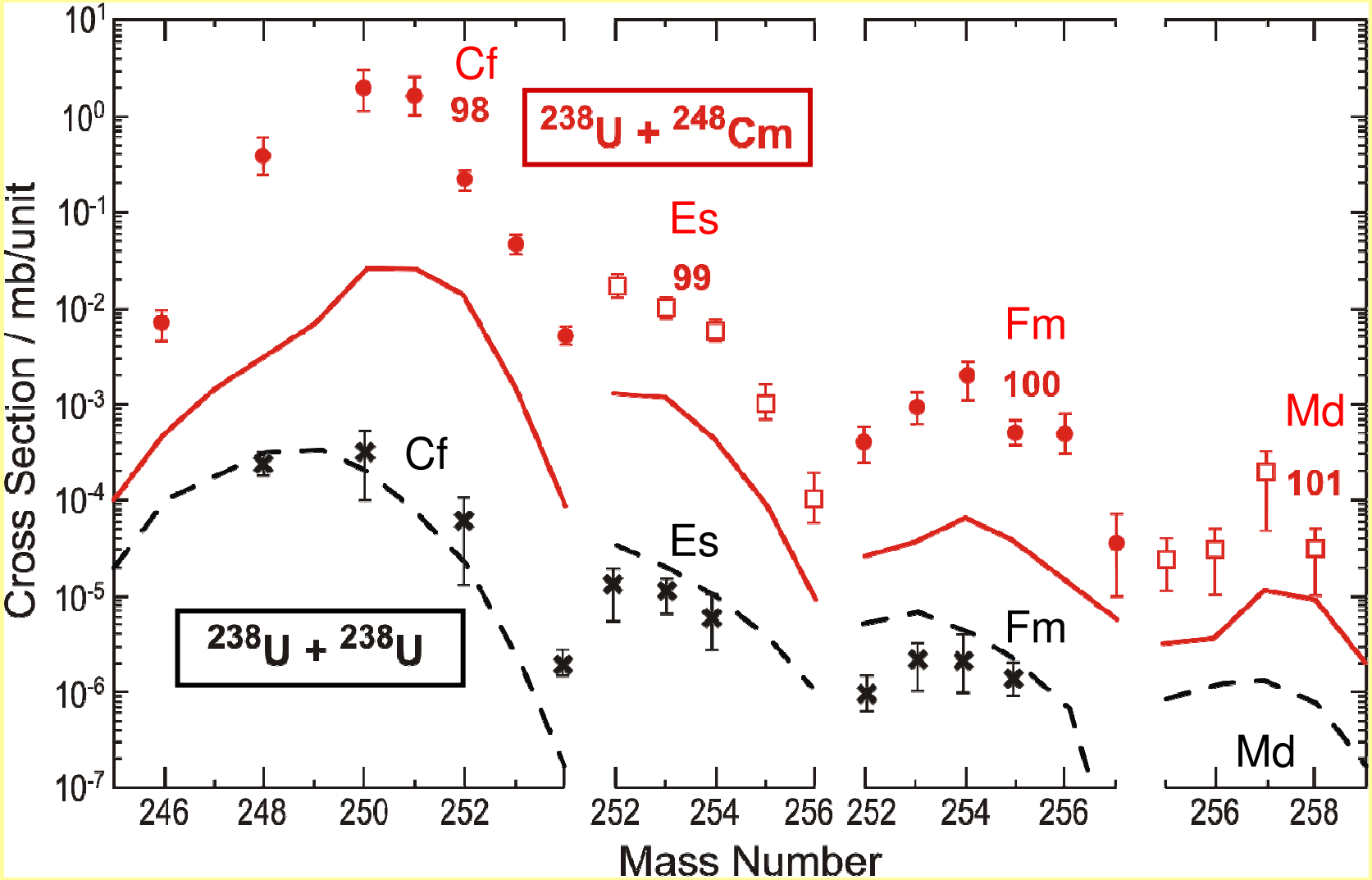
$^{238}U + ^{248}Cm \Leftrightarrow ^{48}Ca + ^{242}Pu$

≈ 1 pb ⇔ ≈ 1 pb



W. Greiner, V. Zagrebaev
J. Nucl. Radiochem. Sci 7 (2006) R1
Nucl. Phys. A 787 (2007) 363c

(^{238}U + ^{238}U) vs (^{238}U + ^{248}Cm) ➔ Actinides; Multi-nucleon Transfer



Experiment (DATA POINTS):

M. Schädel et al.,

-- Phys. Rev. Lett. 41 (1978) 469

-- Phys. Rev. Lett. 48 (1982) 852

Theory (CURVES):

W. Greiner, V. Zagrebaev

-- J. Nucl. Radiochem. Sci 7 (2006) R1

-- Nucl. Phys. A 787 (2007) 363c

Above Target Actinide Production in $^{238}U + ^{238}U(^{248}Cm)$ Multi-nucleon Transfer Reactions Summary

* Use Z_{target} as high as possible; ^{248}Cm as the "workhorse"
* Excitation functions peak at 1.1 E/B
* Products are emitted at grazing angle
* **U-projectile**:
  - \+ highest cross sections, most n-rich distributions
  - ? presumably gain in σ for most n-rich isotopes
  - \- technical difficulties !!!
    (beam intensity, target stability, recoil velocity)

➔ apply for the Z ≥ 106, N ≥ 162 region, but ....

** Use **A < 50 projectiles** for the Z ≤ 106, N ≤ 162 region*