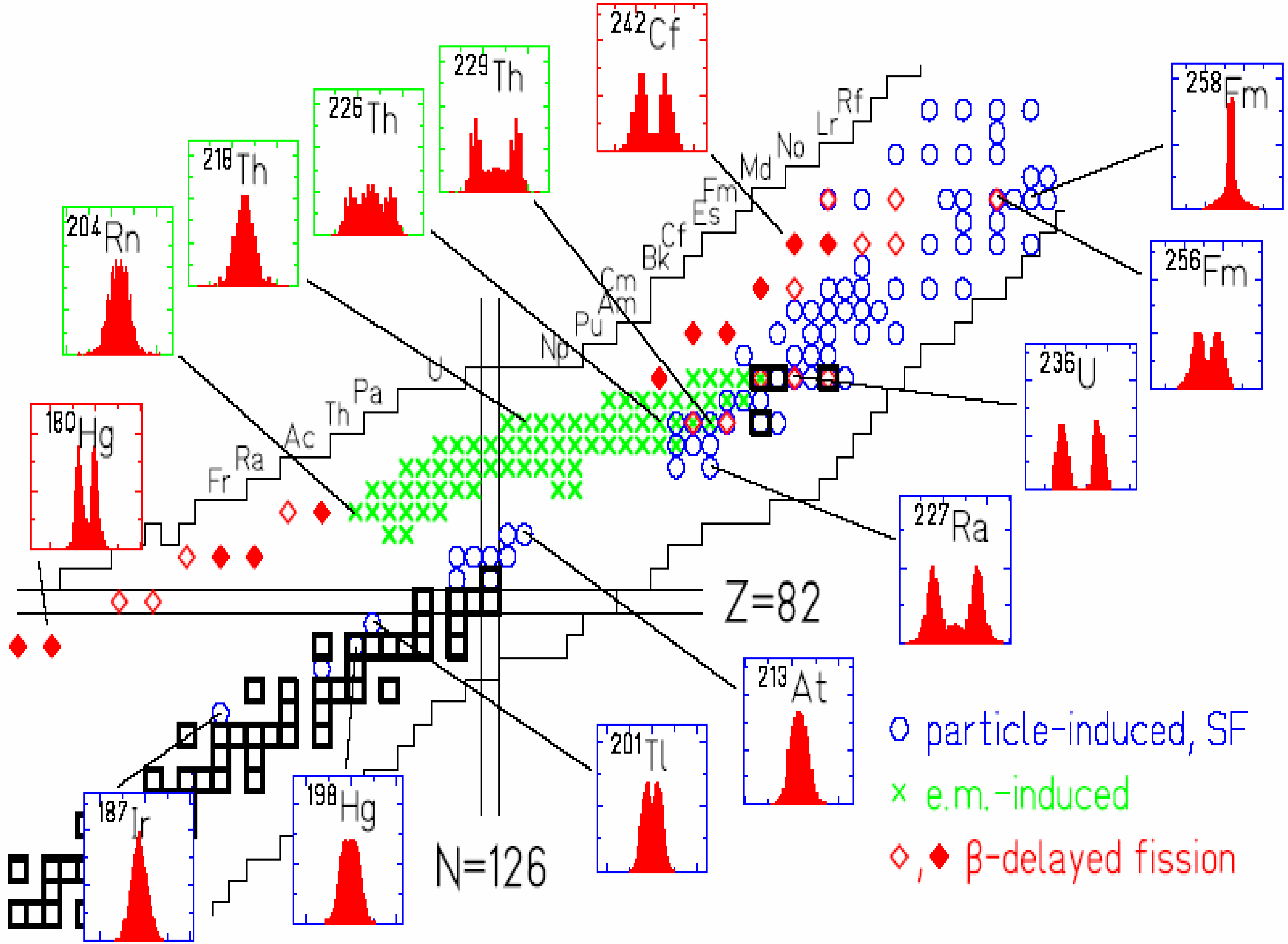
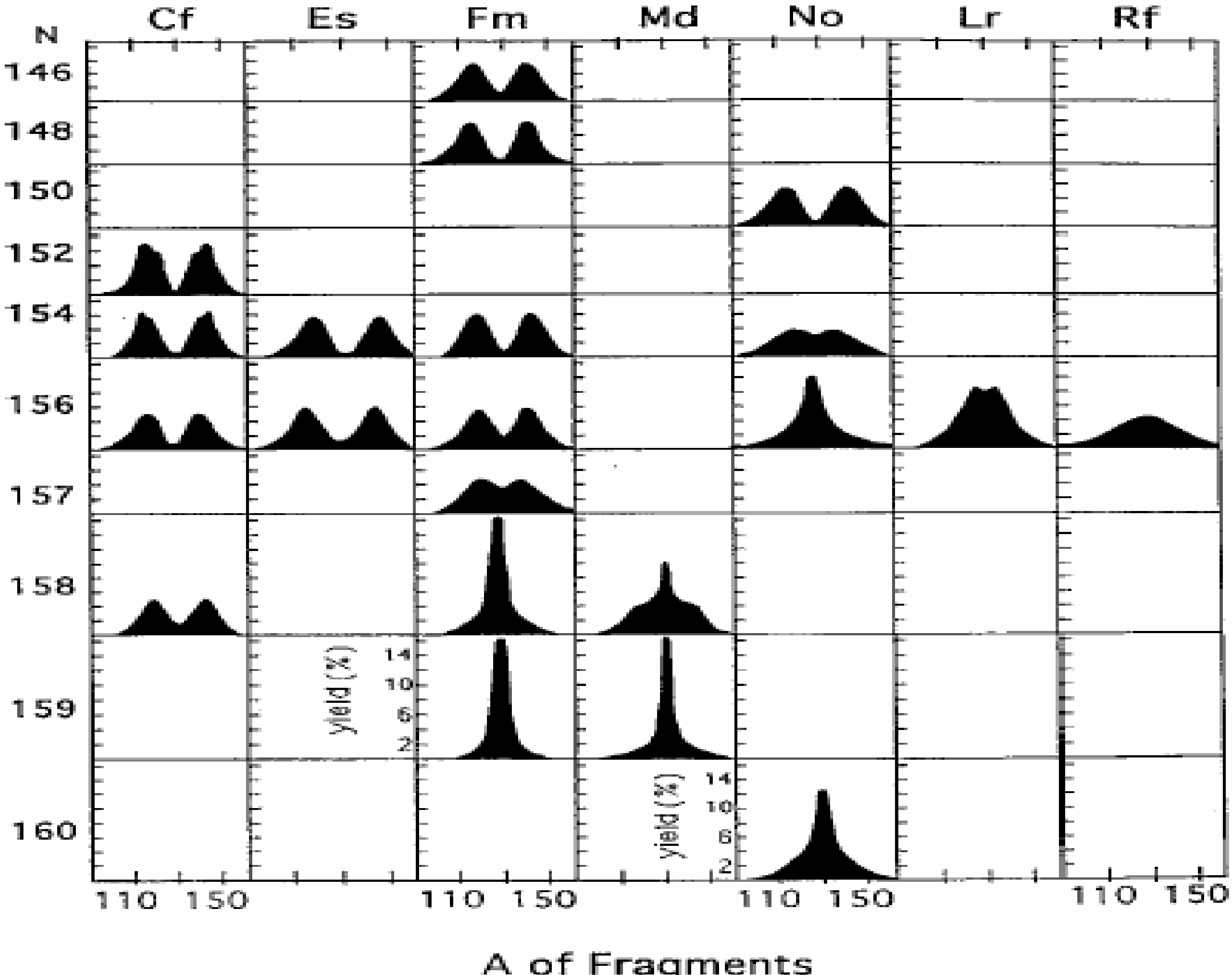
Fission of heaviest nuclei

H. Pasca, A. Andreev, G. Adamian, N. Antonenko



242Cf
229Th
226Th
218Th
204Rn
258Fm
256Fm
236U
227Ra
180Hg
213At
201Tl
198Hg
187Ir
Rf
Lr
No
Md
Fm
Es
Cf
Bk
Cm
Am
Pu
Np
U
Pa
Th
Ac
Ra
Fr
Z=82
N=126
particle-induced, SF
e.m.-induced
β-delayed fission



Cf
Es
Fm
Md
No
Lr
Rf
N
146
148
150
152
154
156
157
158
159
160
yield (%)
14
10
6
2
110
150
A of Fragments

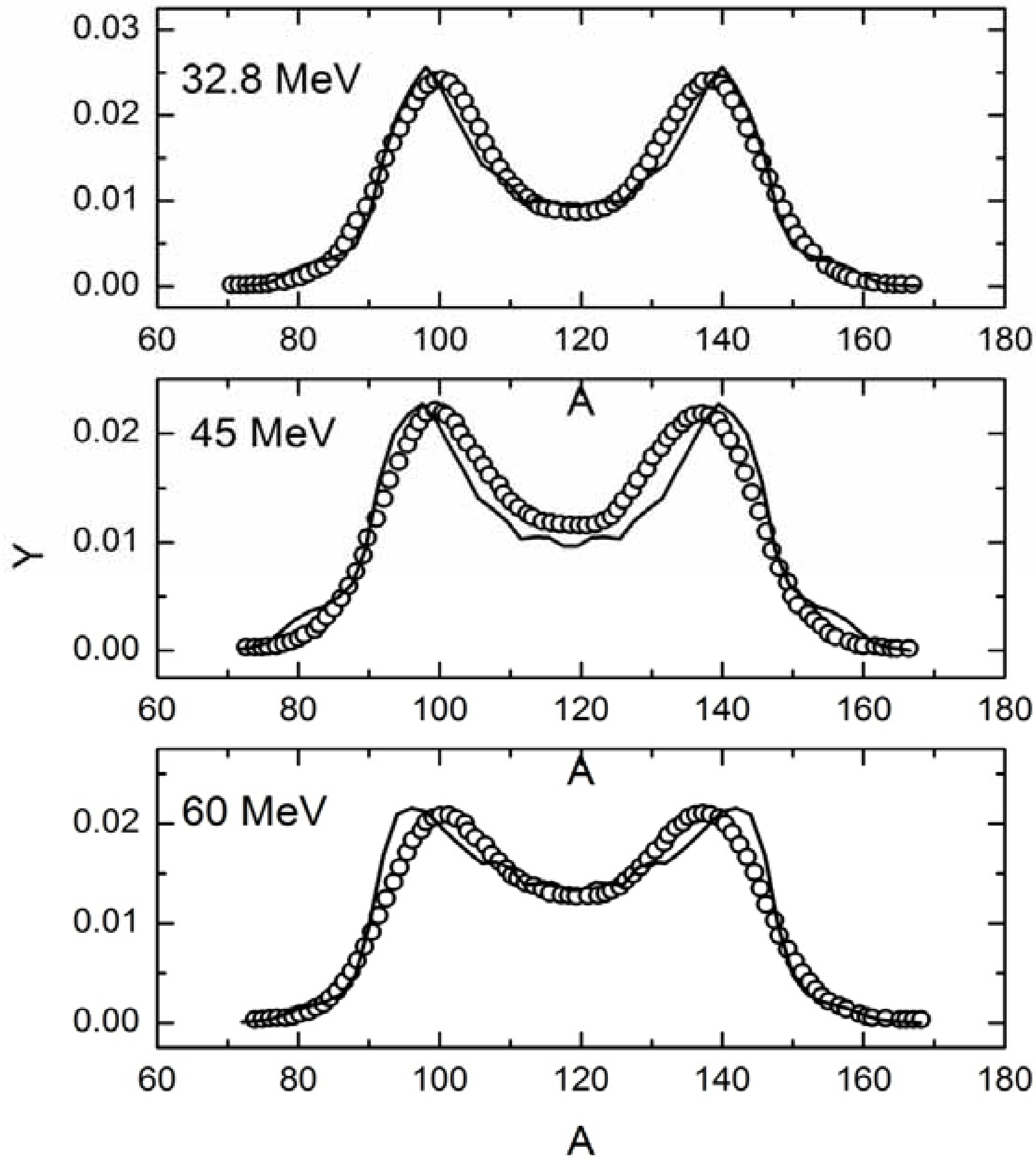
General opinion:

The *competition between symmetric and asymmetric fission is related to shell effects* in deformed fissioning nucleus

U.Brosa, S.Grossmann, A.Muller, Phys.Rep.197(1990)167

Exper. data for high-energy (**60MeV**) **neutron-induced fission of ^{238}U** shows the conservation of asymmetric mass distribution, even though shell effects are supposed to be damped.

I.V.Ryzhov et al. , PRC83(2011) 054603



n + 238U

Exper. asymmetric mass yields result in fission of highly excited (~60 MeV) nuclei 232Th, 237-240U, 239-242Np, 241-244Pu, produced in transfer reactions 18O+232Th,238U,237Np !

K.Hirose PRL119(17)222501; PLB761(16)125

232Th(n,f) V.Simukhin NDS119(14)331; J.King EPJA53(17)238

Conservation of asymmetric mass distribution, even though shell effects are supposed to be damped !

Revolution in fission ?!

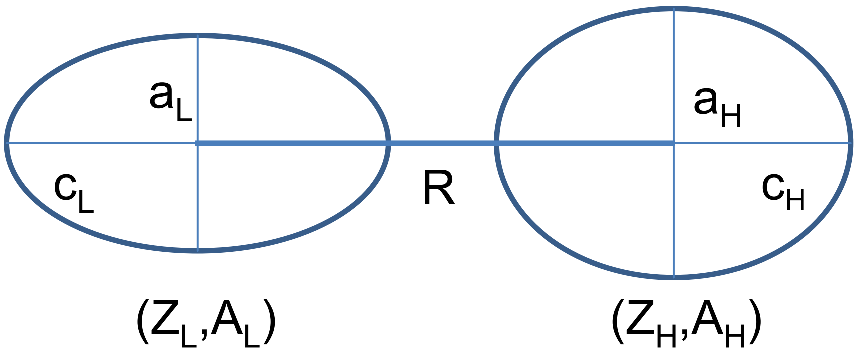
Statistical Scission-point Model
or
Cluster model of fission

- Scission-point model relies on assumption that the statistical equilibrium is established at scission where the observable characteristics of fission are formed.

- Scission system - two well-defined fission fragments in contact [dinuclear system=DNS].

Model

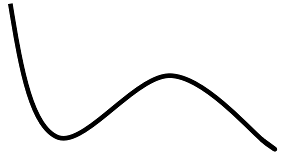
Coordinates Z_i, A_i, β_i (I = L, H) , R *completely describe the geometry of system*

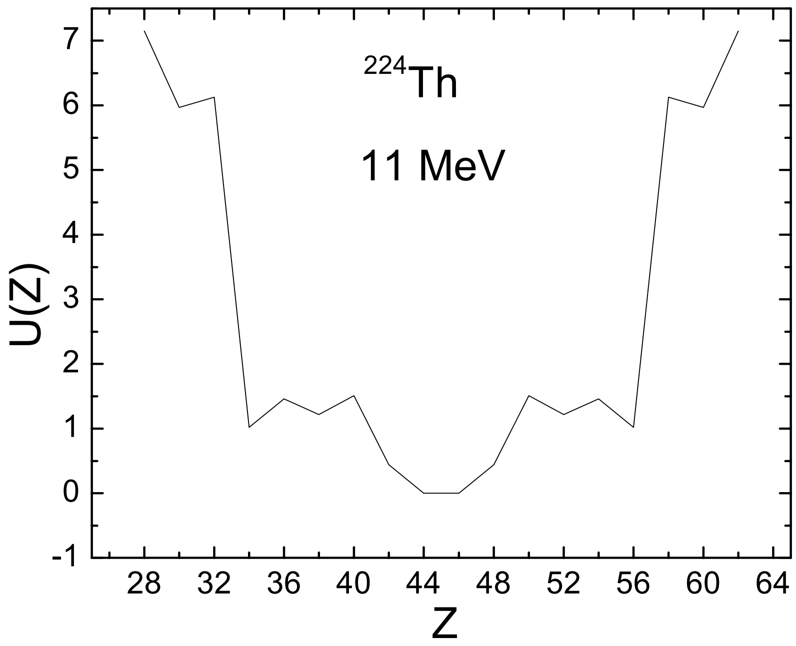


- ***Total Potential Energy*:**

$$U(A_i,Z_i,\beta_i,R) = U_L^{\mathrm{LD}}(A_L,Z_L,\beta_L) + \delta U_L^{\mathrm{shell}}(A_L,Z_L,\beta_L,E_H^*) + U_H^{\mathrm{LD}}(A_H,Z_H,\beta_H) + \delta U_H^{\mathrm{shell}}(A_H,Z_H,\beta_H,E_H^*) + V^C(A_i,Z_i,\beta_i,R) + V^N(A_i,Z_i,\beta_i,R)$$

$V = V^C + V^N$ **- *interaction potential***



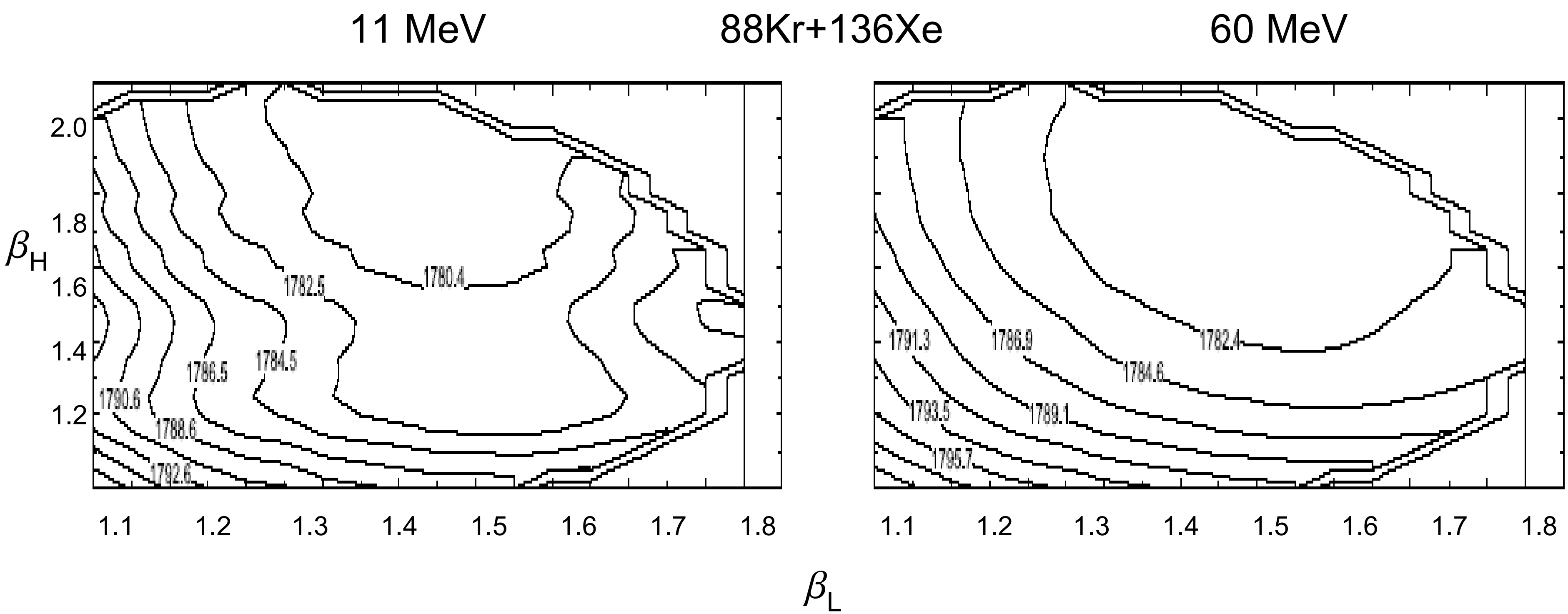


Minima in potential are result of interplay between liquid-drop, interaction, shell correction energies !

1. **Liquid-drop energy** globally increases when mass number deviate from symmetry.

2. **Interaction energy** has the opposite behavior.

3. **Both** depend on deformations of nuclei: larger deformations result in smaller interaction energy, larger liquid-drop energy.



Minimum becomes wider, migrates to larger deformations with increasing excitation energy

Model

Yields:

$$w(A_i, Z_i, \beta_i, E^*) = N_0 \exp\left[-\frac{U(A_i, Z_i, \beta_i, R_b)}{T}\right]$$

$$Y(A_i, Z_i, E^*) = \int d\beta_L d\beta_H w(A_i, Z_i, \beta_i, E^*)$$

$$Y(A_i, E^*) = \frac{\sum_{Z_i} Y(A_i, Z_i, E^*)}{\sum_{Z_i, A_i} Y(A_i, Z_i, E^*)},$$

$$Y(Z_i, E^*) = \frac{\sum_{A_i} Y(A_i, Z_i, E^*)}{\sum_{Z_i, A_i} Y(A_i, Z_i, E^*)}.$$

Ratio of yields of fragments with different charge/mass is governed by difference in energy and width between their potential minima in PES $(\beta_L,\ \beta_H)$.

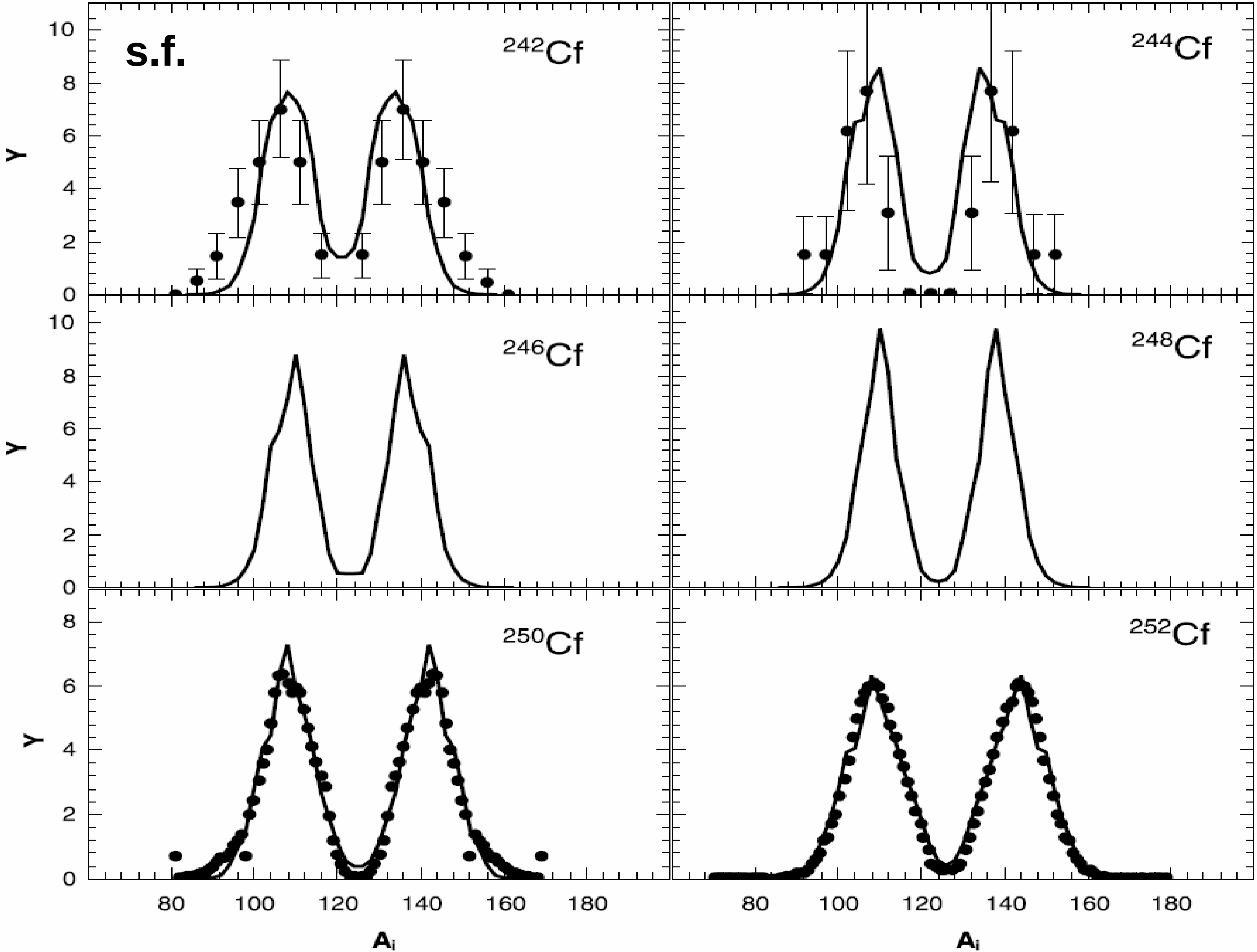
If two minima are close in energy, higher yield stems from $(\beta_L,\ \beta_H)$. with wider-shallower minimum, lower yield emerges from abrupt-narrow minimum.

Results

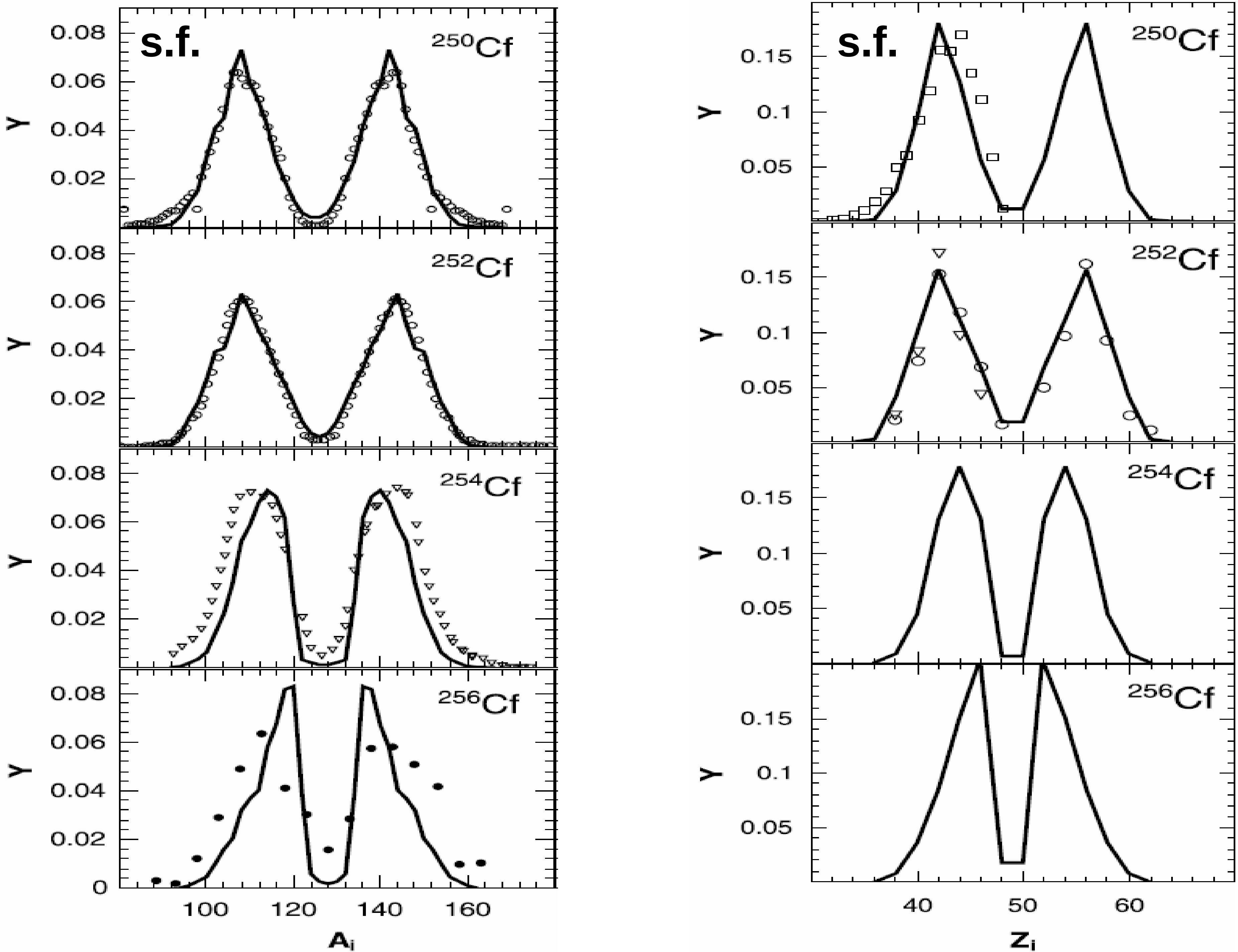
1.Fission at Low Excitation Energy (s.f., thermal neutron)

2.Fission at High Excitation Energy(e.-m.-,n-,HI-induced)

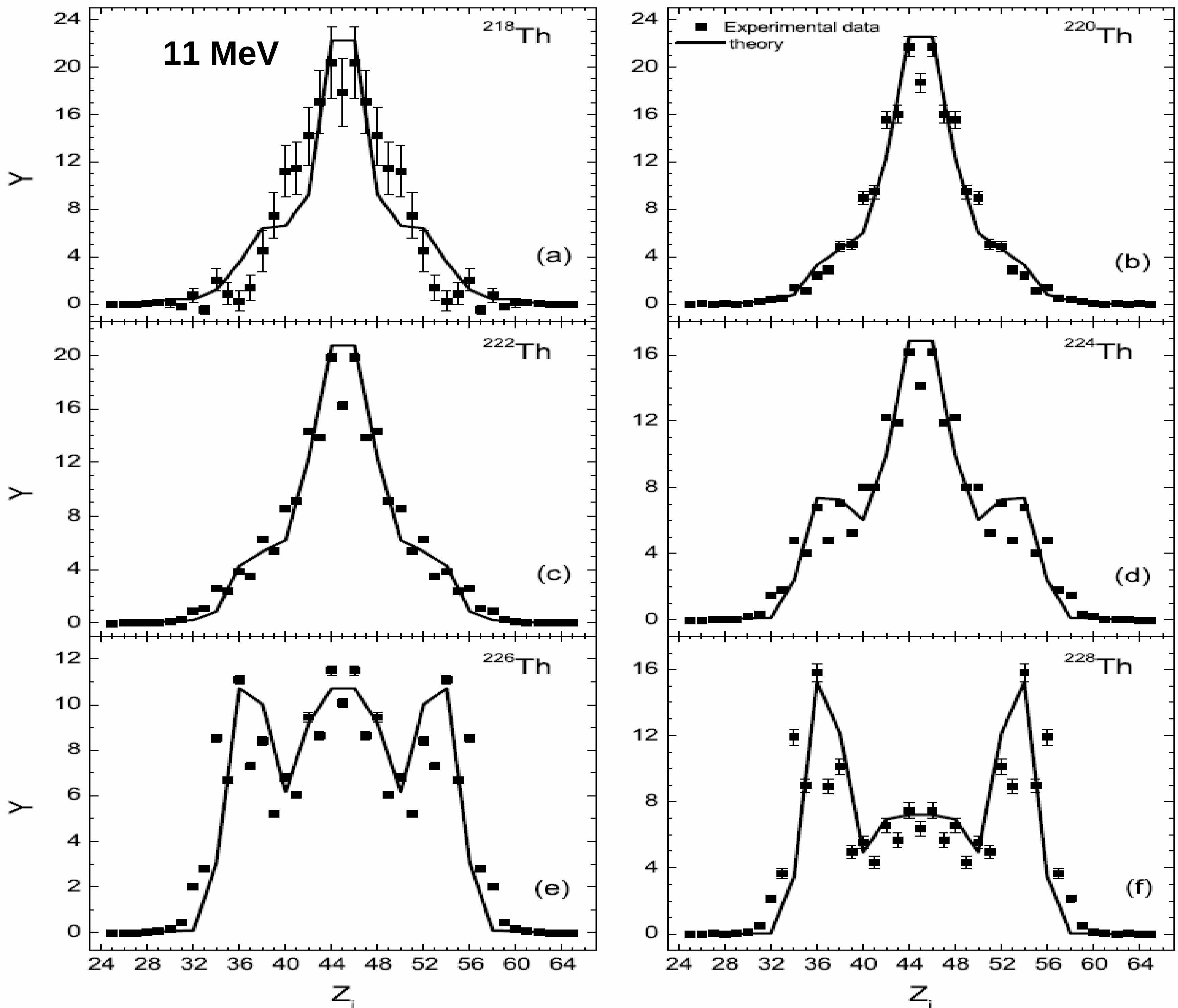
3. Fission of Heavy Actinides: **Fm, No, Rf**



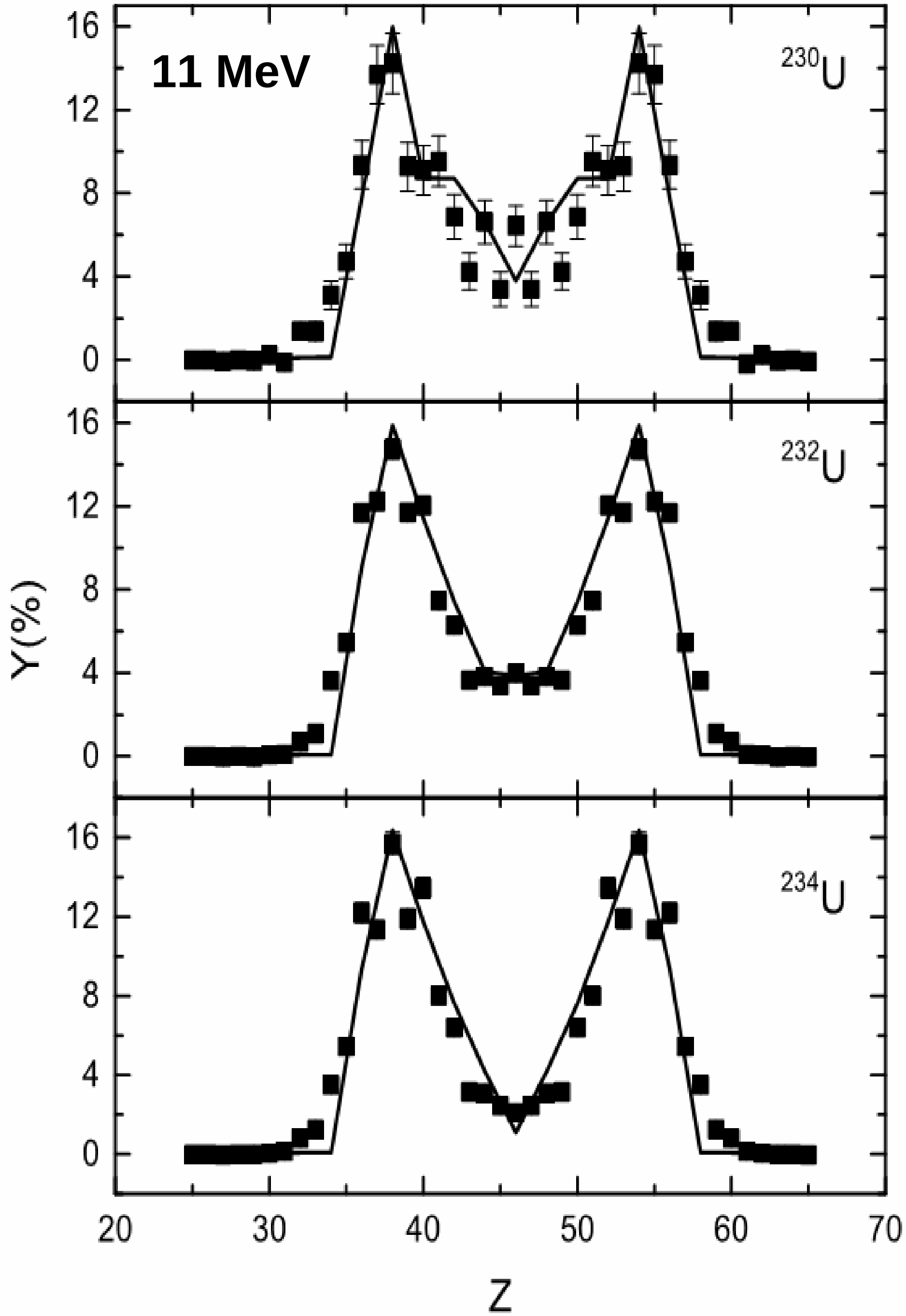
s.f.
^{242}Cf
^{244}Cf
^{246}Cf
^{248}Cf
^{250}Cf
^{252}Cf
Y
A_i



s.f.
^{250}Cf
^{252}Cf
^{254}Cf
^{256}Cf
Y
A_i
Z_i



11 MeV
^{218}Th
^{220}Th
^{222}Th
^{224}Th
^{226}Th
^{228}Th
Experimental data
theory
(a)
(b)
(c)
(d)
(e)
(f)
Y
Z_i

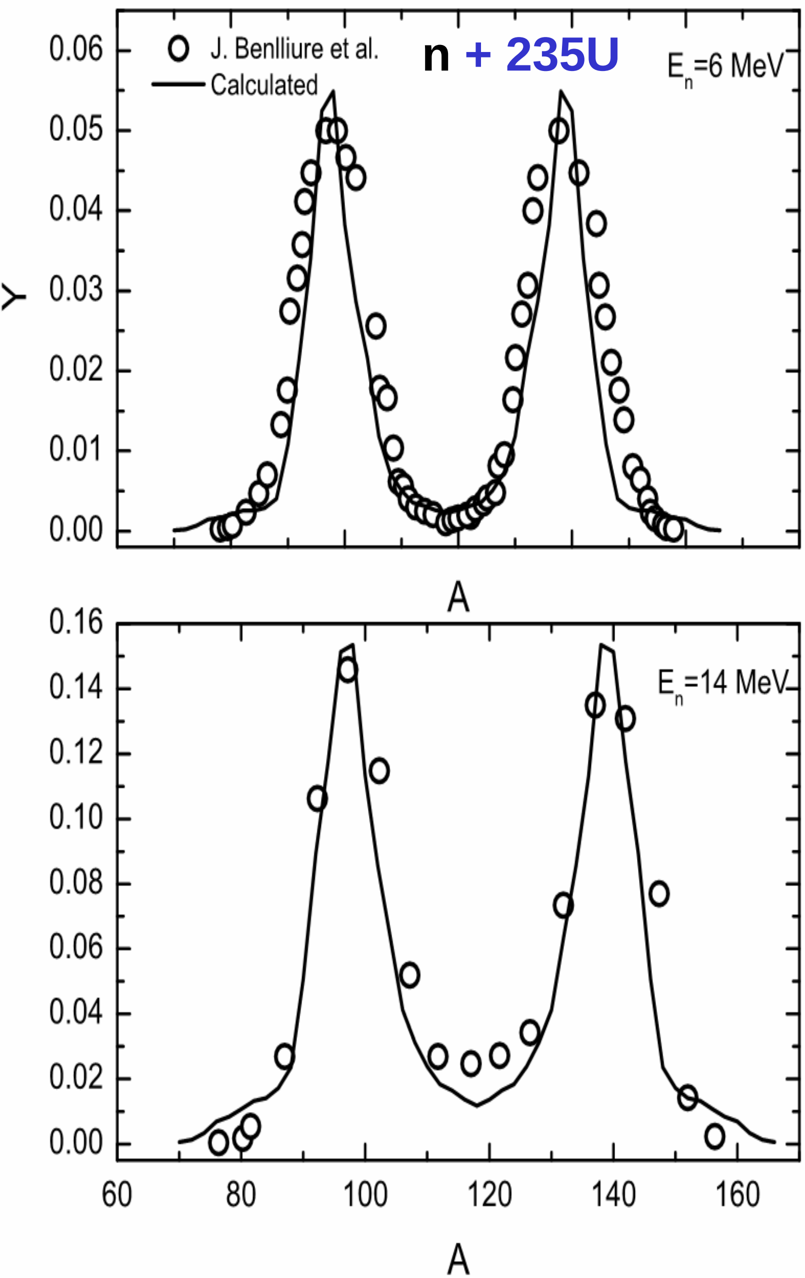


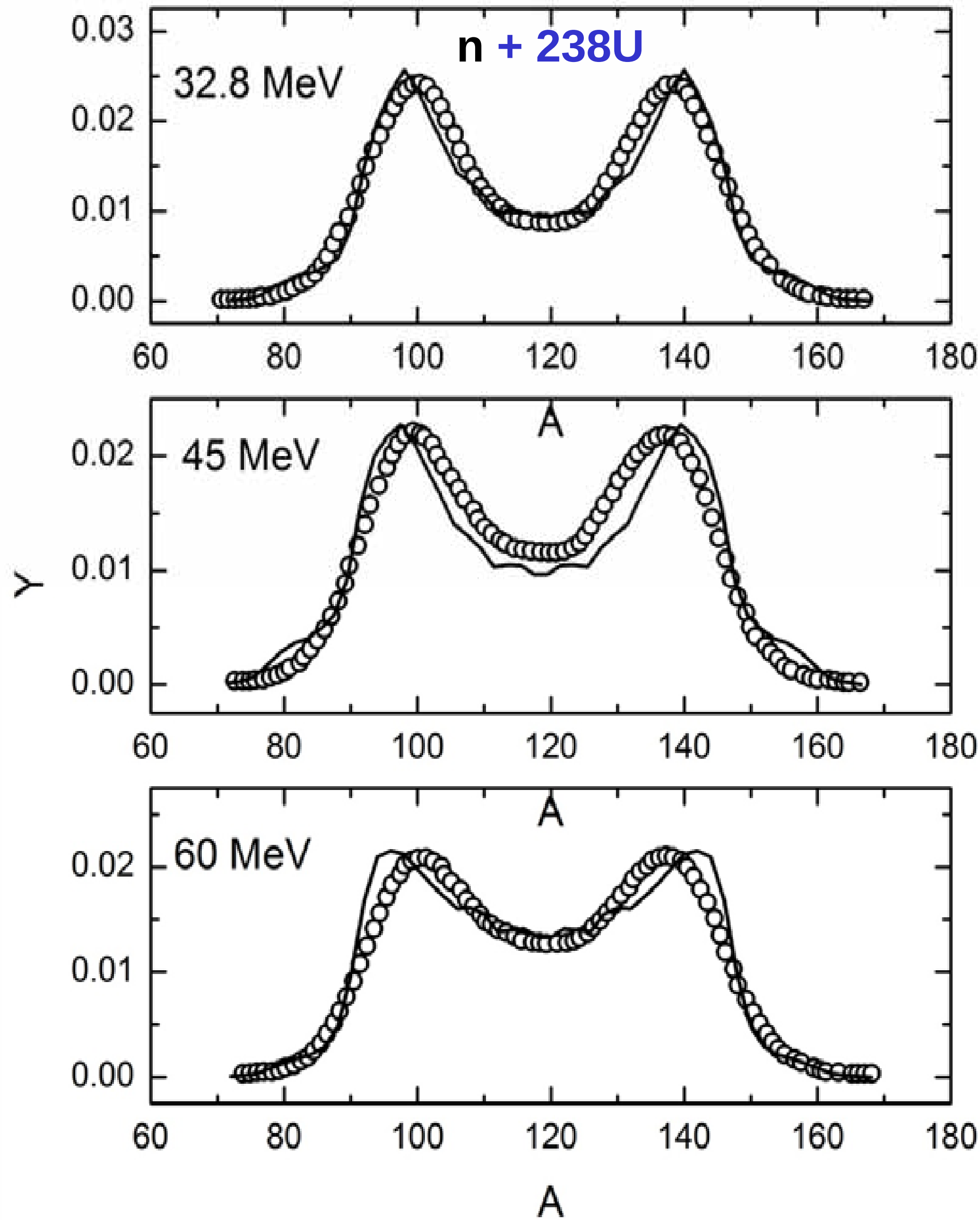
Calculated charge distributions for electromagnetic-induced fission of $^{230-234}$U at exc. energy about 11 MeV

Exper. : K.-H.Schmidt *et al.*, NPA 665(2000)221.

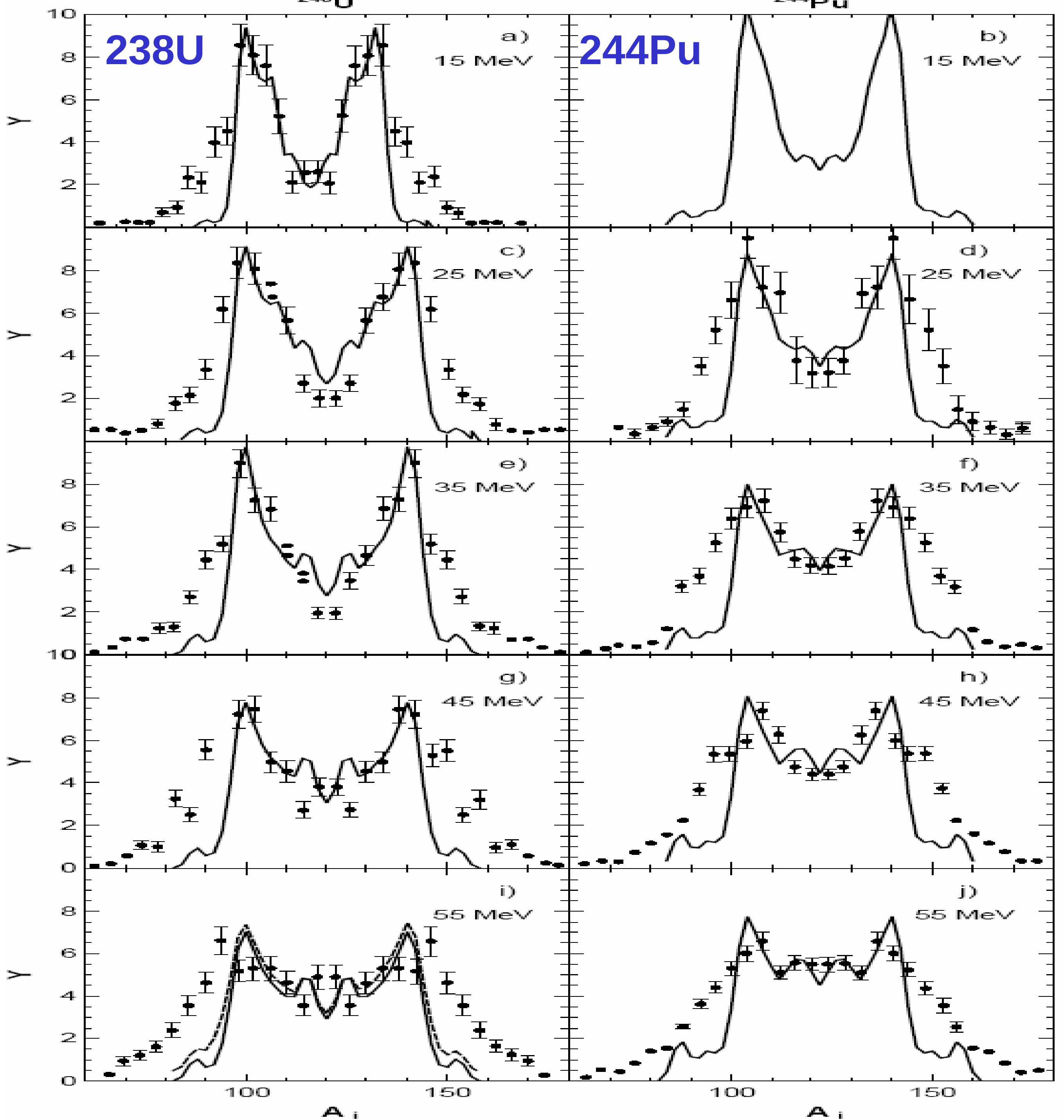
Model is well suited for describing both asymmetric and symmetric fission distributions as well as transition between two.

High excitation energy of fissioning nucleus

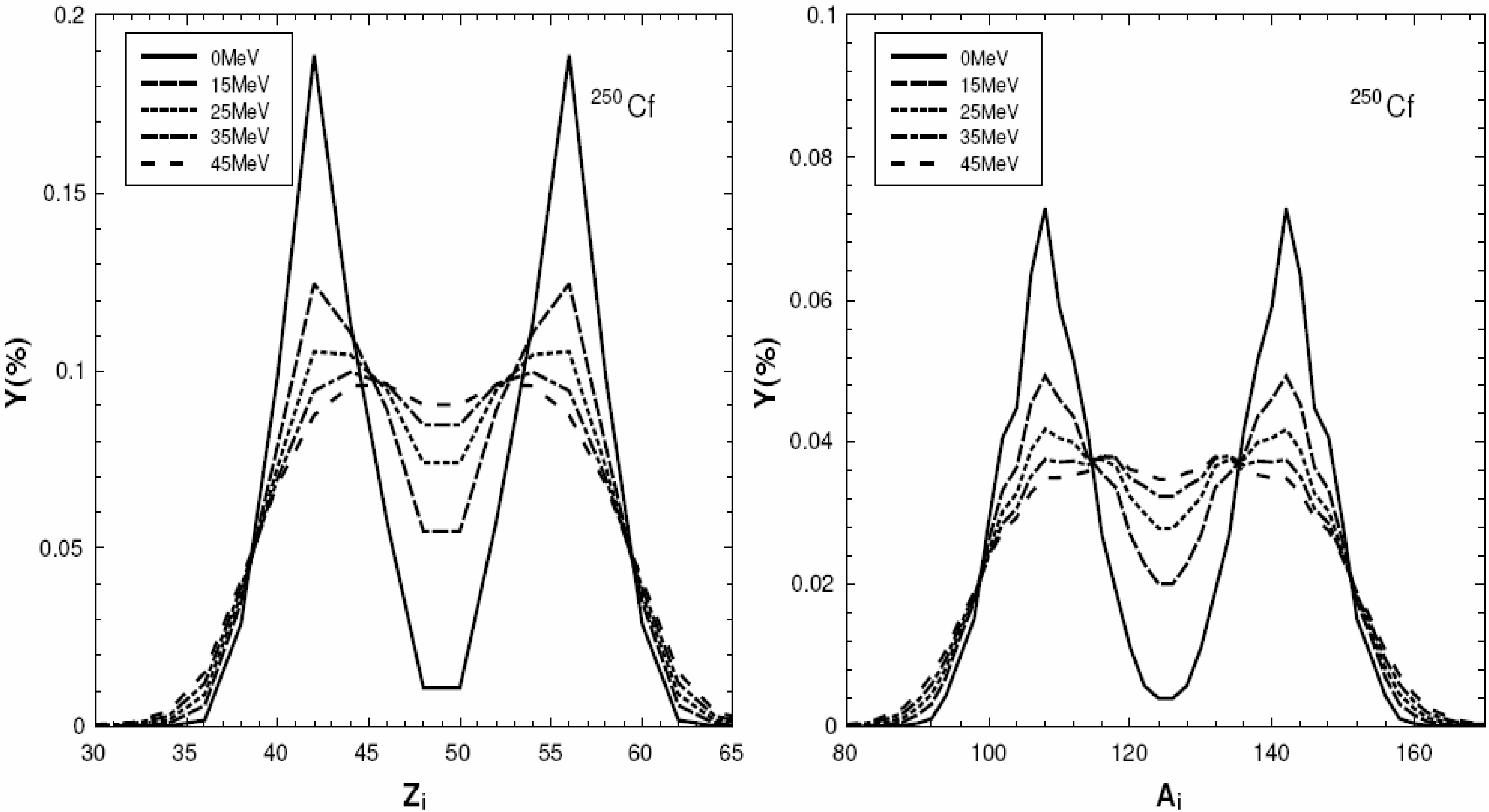




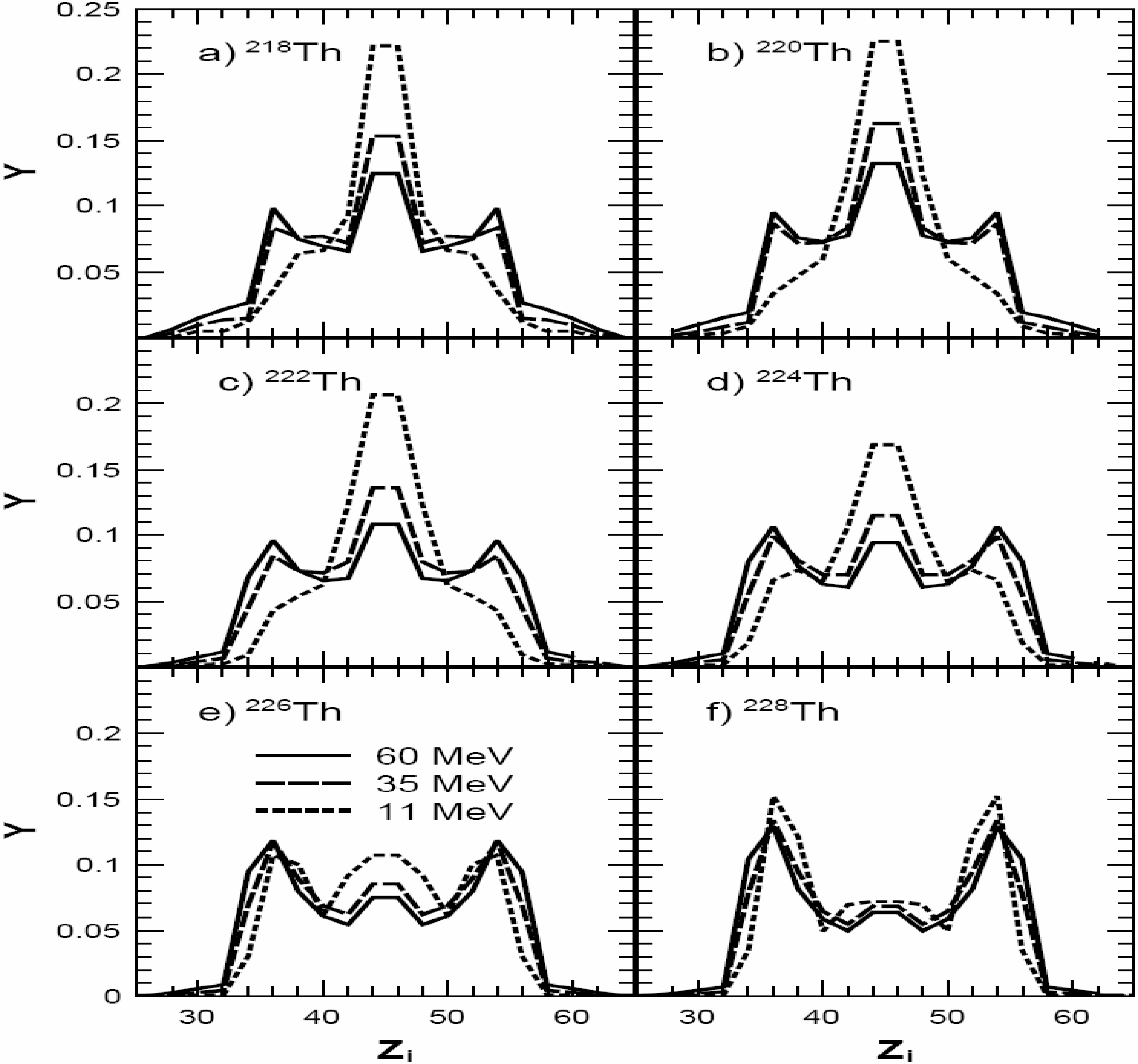
Exper.:K.Hirose et al. PRL119(2017)222501



The change of charge/mass-yields with increasing isospin or excitation energy is related to the change of PES at scission point

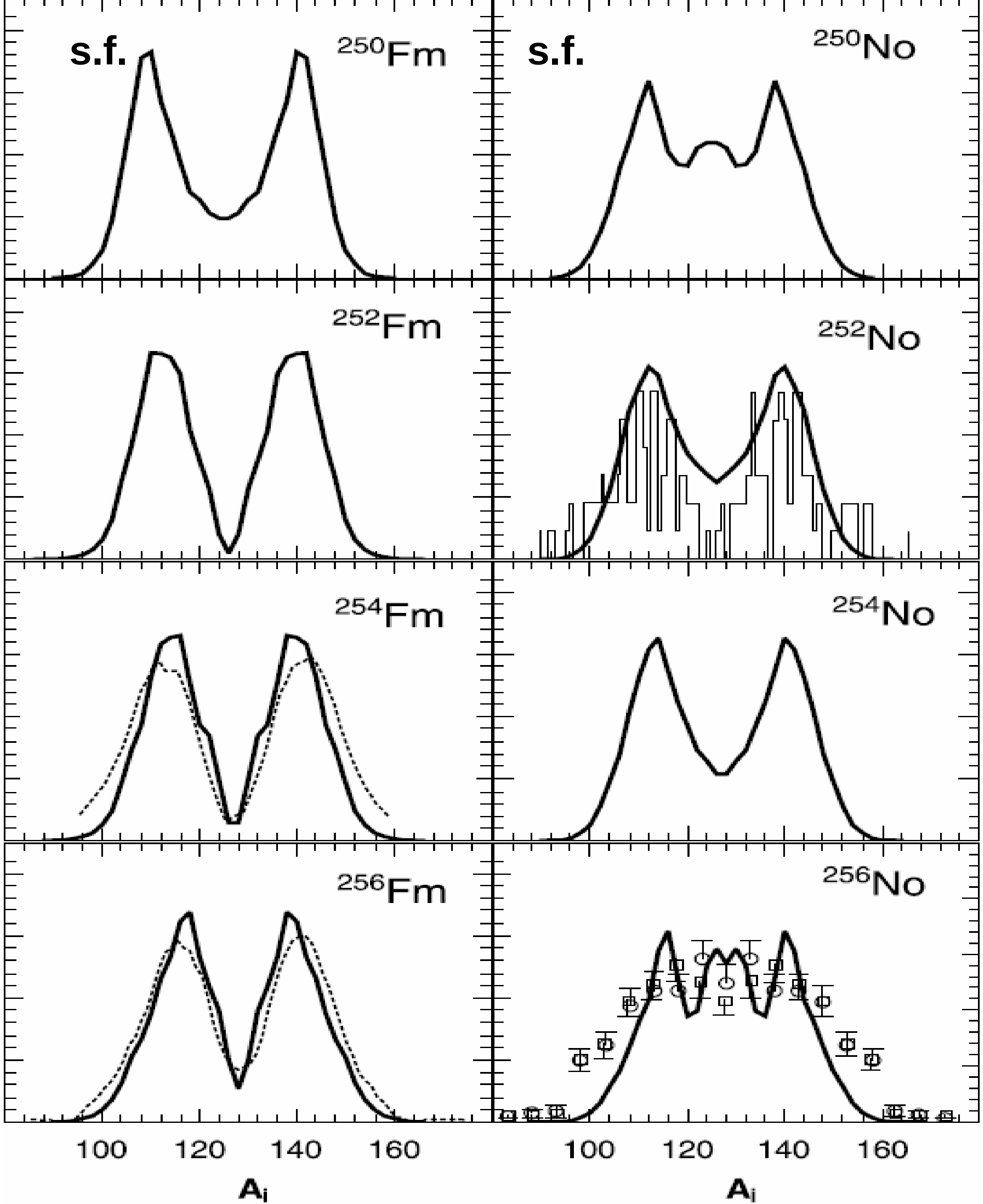


0MeV
15MeV
25MeV
35MeV
45MeV
^{250}Cf
Y(%)
Z_i
A_i

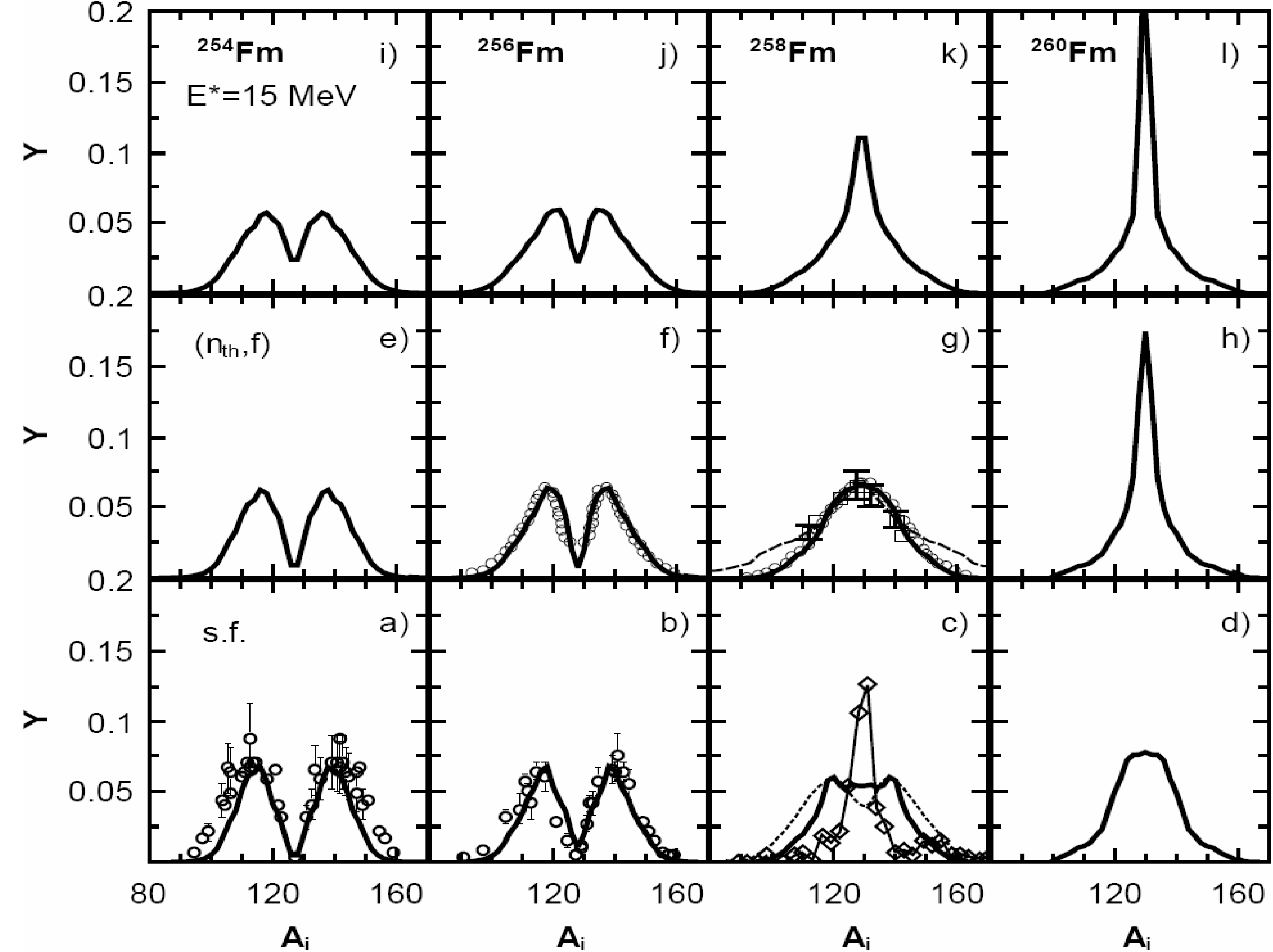


a) ^{218}Th
b) ^{220}Th
c) ^{222}Th
d) ^{224}Th
e) ^{226}Th
f) ^{228}Th
60 MeV
35 MeV
11 MeV
Y
Z_i
0
0.05
0.1
0.15
0.2
0.25
30
40
50
60

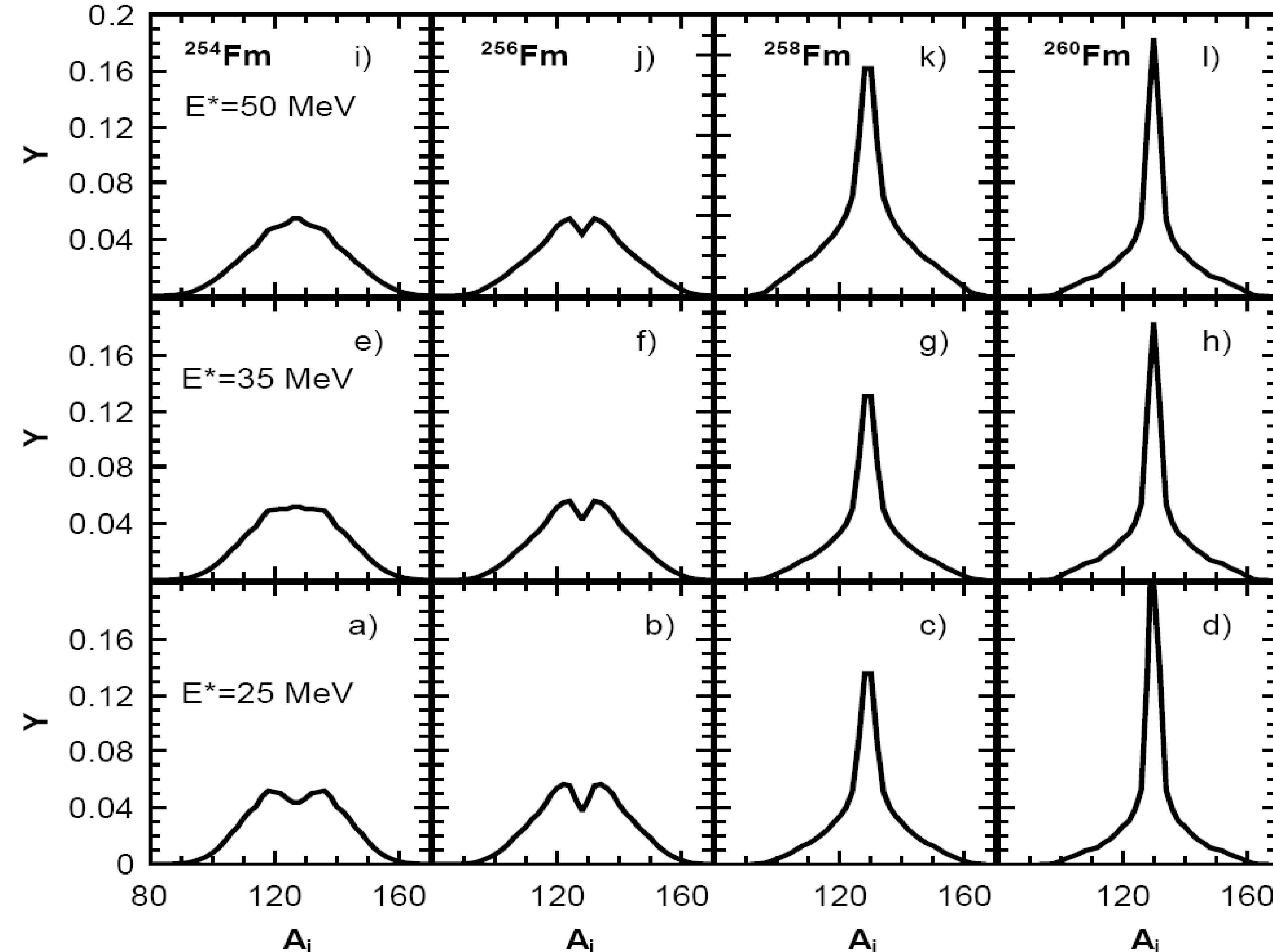
Fission of heavy actinides



s.f.
250Fm
s.f.
250No
252Fm
252No
254Fm
254No
256Fm
256No
100
120
140
160
Ai
100
120
140
160
Ai



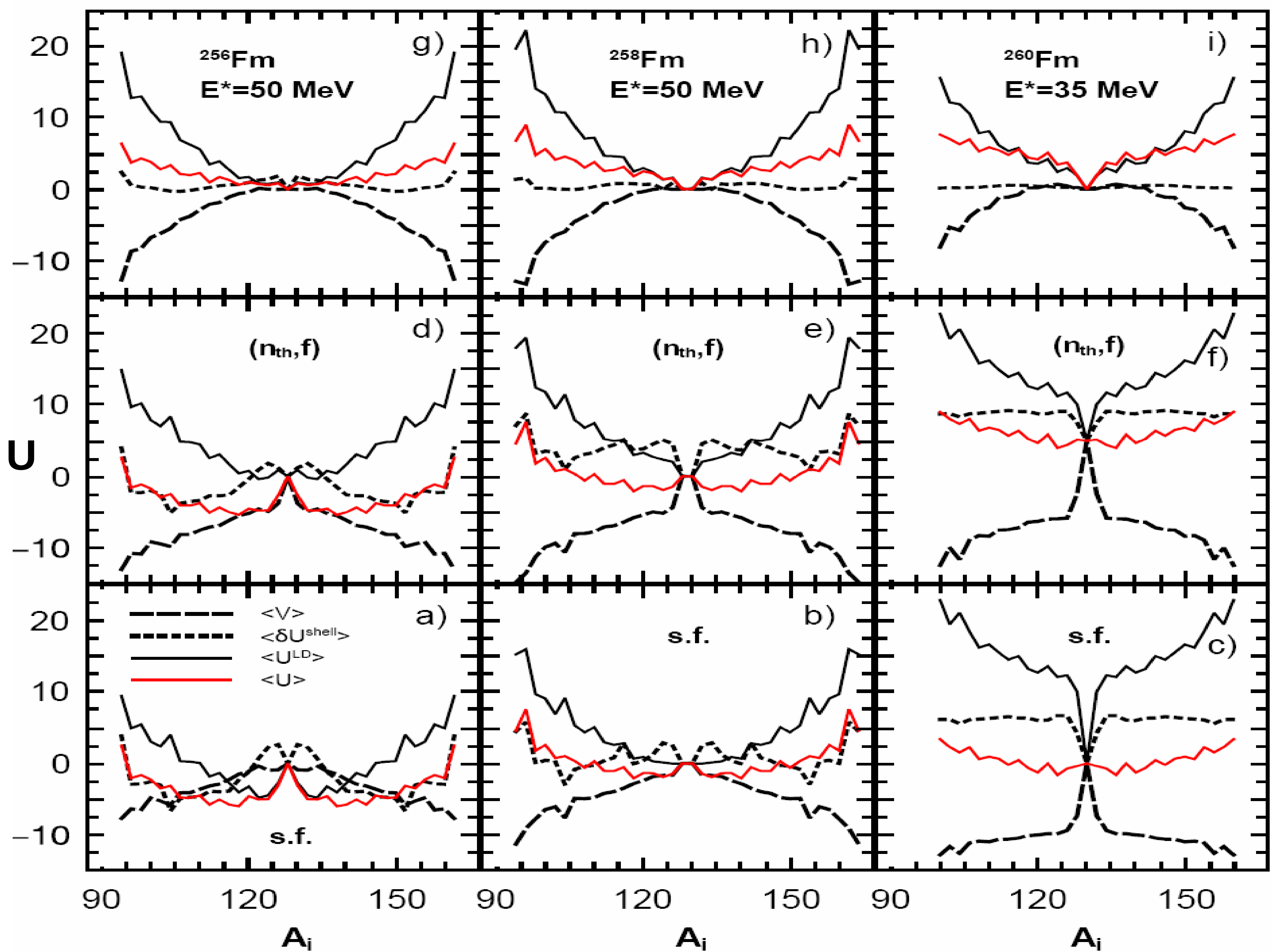
^{254}Fm
i)
E*=15 MeV
^{256}Fm
j)
^{258}Fm
k)
^{260}Fm
l)
(n$_{th}$,f)
e)
f)
g)
h)
s.f.
a)
b)
c)
d)
Y
0.2
0.15
0.1
0.05
80
120
160
A$_i$



0.2
0.16
0.12
0.08
0.04
0
Y
Y
Y
^{254}Fm
i)
E*=50 MeV
^{256}Fm
j)
^{258}Fm
k)
^{260}Fm
l)
e)
E*=35 MeV
f)
g)
h)
a)
E*=25 MeV
b)
c)
d)
80
120
160
A_i

Potential energy at scission is main ingredient

1) **Liquid-drop energy** globally increases when mass number deviate from symmetry.
2) **Interaction energy** has the opposite behavior.
3) **Both** depend on deformations of nuclei: larger deformations result in smaller interaction energy, larger liquid-drop energy.
4) **Deformations** depend on shell effect: **magic** nuclei are expressed in small deformations.
5) **Shell correction energy**



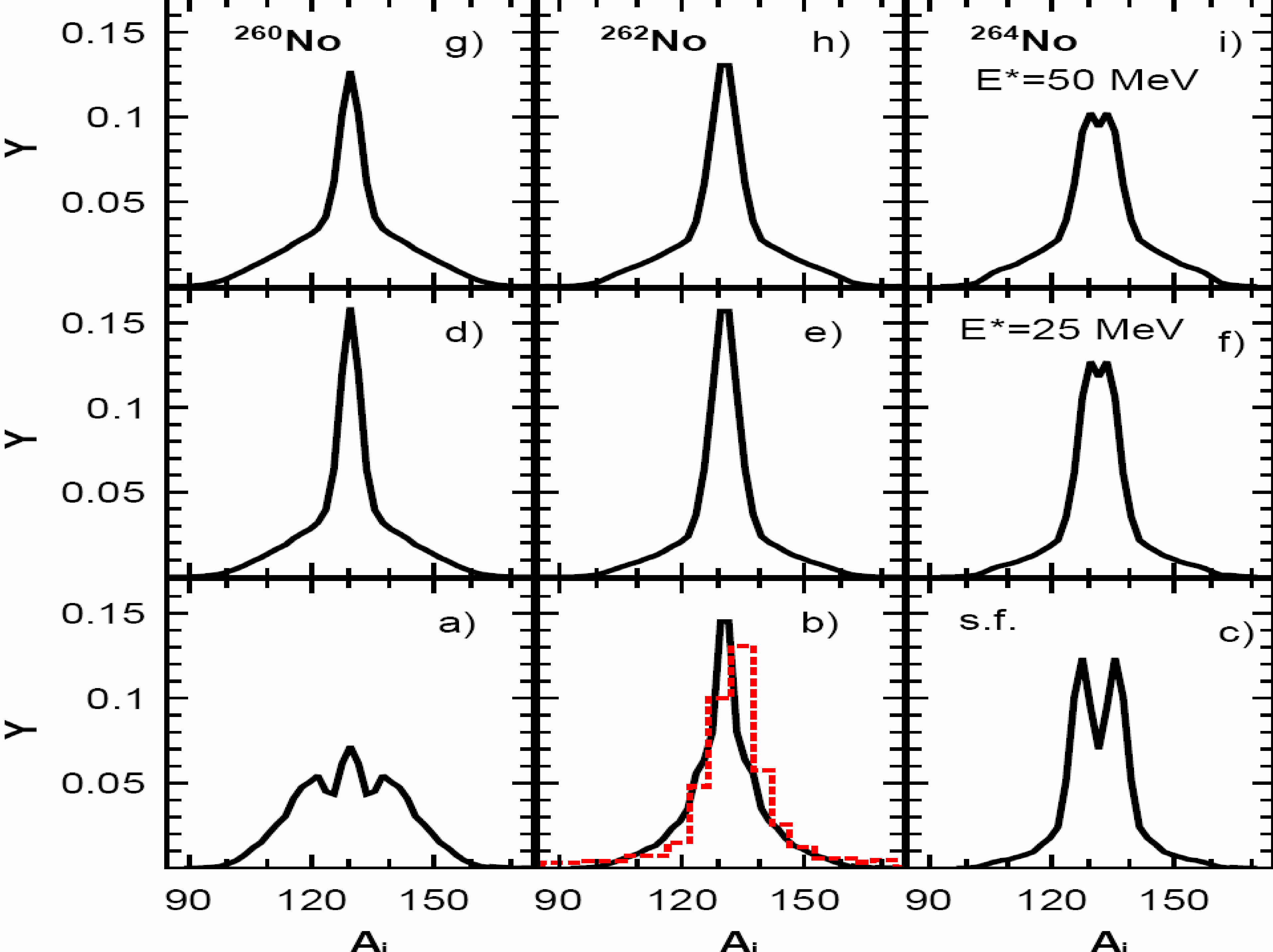
^{256}Fm
E*=50 MeV
g)
^{258}Fm
E*=50 MeV
h)
^{260}Fm
E*=35 MeV
i)
(n$_{th}$,f)
d)
(n$_{th}$,f)
e)
(n$_{th}$,f)
f)
a)
s.f.
b)
s.f.
s.f.
c)
<V>
<δU^{shell}>
<U^{LD}>
<U>
U
A$_i$

Minima in potential or Maxima in yields are result of interplay between liquid-drop, interaction, shell correction energies.

Shell effects affect indirectly (through deformations) appearance of minima of PES, facilitation of large number of magic fragments.

As E* increases, shell and stiffness diminish, shifting and widening minima on PES.

Direct role of **shell effects** is expressed by their ability to enhance or suppress formation of minima of PES.



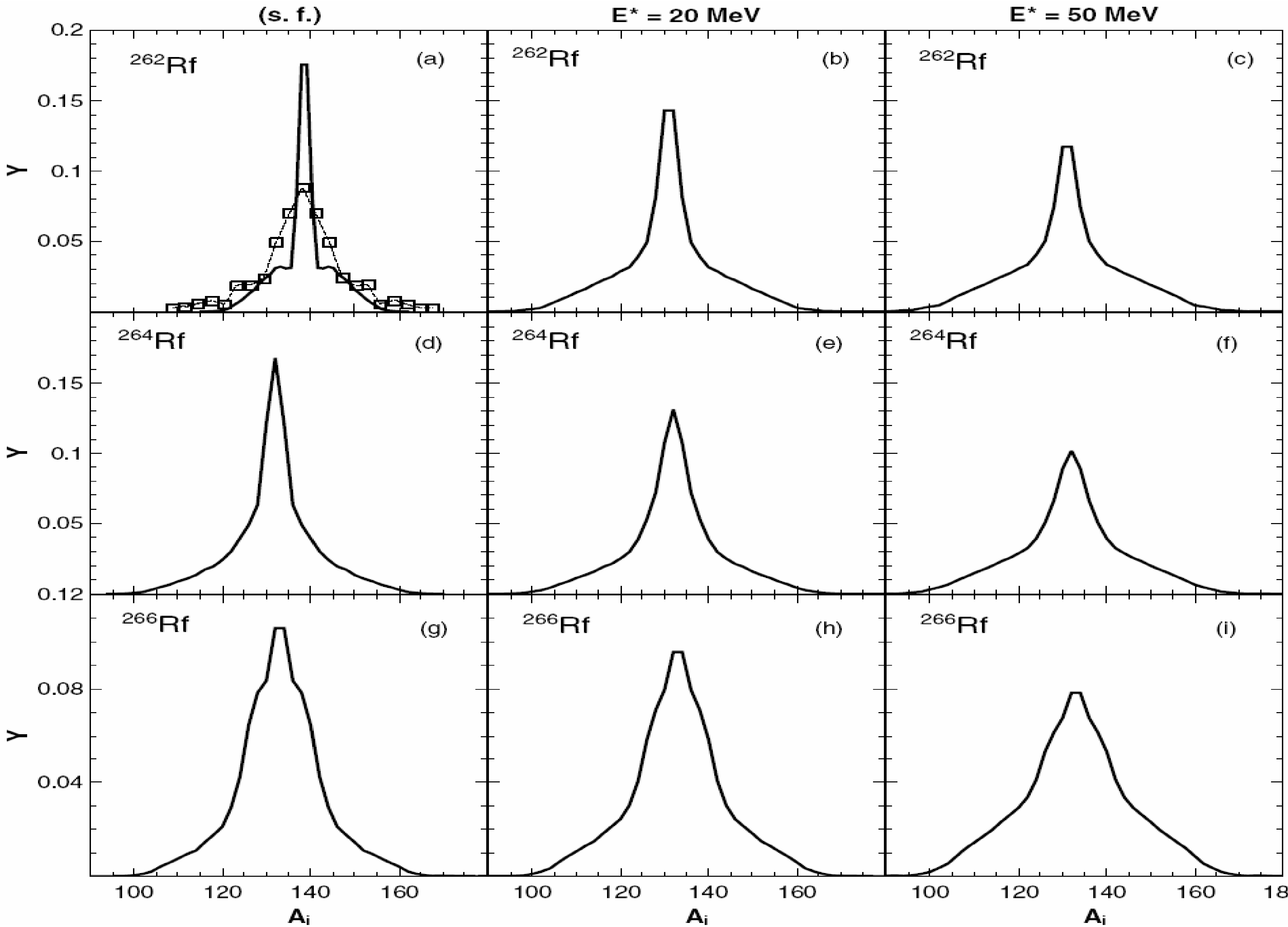
²⁶⁰No
²⁶²No
²⁶⁴No
g)
h)
i)
E*=50 MeV
d)
e)
E*=25 MeV
f)
a)
b)
s.f.
c)
Y
0.15
0.1
0.05
90
120
150
Aᵢ

Saturation effect

At some critical excitation energy saturation of symmetric yields occurs.

Further increase of E* leads only to population of more asymmetric accessible configurations.

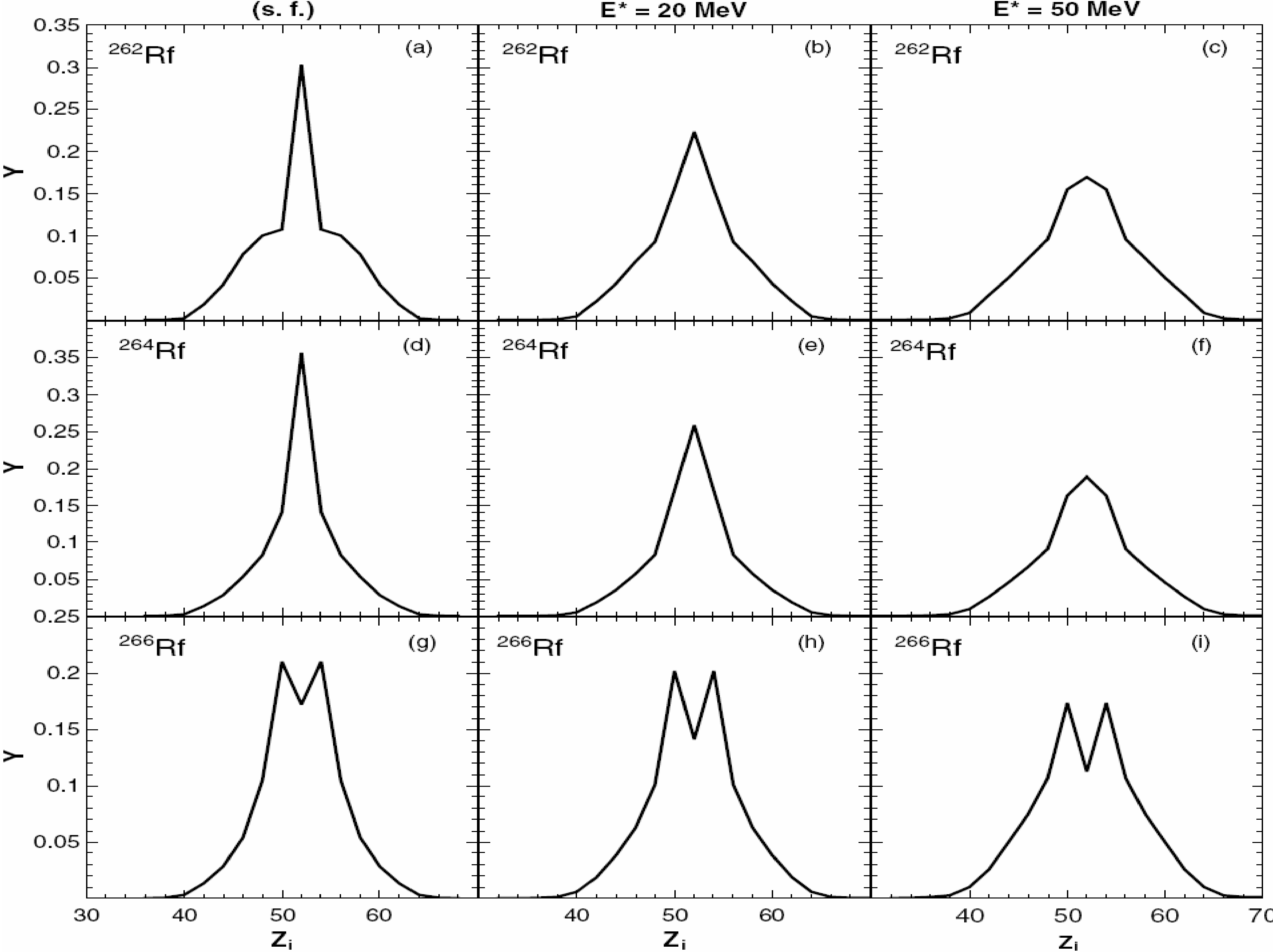
It is worth to be studied experimentally!


(s. f.)
E* = 20 MeV
E* = 50 MeV
262Rf
(a)
(b)
(c)
264Rf
(d)
(e)
(f)
266Rf
(g)
(h)
(i)
Y
0.2
0.15
0.1
0.05
0.12
0.08
0.04
100
120
140
160
18
Aᵢ

Charge distributions:

comparison of mass & charge yields

Is there a difference between mass and charge distributions ?



(s. f.)
E* = 20 MeV
E* = 50 MeV
262Rf
264Rf
266Rf
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
Y
Zi
0.05
0.1
0.15
0.2
0.25
0.3
0.35
30
40
50
60
70

Experimental verifications of this unexpected difference between mass and charge distributions are desirable !

Transformation of shape of charge yields occurs in a similar fashion like one of mass yields, but slower with increasing E* .

Conclusions

- **The change of charge-, mass-yields with increasing isospin or excitation energy is related to the change of PES at scission point**

- **Maxima in yields are direct result of interplay between liquid-drop, interaction, shell correction energies**

- **Evolution of mass-yield shape with increasing isospin N - Z occurs gradually**

- **Unexpected difference between charge and mass yields, 258Fm(sf), 260No(sf), 266Rf(sf)**

Conclusions

- **With increasing excitation energy the shapes of mass- , charge-yields change with different rates**

- **Saturation of symmetric yield occurs at excitation energy about 15 - 30 MeV**

Thank You For Your Attention !