Adiabatic fusion barriers from self-consistent calculations

1. Motivation
2. Important problems:

A) Specification of the entrance channel

B) Continuous change of pairing between 2- and 1-piece shape

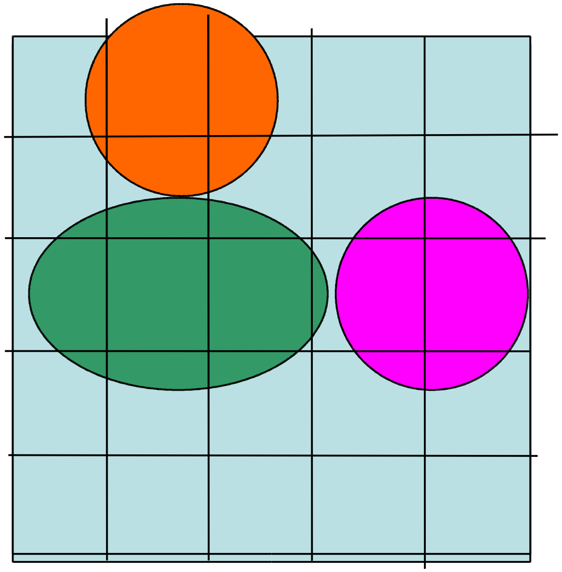
C) Question of relative kinetic energy (!)

3. Examples of results& comparisons to data

A) Barriers

B) Landscapes

4. Conclusions



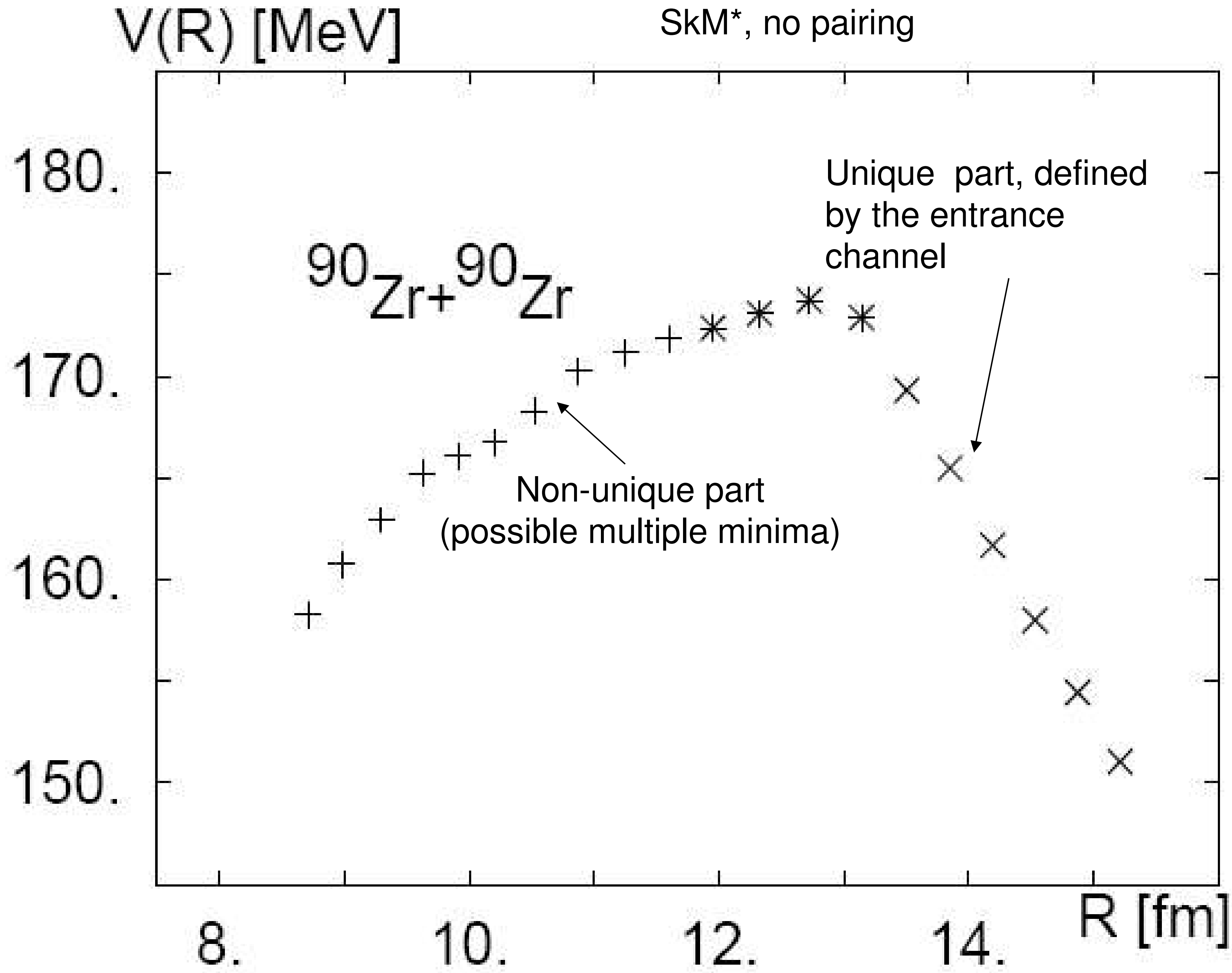
Our code assumes two symmetry planes, so we can study tip- and
side collisions.
The HF (BCS) problem is solved on
a spatial mesh.

Static barrier:

$$V(R) = E[1+2](R)+B1+B2, \qquad (1)$$

where B1&B2 positive binding energies and E[1+2]
- negative HF(BCS) energy of the combined system.

We calculate V(R) for l=0,
use Skyrme forces SkM* nad SLy6,
include no pairing, or delta-pairing with cut-off.
The latter ensures smooth transition of pairing from
2- to 1-piece shape.



V(R) [MeV]
SkM*, no pairing
180.
170.
160.
150.
$^{90}Zr+^{90}Zr$
Unique part, defined by the entrance channel
Non-unique part (possible multiple minima)
8.
10.
12.
14.
R [fm]

Various forces have specific prescriptions to correct for the c.m. motion of the system:

-one-body part of P^2/2Am – amounts to 16.5-18.5 MeV (like SkM*)

-total P^2/2Am (with two body part) – amounts to 5-8 MeV (like SLy6)

To have V=0 at infinity, one has to replace: V by V-E rel. kin., where the relative kinetic energy at infinity is:

(A2*t1+A1*t2)/(A1+A2),

with t1 & t2 c.m. kinetic energies of the fragments.

Example: for the merging fragments 48Ca and 208Pb one has with SLy6:

Ecm(48Ca)=8.2 MeV,
Ecm(208Pb)=5.9 MeV,
Ecm(256No)=5.7 MeV,

so one has to subtract 8.4 MeV from (1).

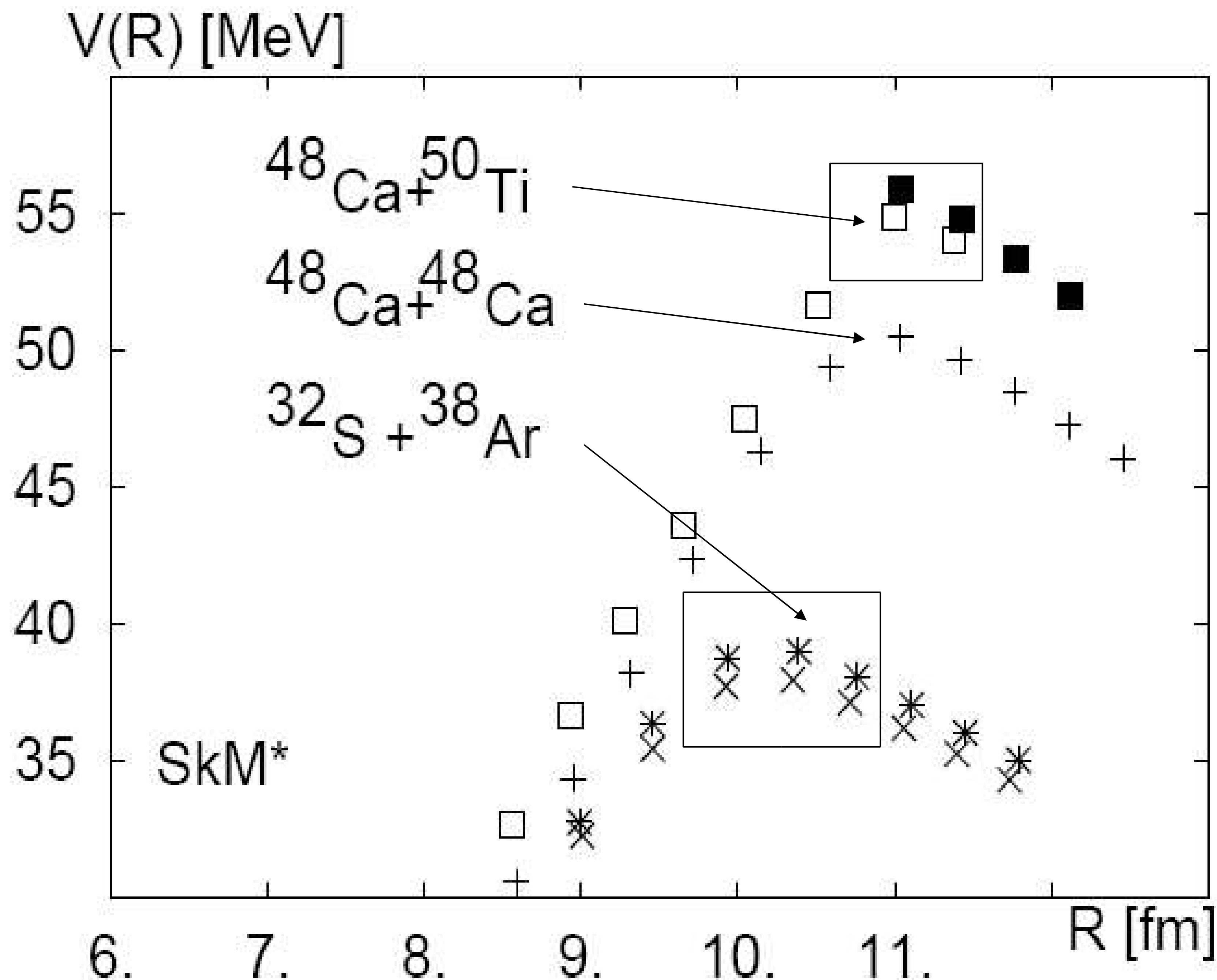
This subtraction is clear for light fusing systems, with barriers at nearly separated shapes.
For heavier systems the barriers correspond to some density overlap, so the subtraction should be partial.

When two fragments merge into one, their relative kinetic energy becomes a part of the potential energy.

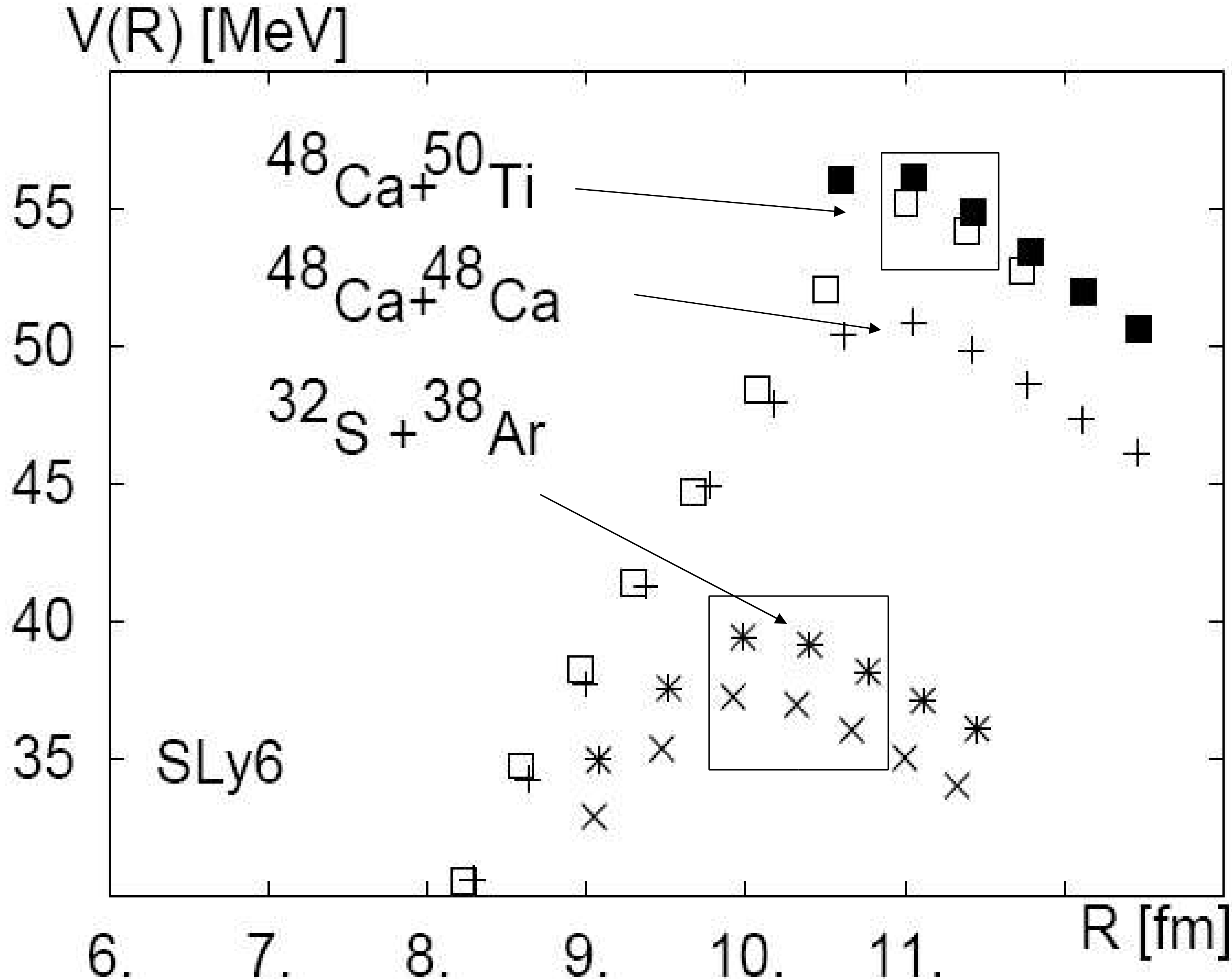
No exact treatment of this problem is known.

Our choice:
-apply subtraction for all points of the fusion barrier,
- suppress it when presenting energy landscapes for one system.

Results: - light projectile & target
- one of them heavy



V(R) [MeV]
55
50
45
40
35
$^{48}Ca+^{50}Ti$
$^{48}Ca+^{48}Ca$
$^{32}S+^{38}Ar$
SkM*
6.
7.
8.
9.
10.
11.
R [fm]

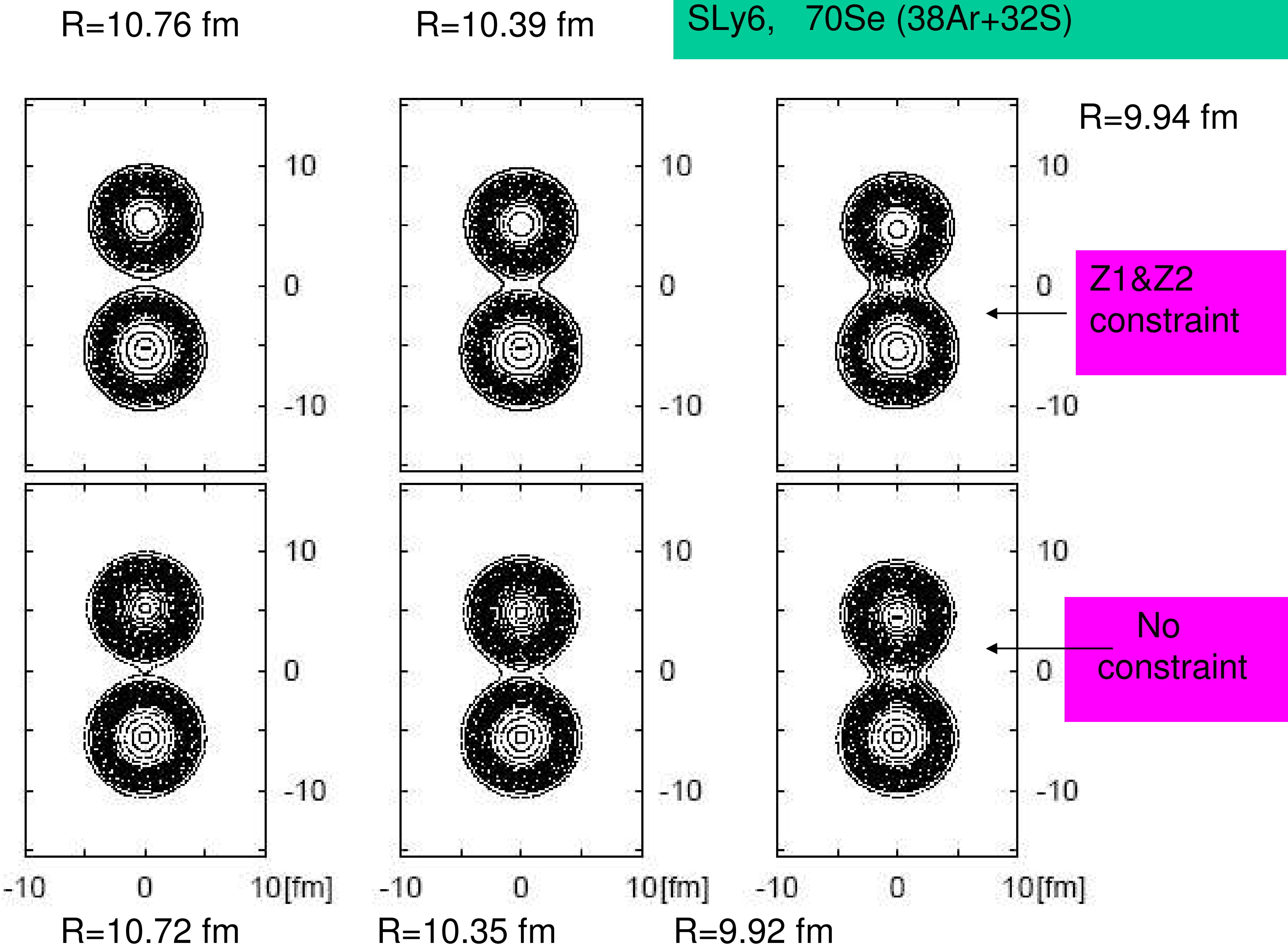

V(R) [MeV]
55
50
45
40
35
6.
7.
8.
9.
10.
11.
R [fm]
48Ca+50Ti
48Ca+48Ca
32S +38Ar
SLy6

For these three reactions the results for SkM* and Sly6 are very similar.
Double points at the barrier region for two asymmetric reactions reflect two ways of calculating them: 1) without (lower points) & 2) with the imposed constraint on the charge partition (upper points).
For the symmetric reaction the way of calculation does not play a role.

The differences between energies amount to 1-1.5 MeV.
Which points should be chosen to determine the fusion barrier?
It helps to check the density distributions.
In the next slide they are shown for 70Se with the SLy6 force, for three distances, with & without constraint on charge partition.

Density distributions suggest that the charge partition should be kept for the largest distance, and released for the smallest one. At the middle distance the arbitrariness remains: the value of V(R) has uncertainty of the order of 1-2 MeV.

SLy6,   70Se (38Ar+32S)



Calculated fusion & conditional fission barriers vs. data.

Fission barriers in parentheses: without rel. kinetic energy correction.

System	B_{fus}(SkM*)	B_{fus}(SLy6)	B_{fus}exp
$^{38}Ar+^{32}S$	38.97	39.13	-
$^{48}Ca+^{48}Ca$	50.46	50.85	51.2[1]
$^{50}Ti+^{48}Ca$	54.88	55.24	-

[1] M. Trotta et al., Phys. Rev. C 65, 011601(R) (2001)

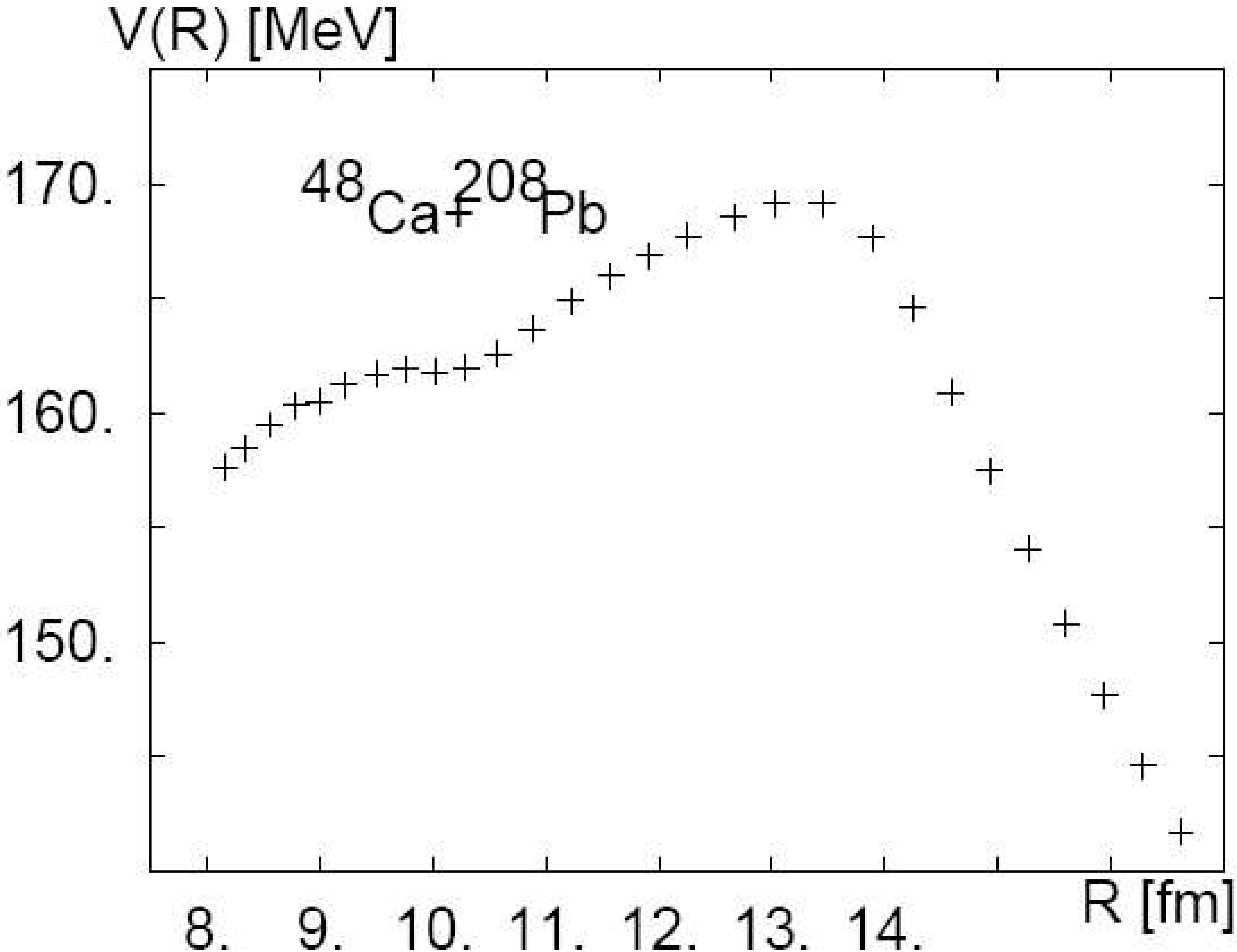
System	B_{fis}(SkM*)	B_{fis}(SLy6)	B_{fis}exp
$^{70}Se \rightarrow ^{38}Ar+^{32}S$	(49.8) 32.7	(49.3) 40.8	35.35[2]
$^{96}Zr \rightarrow ^{48}Ca+^{48}Ca$	(56.9) 39.3	(51.5) 43.4	-
$^{98}Mo \rightarrow ^{50}Ti+^{48}Ca$	(57.5) 39.7	(53.6) 45.5	44.45[3]

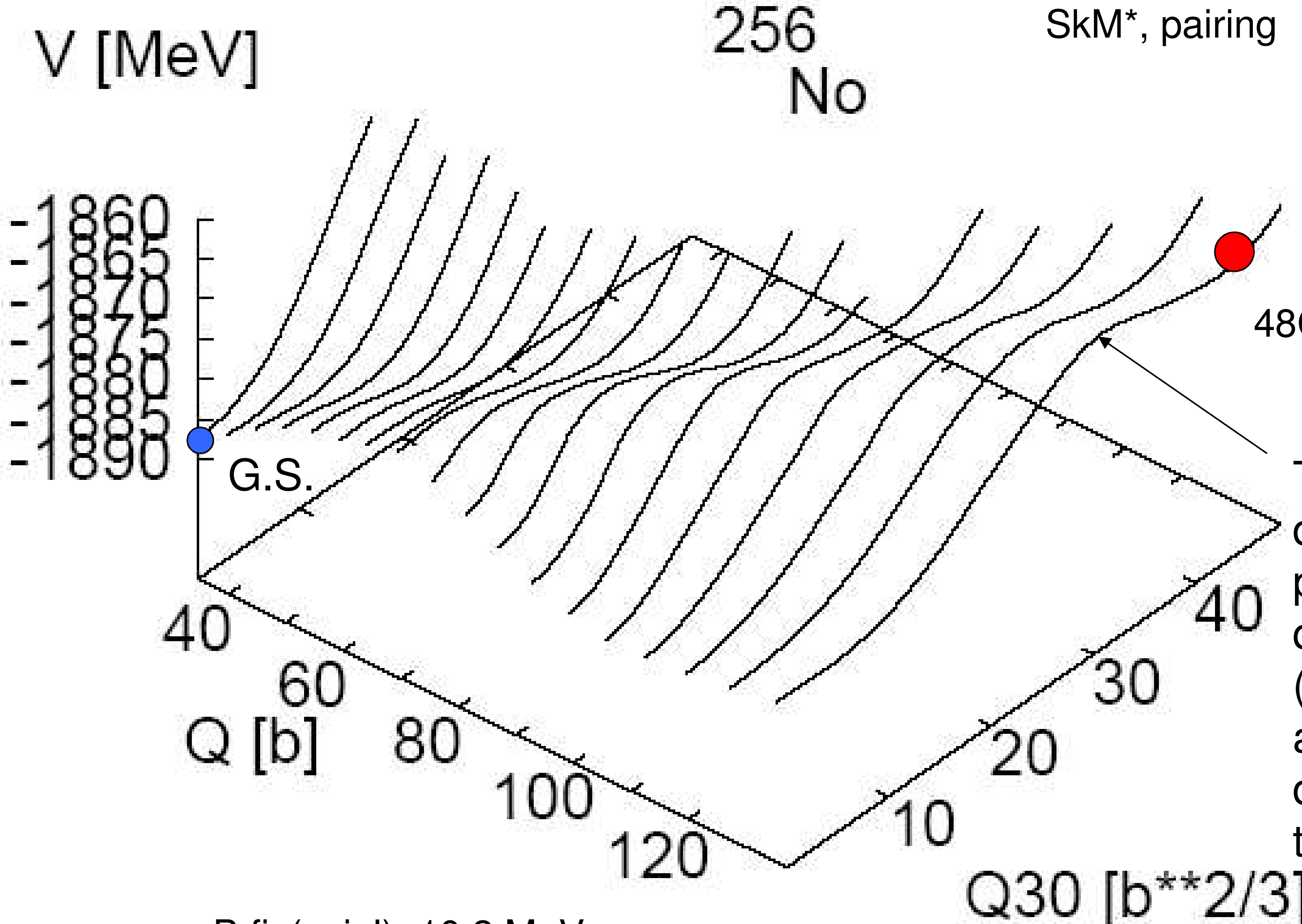
Importance of rel. kinetic energy correction for predicted fission barriers in light nuclei

[2] T.S. Fan et al., Nucl. Phys. A 679, 121 (2000)

[3] K.X. Jing et al., Nucl. Phys. A 645, 203 (1999)

SkM*, no pairing

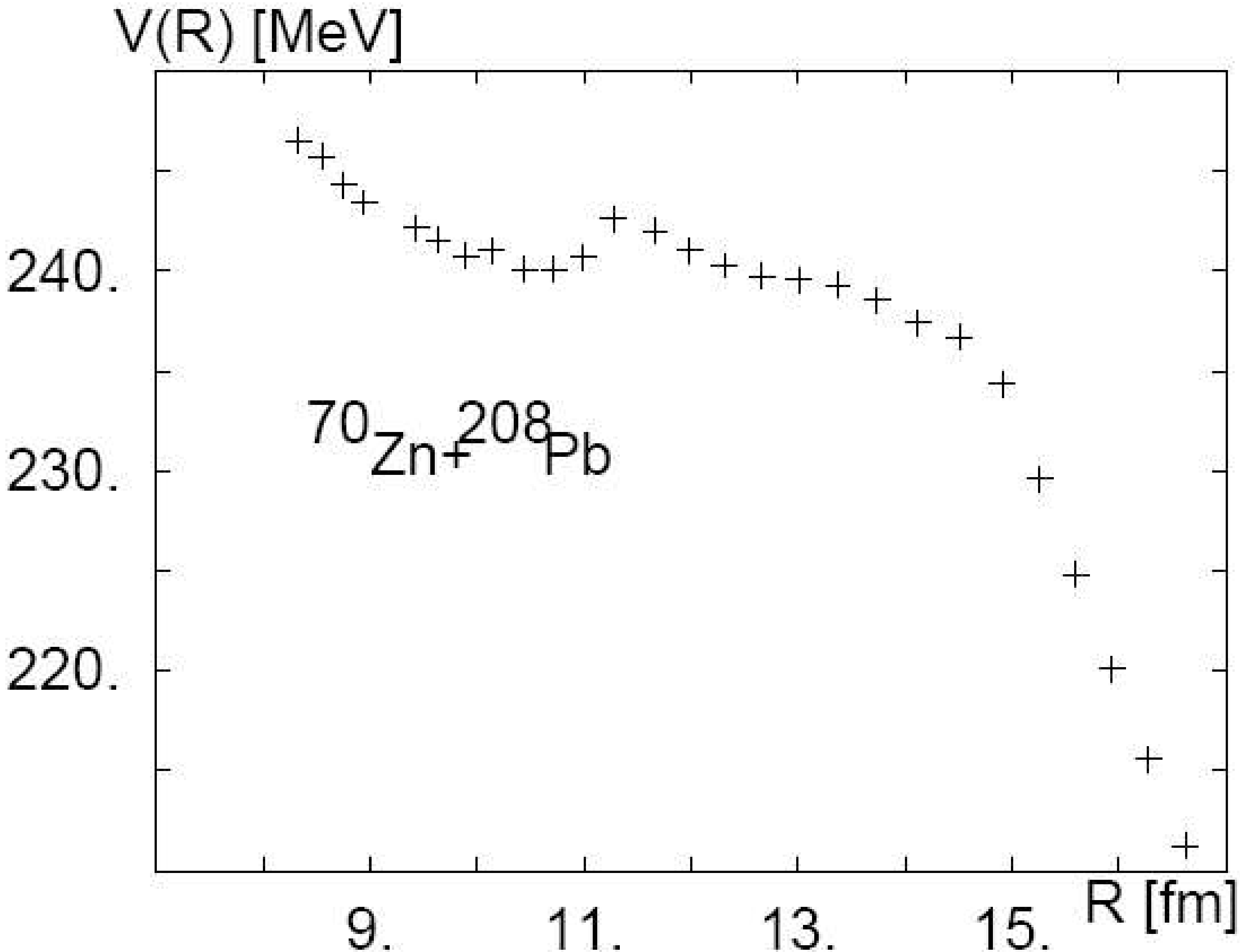


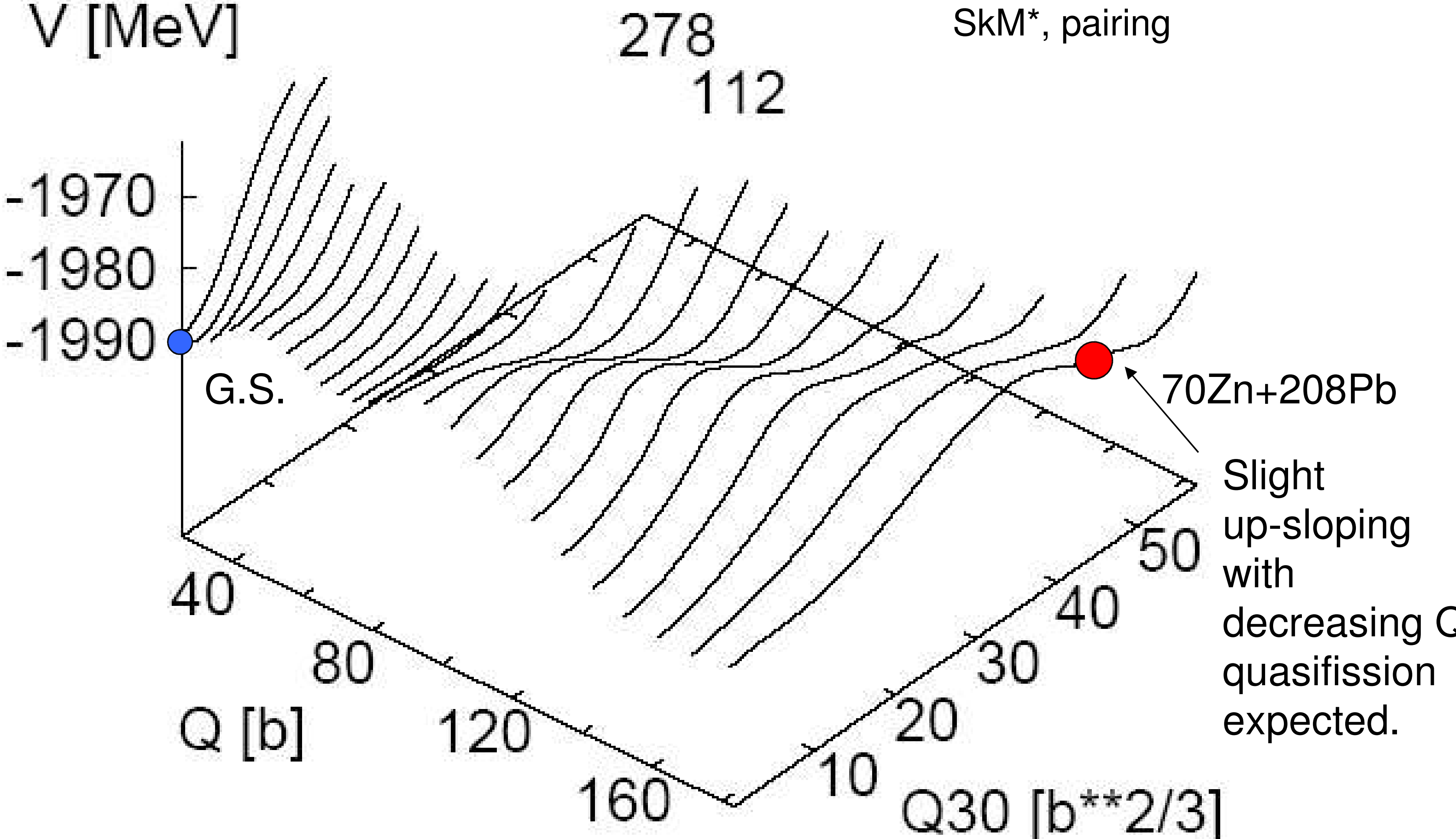


This ridge an
down-sloping
protect from
quasi-fission
(partially)
all the way
down to
the G.S.

B fis(axial)=10.2 MeV
lowered by nonaxiality by 2 MeV

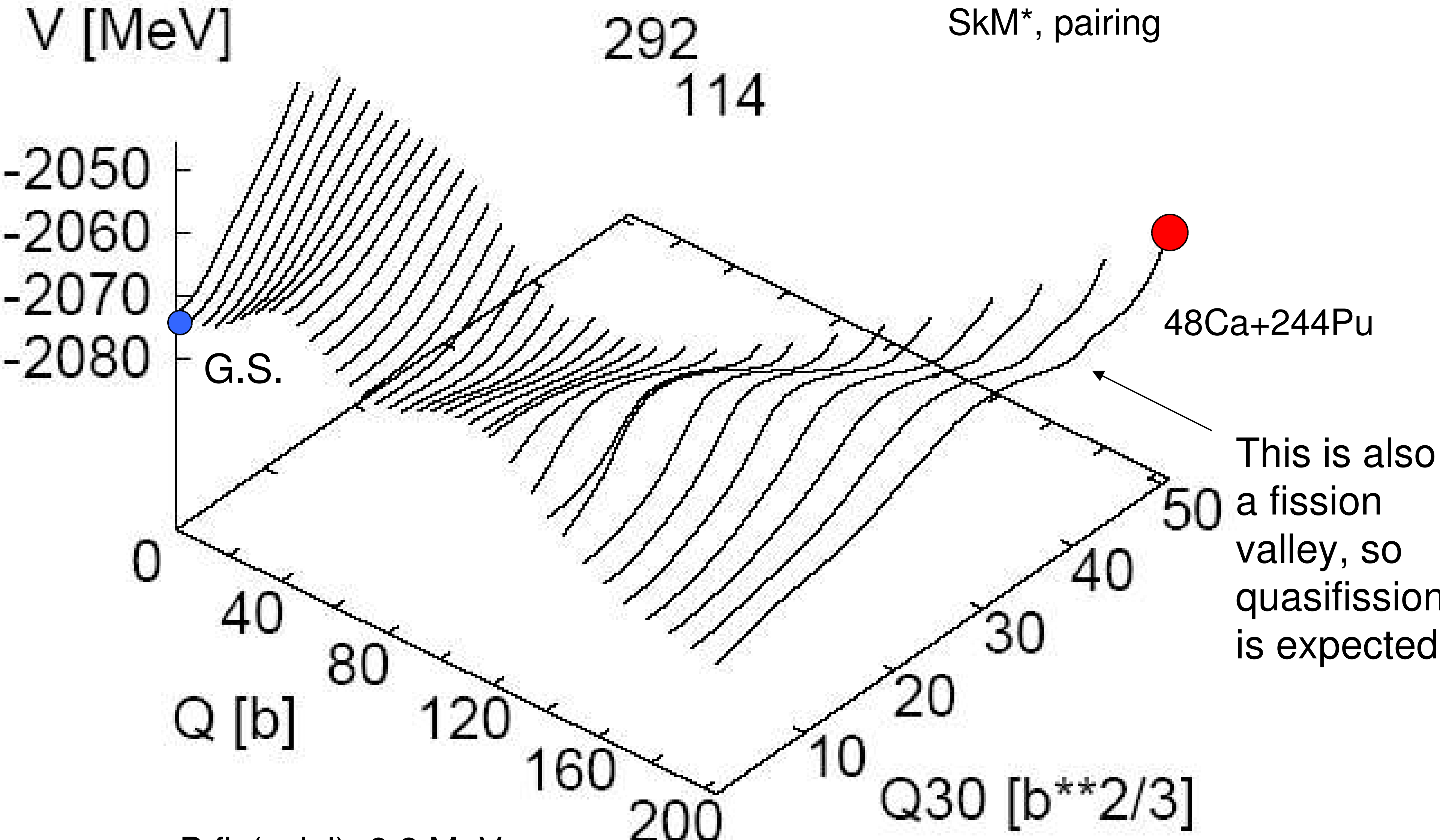
SkM*, no pairing





B fis(axial)=5.1 MeV

SkM*, pairing



B fis(axial)=8.2 MeV,
lowered by nonaxiality by 1.5 MeV.

PRELIMINARY

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)	-	≥ 228	228.3
$^{182}W+^{32}S$	84.9		123(133.5)	-	≥ 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	-	≥ 143	155.7
$^{132}Sn+^{132}Sn$	260.8 *	25	254.5	-	-	257.4

SkM*,
No pairing

Continued

System	Q	$Q_{th.err.}$	B_{cal}	B_{thre}	$E_{cm}(ER)$	B^{int}_{Bass}
^{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

Calculated barriers: tip (side) collision

Q th err – errors in the calculated Q values

Threshold barriers data:K. Wilczynska&J. Wilczynski, Phys. Rev.C 64, 024611

C – from capture data

*- from extrapolations (Myers&Swiatecki)

Ecm(ER) – c.m. energies, at which evaporation residues were produced.

Conclusions:

3. B(fusion) seem to be better reproduced than masses or reaction Q values.

2. Relative kin. energy correction is important for the mean-field predictions for barriers – also for fission barriers in light nuclei.

3. Calculated V(R) compared to the data suggest fusion hindrance in tip collisions for heavier systems.

4. Energy landscapes provide some hints for CN formation hindrance.

5. (?) Superheavy CN formation may be easier in side-collisions on deformed targets (projectiles).