FUSION (& fission) BARRIERS

FROM SELF-CONSISTENT CALCULATIONS AS A DF TEST

1. SHORT REVIEW OF FISSION BARRIERS

2. FUSION BARRIERS:

   - STATIC CALCULATIONS
   - PROBLEMS
   - RESULTS

3. CONCLUSIONS

Fissions barriers: from (n,f), (d,pf), ...
If those are impossible $(Z>100)$:

$$\sigma_{ER}^{A_1+A_2\to B}(E) \approx \pi\frac{\hbar^2}{2\mu E} \times$$

$$\sum_{l=0}^{\infty}\Big\{(2l+1)\,T(E,l) \times$$ ← fusion barrier A_1+A_2

$$P_{CN}(A_1+A_2\to C;\,E,l) \times$$ ← ?

$$P_{ER}(C\to B;\,E^*,l)\Big\}$$ ← fission barrier C (statistical model)

$$\sigma_{capture}(E) = \pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)\,T(E,l)$$

$$\sigma_{fusion}(E) = \pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)\,T(E,l)\,P_{CN}(E,l)$$

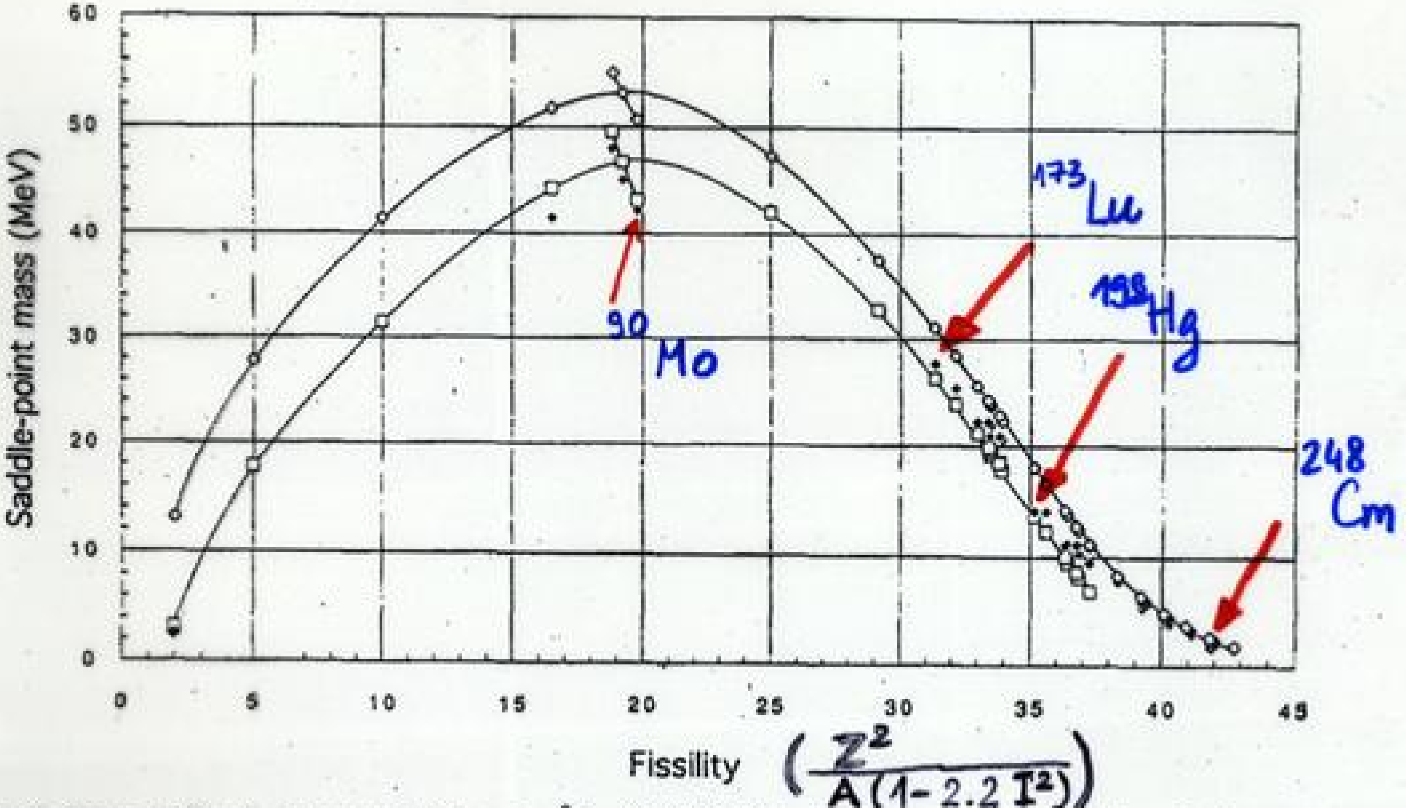


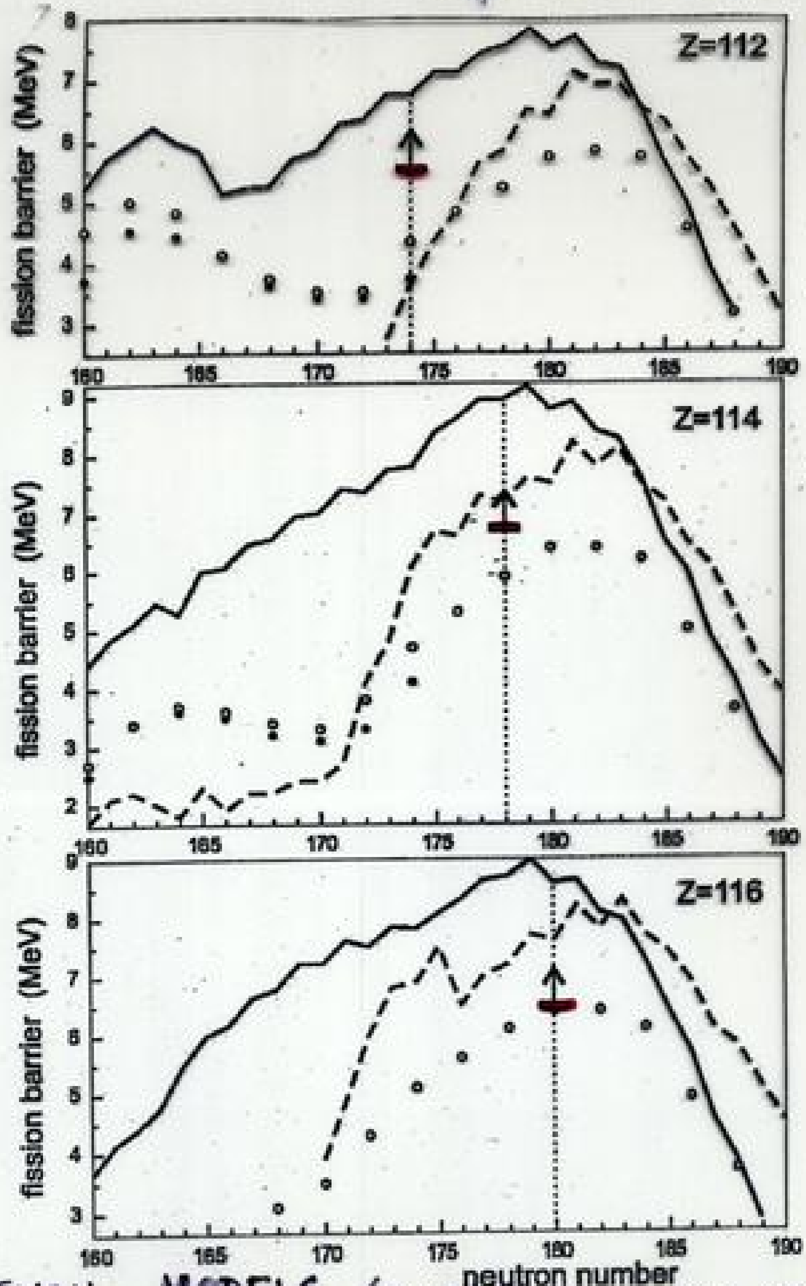
Fig. 3. Same as Fig. 2, but extended down to ^{8}Be (Ref. [5]). The four points around fissility 16–20 refer to ^{75}Br and ^{90,94,98}Mo (Ref. [9]).

(Fission barriers − G.S. Shell Correction) (◆) - measured

← "MACROSCOPIC" BARRIERS

(W.D. Myers & W.J. Swiatecki, N.P.A 612, p. 249

Experimental barriers for the heaviest nuclei
M.G. Itkis, Yu. Ts. Oganessian & V.I. Zagrebaev
Phys. Rev. C 65 044602 (2002)



VS PHENOM. MODELS (SMOOTH ENERGY + SHELL CORR.)

—— P. Möller et al., At. Data 59, 185 (1995)

---- A. Mamdouh et al., N.P.A 679, 337 (2001)

oooo R. Smolańczuk et. al.

* Results from Skyrme HF :
& relativistic MF

(T. Bürvenich et al., Phys. Rev. C 69, 014307 (2004))

	Expt.	NL3	SLy6
$^{286}112$	5.5	3.38	6.06
$^{292}114$	6.7	(290) 3.56	(290) 8.52
$^{296}116$	6.5	(294) 3.80	(294) 9.59

← WITHOUT NONAXIALITY
NO CORRECTIONS

Too large barriers for actinides.

* Skyrme SkM* :

(L. Bonneau et al., Eur. Phys. J A 21, 391 (2004))

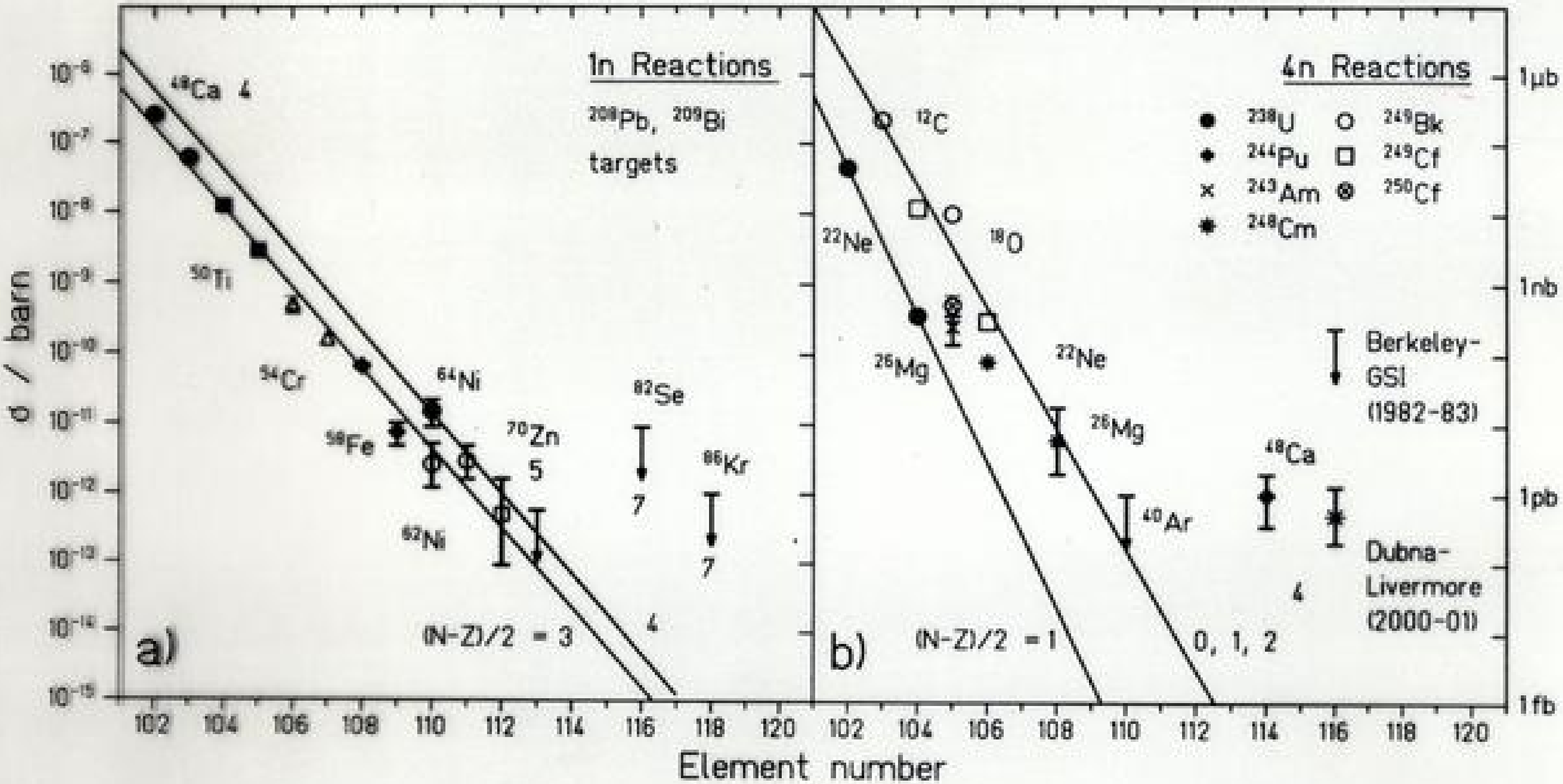
	B_A exp.	B_A cal.	B_B exp.	B_B cal.
^{230}Th	6.1	4.9	6.5	4.4
^{232}Th	5.8	5.5	6.2	4.1
^{234}U	5.6	5.3	5.5	5.1
^{236}U	5.6	6.2	5.6	4.6
^{240}Pu	5.6	7.1	5.1	4.1
^{252}Cf	5.3	7.1	3.5	2.9

WITH NONAXIALITY
&
ROT. CORRECTION
$\left(-\frac{I^2}{2\mathcal{J}}\right)$

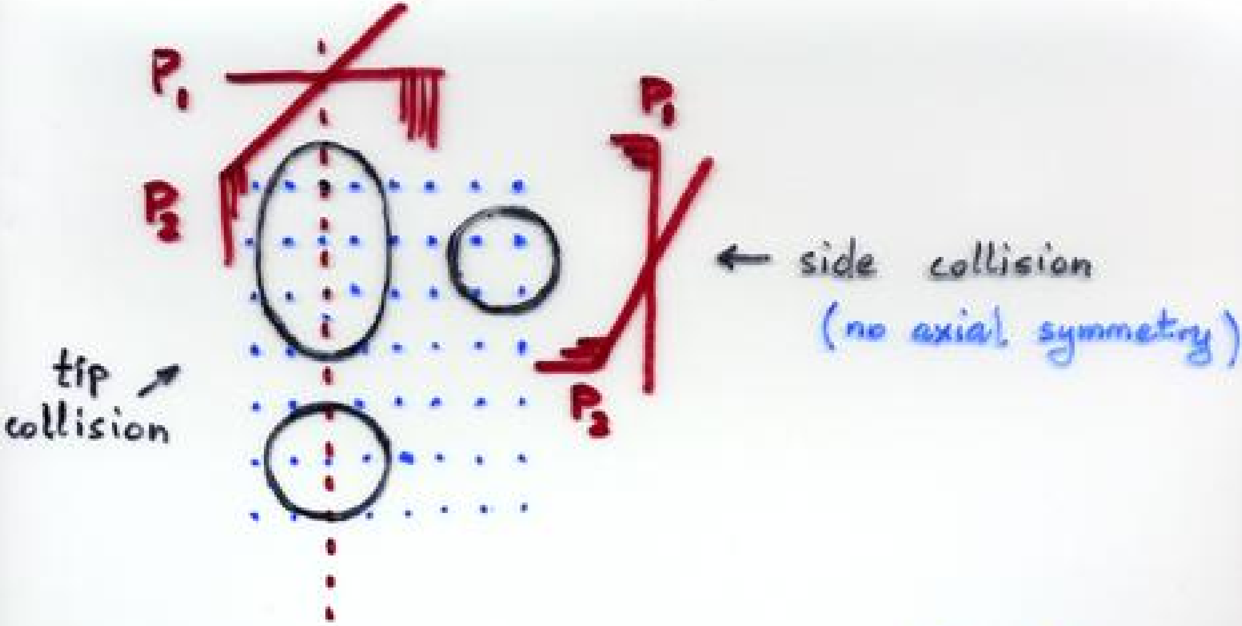
(Probably too large barriers for superheavy)

Nucleus-nucleus potentials at near-barrier energies from selfconsistent calculations.

0. Motivation
1. Definition of the static potential.
2. Important technical problems:
   A. Specification of the entrance channel.
   B. Question of the relative kinetic energy.
   C. Continuous change of pairing in a system undergoing fusion or fission
3. Examples of results and comparisons to data.
   A) Barriers
   B) Landscapes
4. Conclusions.



S. Hofmann (GSI)



static barrier :

$$V(R) = \overbrace{\underset{\overset{\wedge}{0}}{E_{1+2}(R)} + \underbrace{B_1 + B_2}_{\overset{\vee}{0}}}^{\text{for } E_{1+2}(g.s.) \to Q \text{ value}}$$

Within HF: To have $V = 0$ at $R \to \infty$:

$$V \to V - E_{\text{kinetic relative}}$$

$$\downarrow$$

$$\frac{A_2 \langle t_1 \rangle + A_1 \langle t_2 \rangle}{A_1 + A_2}$$

- We calculate V for $\ell = 0$.
- We use Skyrme force SkM*
  (also SkP and SLy6)
- No pairing or δ pairing with cutoff

Fragments A_1 and A_2 ;

$$i=1,2: \overline{P}_i = \left(\sum_{k\in i} \overline{p}_k\right) \quad ; \quad \overline{P} = \overline{P}_1 + \overline{P}_2$$

$$\underbrace{\frac{\overline{P}_1^2}{A_1} + \frac{\overline{P}_2^2}{A_2}}_{} = \underbrace{\frac{A_2\,\overline{P}_1^2 + A_1\overline{P}_2^2}{A_1+A_2}}_{} + \underbrace{\frac{\overline{P}^2}{A_1+A_2}}_{} - \frac{\overline{P}_1\cdot\overline{P}_2}{A_1+A_2}$$

E_{cm} correction for 2 fragments

$E_{kinetic}$ relative

E_{cm} for a compound fragment

With the 2-body part:

SLy6

$$E_{cm} = \frac{\langle P^2\rangle}{A} = \begin{cases} 5.85 \text{ MeV for } ^{208}Pb \\ 8.20 \text{ MeV for } ^{48}Ca \\ 5.7 \text{ MeV for } ^{256}No \end{cases}$$

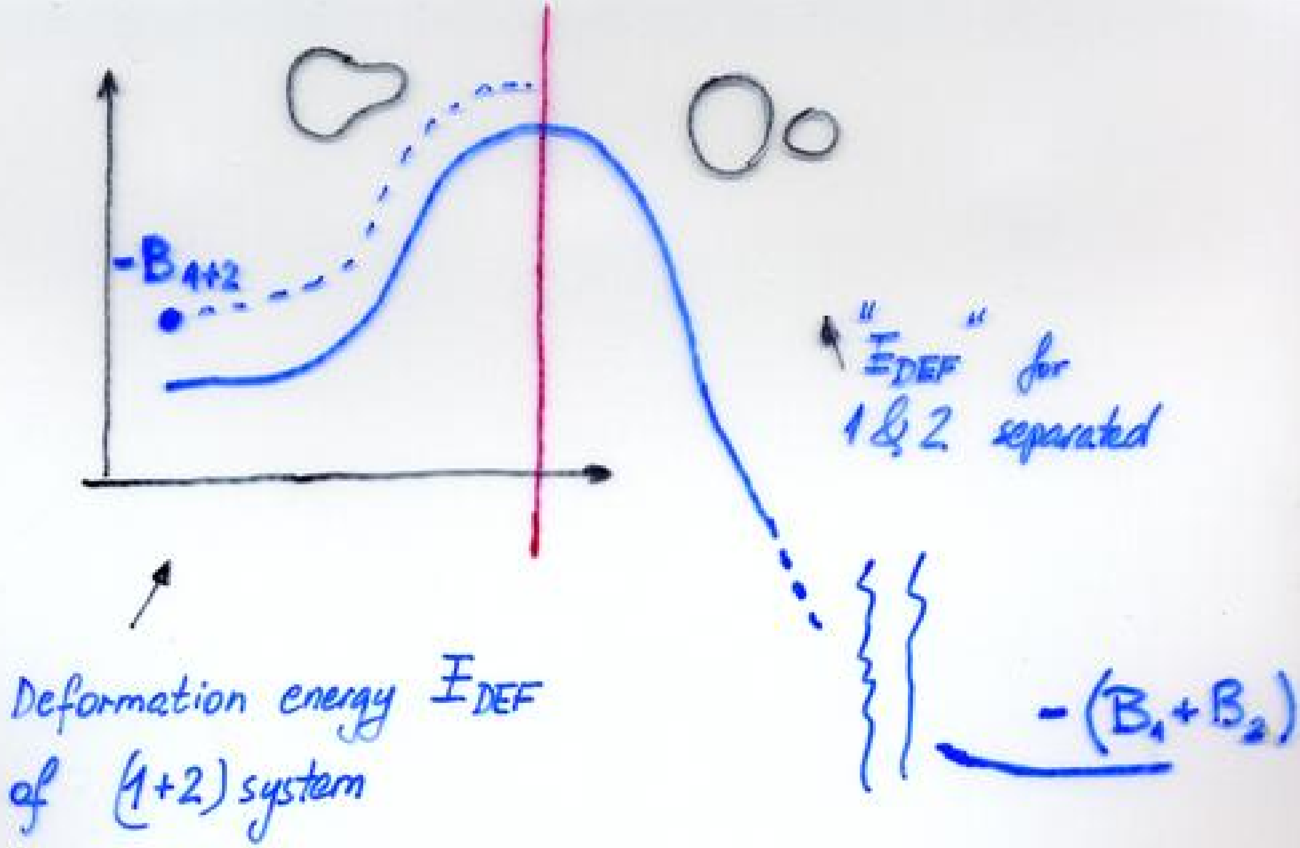
$$\rightarrow \quad E_{cm}(^{208}Pb) + E_{cm}(^{48}Ca) - E_{cm}(^{256}No) \approx$$

e.g. J.F. Berger & D. Gogny N.P.A333, 302 (1980) $= \underline{8.3 \text{ MeV}}$

By this amount one has to lower the barrier for separating fragments.

It should have effect on barriers for fission of the light nuclei. (They are close to scission.)

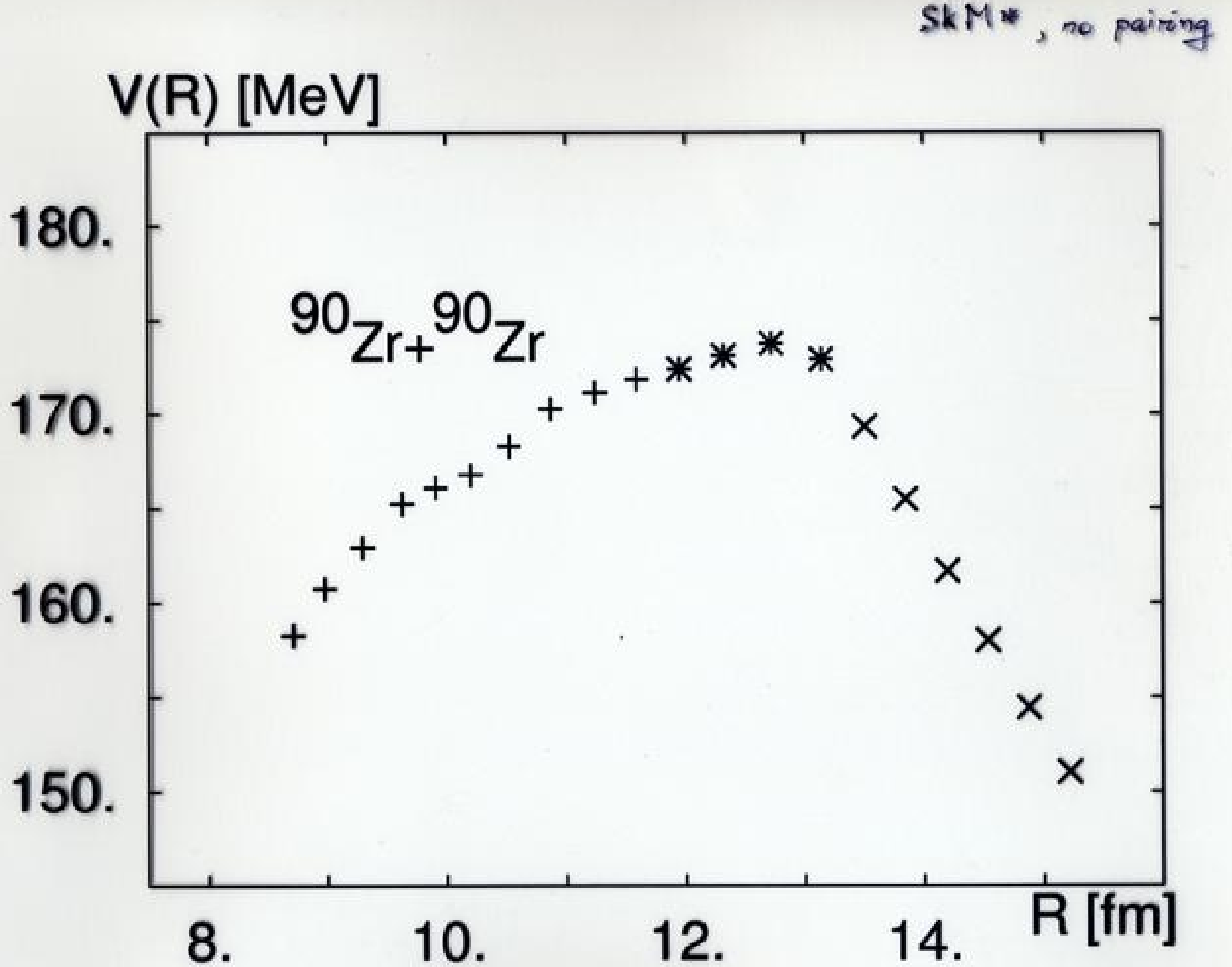
For SkM* : $E_{cm} \simeq \langle \hat{t} \rangle_{\text{one body}} = 14-18$ MeV

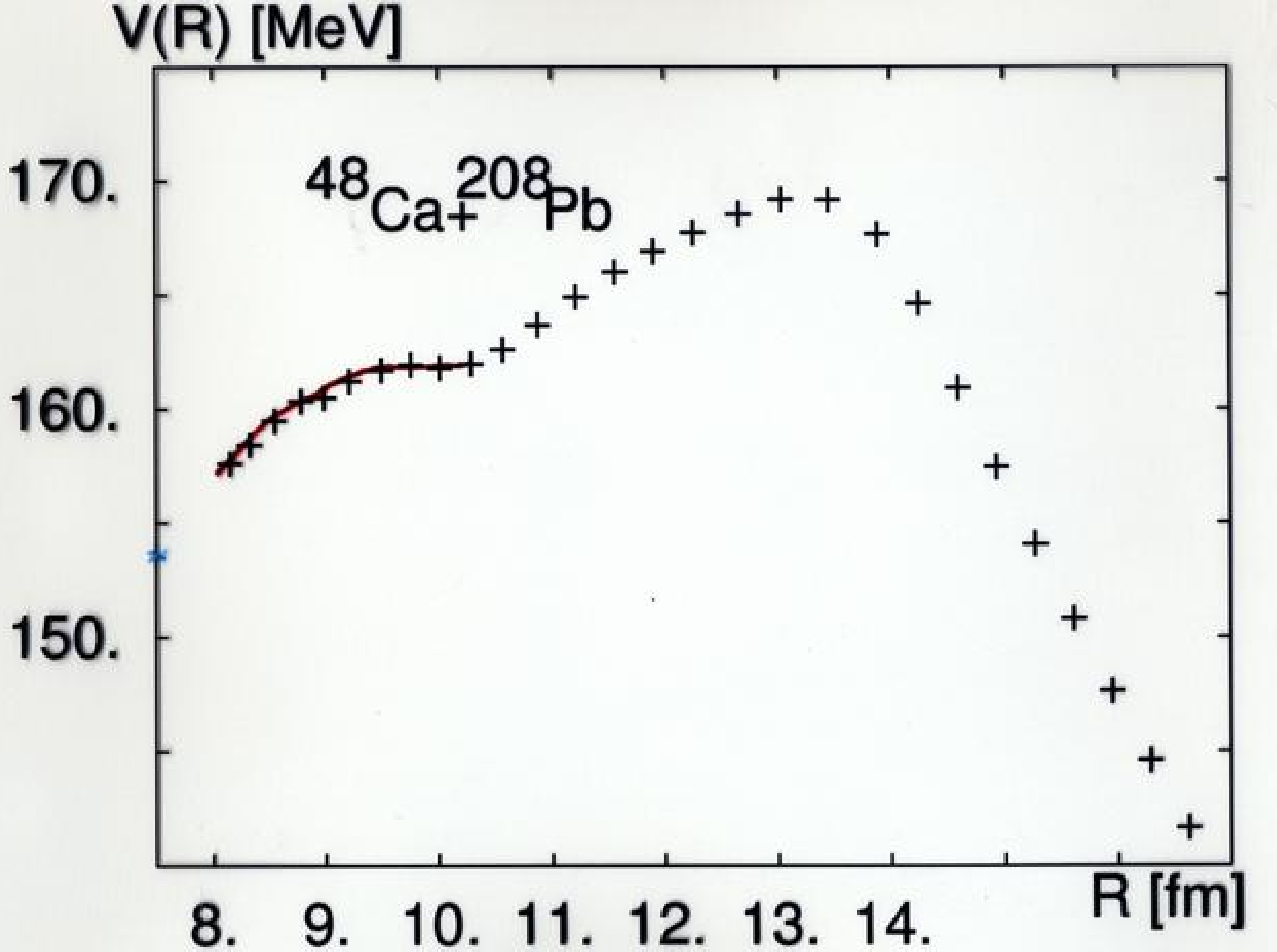


$$E^* - B_{1+2} = -(B_1 + B_2) + \underbrace{V_{fus} + \varepsilon}_{E_{kin}(CM)}$$

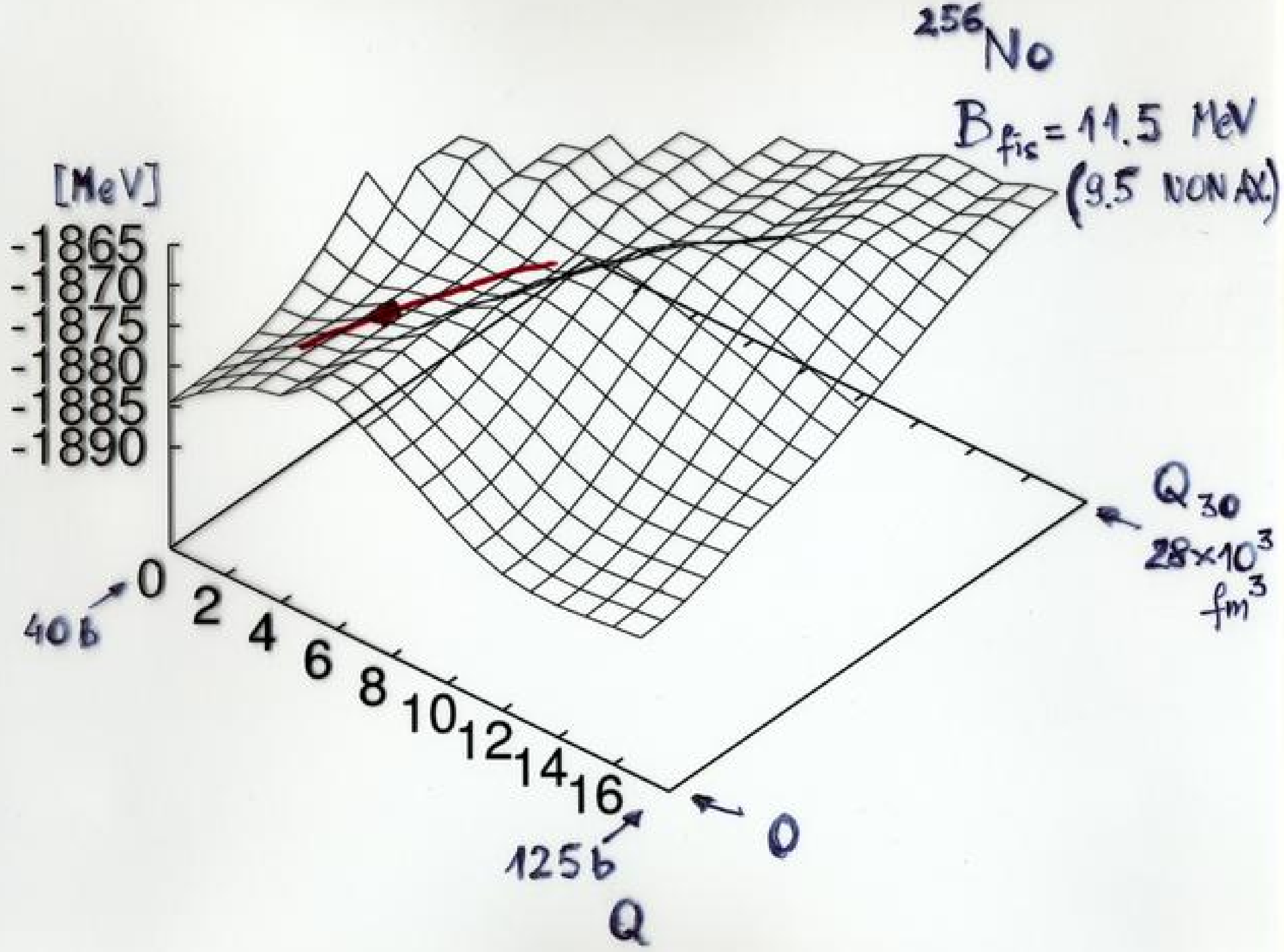
$$E^*_{min} = Q + V_{fus}$$

(no tunneling)

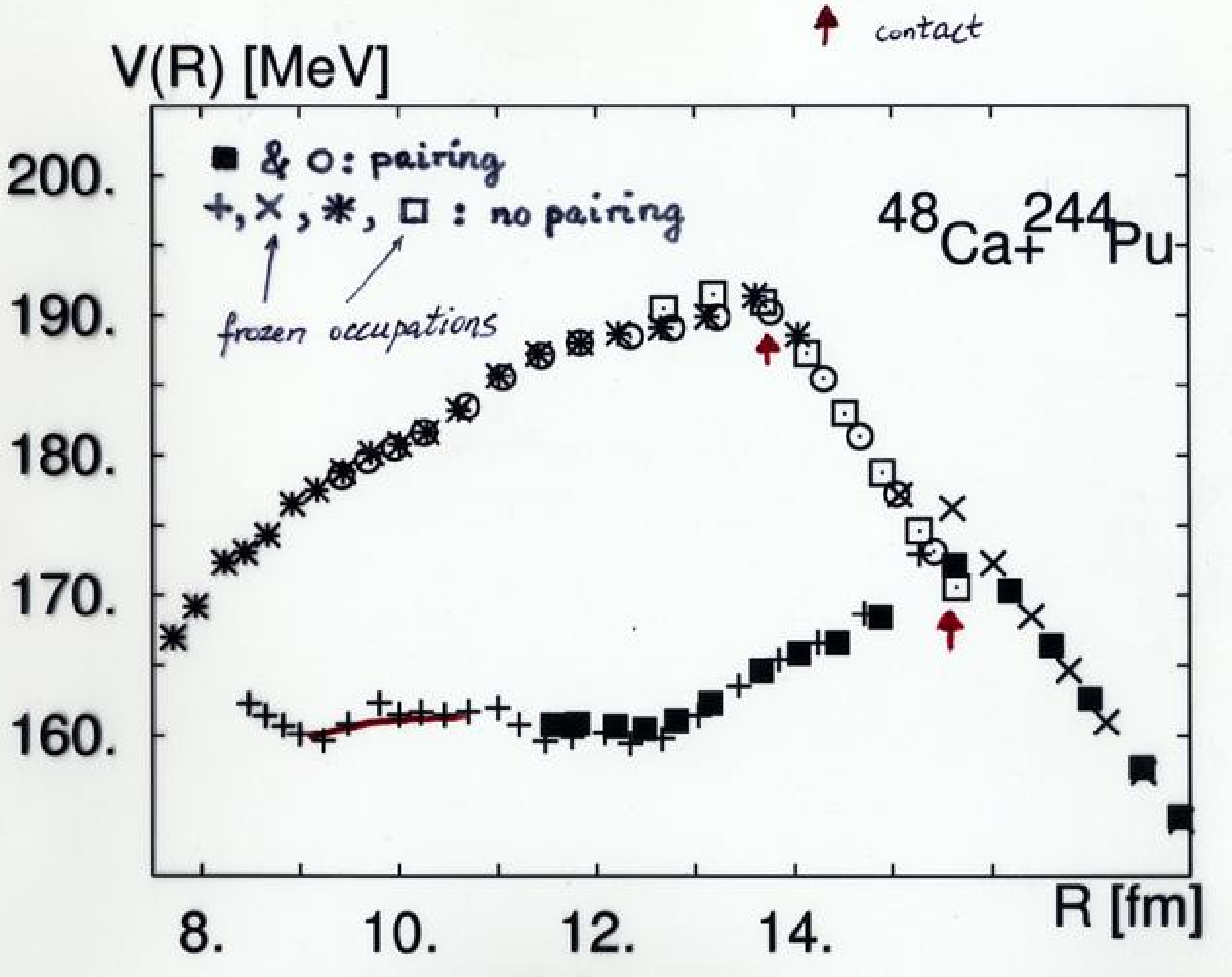

SkM*, no pairing
V(R) [MeV]
180.
170.
160.
150.
^{90}Zr+^{90}Zr
8.
10.
12.
14.
R [fm]



V(R) [MeV]
170.
160.
150.
^{48}Ca+^{208}Pb
8.
9.
10.
11.
12.
13.
14.
R [fm]

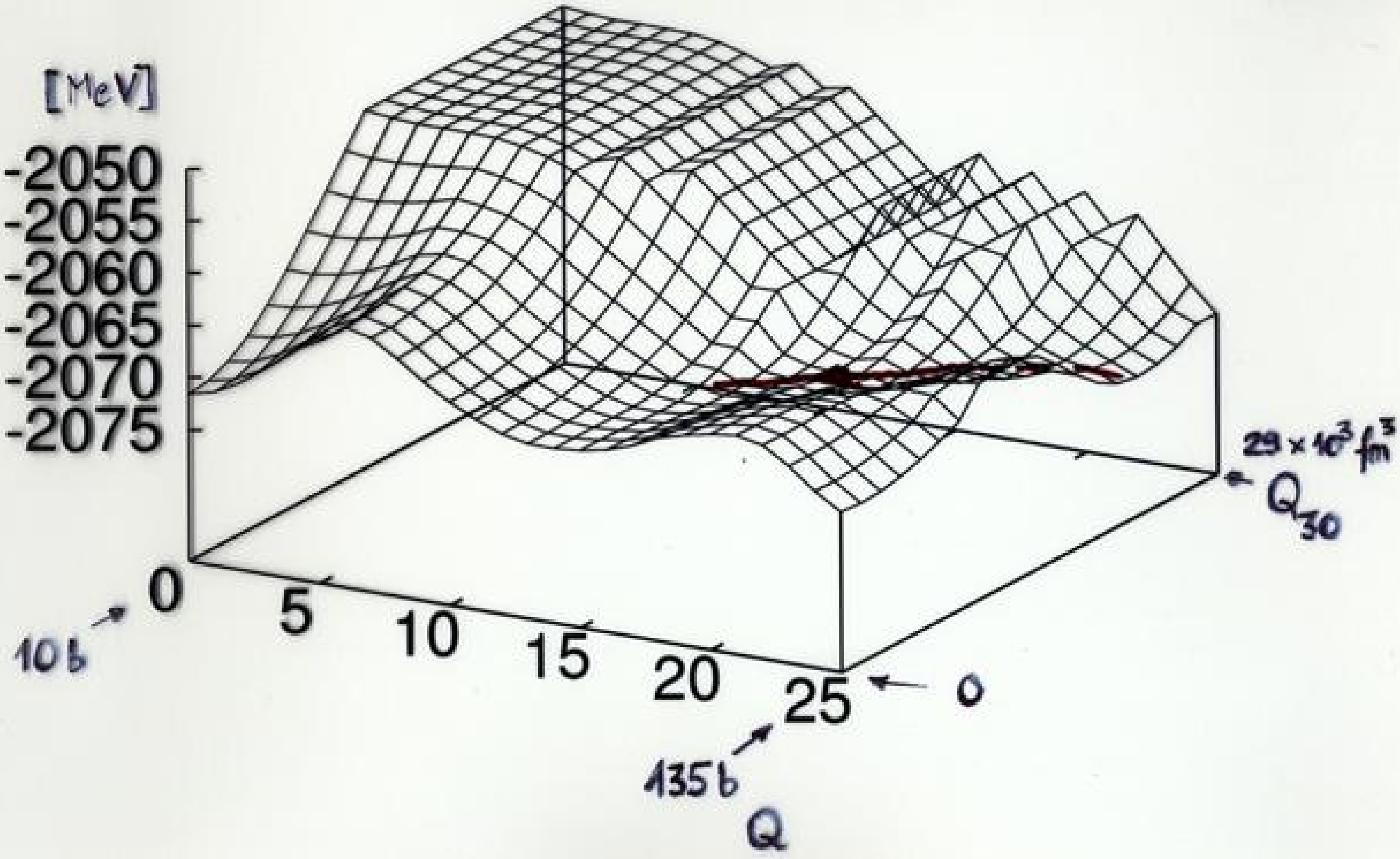


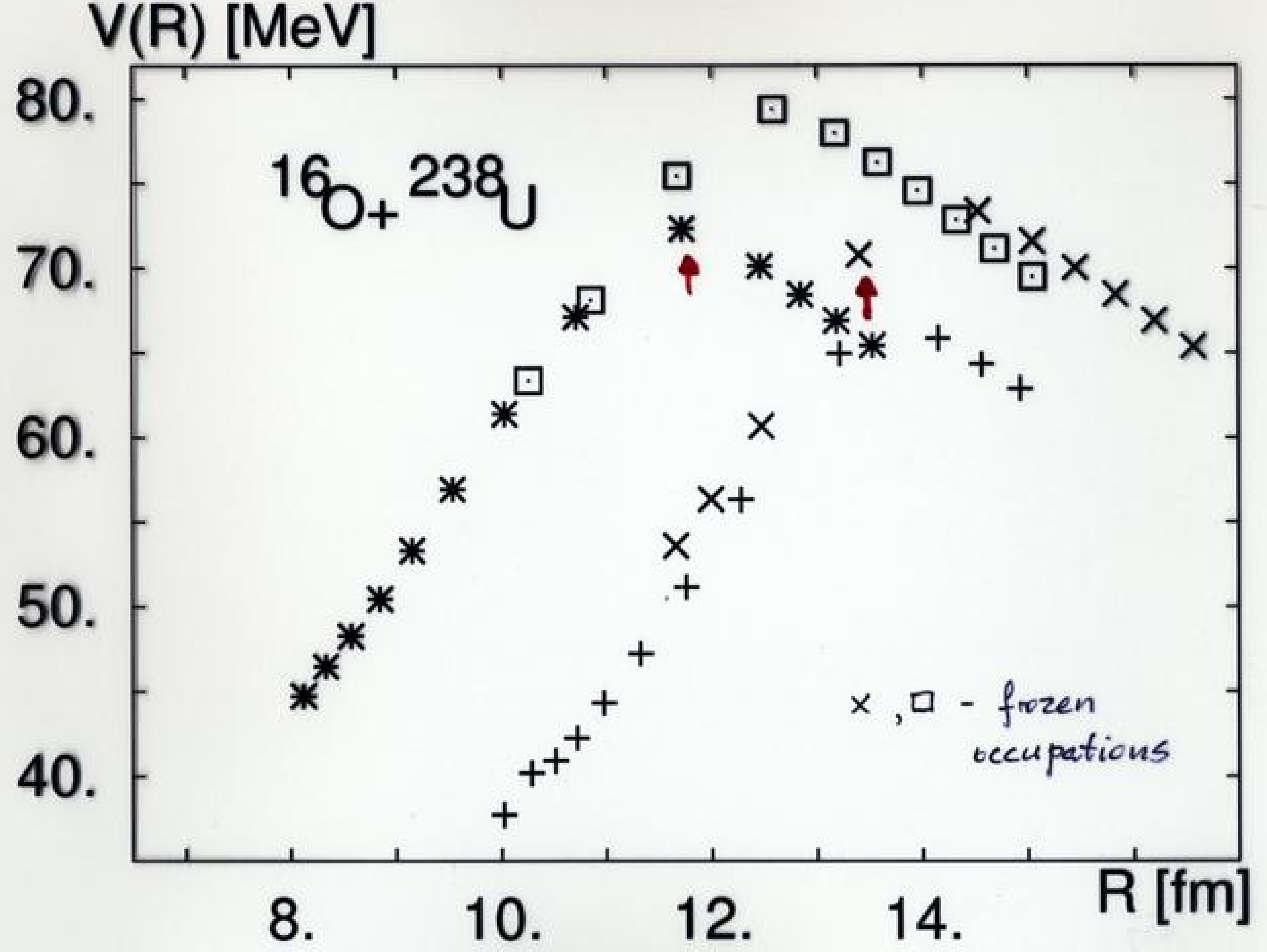
256No
B fis = 11.5 MeV
(9.5 NON AX)
[MeV]
-1865
-1870
-1875
-1880
-1885
-1890
0
2
4
6
8
10
12
14
16
40 b
125 b
Q
Q 30
28×10³ fm³
0


contact
V(R) [MeV]
■ & ○: pairing
+, ×, ✱, □ : no pairing
frozen occupations
^{48}Ca+^{244}Pu
200.
190.
180.
170.
160.
8.
10.
12.
14.
R [fm]

$^{292}114$

$B_{fis} = 9.1$ ($\to 7.5$ NONAX.)





V(R) [MeV]
80.
70.
60.
50.
40.
^{16}O+^{238}U
×, □ - frozen occupations
8.
10.
12.
14.
R [fm]

System	Q	$Q_{th.err}$	B_{cal}	B_{thre}	$E_{cm}(ER)$	B^{int}_{Bass}
^{40}Ca+^{40}Ca	14.3	3.5	52	50.2±0.2		52.5
^{64}Ni+^{64}Ni	48.8		86.5	89.5±0.3		94.5
^{90}Zr+^{40}Ca	57.3	5	92	92.7±0.6		97.7
^{96}Zr+^{40}Ca	41.1	6	85	87.5±0.3		96.6
^{90}Zr+^{90}Zr	157.3	11	173.5	~175.85		181.0
^{110}Pd+^{32}S	35.4	6	82.5(87.5)	80.4±0.2		88.9
^{110}Pd+^{110}Pd	199.7		199(220.5)	-	$\geq$ 228	228.3
^{182}W+^{32}S	84.9		123(133.5)	-	$\geq$ 124	134.3
^{154}Sm+^{60}Ni	147.6		166.5(184.5)	-	> 182	191.5
^{238}U+^{16}O	38.3	5	73.5(79.5)	~71		82.9
^{132}Sn+^{64}Ni	111.1	11	147	-	$\geq$ 143	155.7
^{132}Sn+^{132}Sn	260.8 *	25	254.5	-	-	257.4
^{208}Pb+^{48}Ca	153.8	17	169	169±2^{C}		176.1
^{208}Pb+^{64}Ni	225.1		229	-	235.3-238.2	241.3
^{208}Pb+^{70}Zn	244.9 *		240	-	257.2-259.1	256.3
^{208}Pb+^{82}Ge	262.5 *		260.5	-	-	268.8
^{238}U+^{48}Ca	160.8 *		167.5(188)	182±2^{C}	192.2	193.8
^{244}Pu+^{48}Ca	163.0 *	13	173(191.5)	-	194.5-202	197.3
^{248}Cm+^{48}Ca	169.3 *		179.5(195.5)	-	199.7-205.1	201.0
^{250}Cf+^{48}Ca	177.0 *		184(200.5)	-	-	205.1

B_{thre} : Phys. Rev. C 64, 024611 (2001)
K. Siwek Wilczyńska & J. Wilczyński ; C – capture data

Conclusions

1. $B^{fusion}_{calculated}$ seem to be better than the Q values and masses : probable error cancellation.

2. V(R) suggest fusion hindrance in tip collisions for heavier systems.

3. Energy landscapes provide additonal hints for CN formation hindrance.

4. Superheavy CN formation easier on deformed targets (projectiles).

Conclusions (general)

1. Barriers are important data for DFT

2. There are still problems with proper calculation of barriers.

3. Medium - heavy nuclei important (macroscopic effect)

4. Possible new terms pertaining to barriers:

$$-(\nabla\rho)^2\tau \xrightarrow[\text{it safe}]{\text{to make}} \frac{M}{1+C(\nabla\rho)^2}\tau$$

$\downarrow$

surface peak
of the effective mass