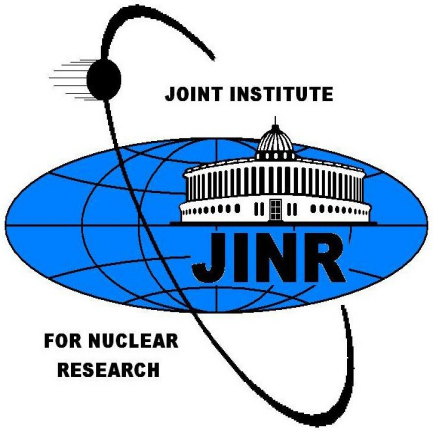
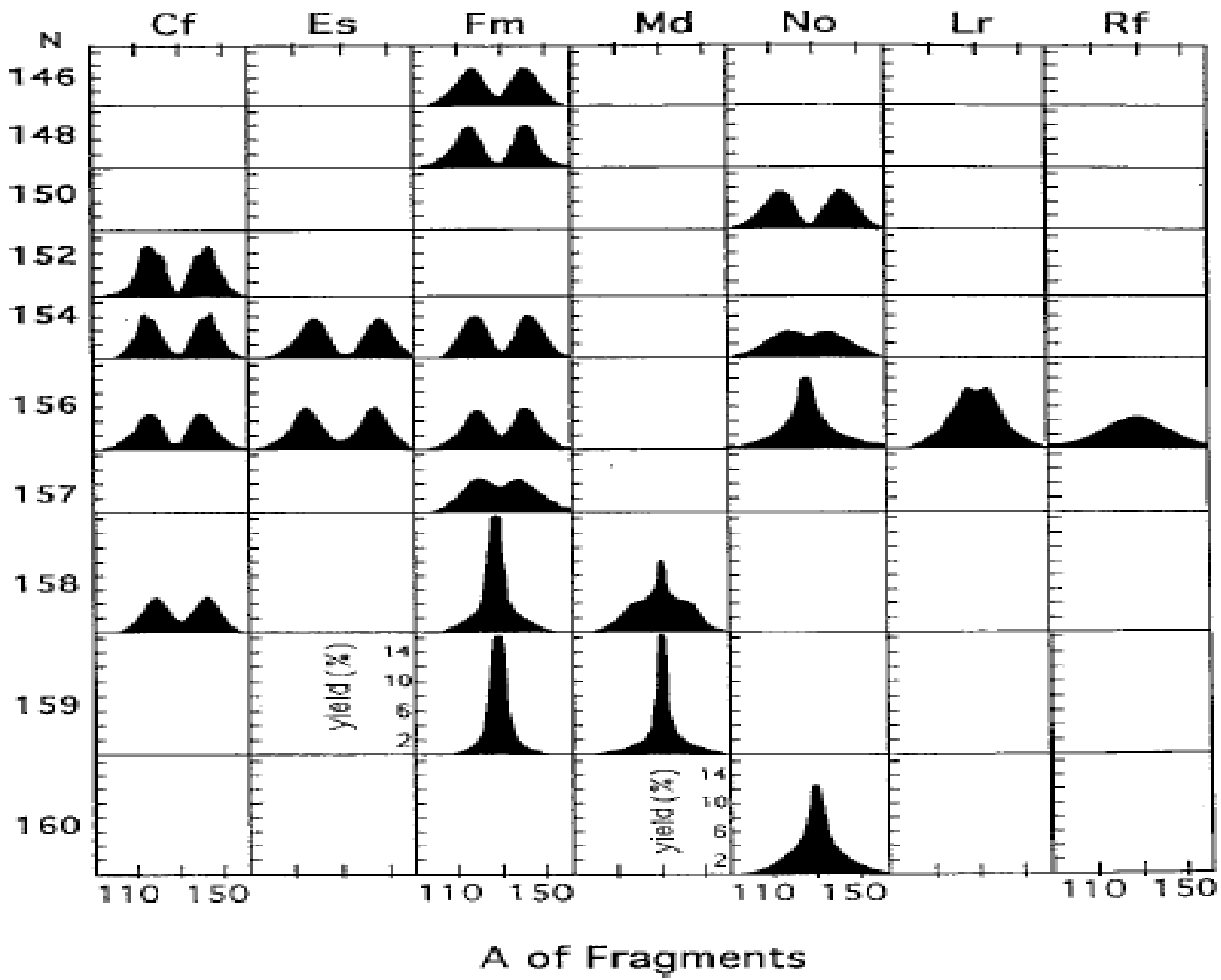


Charge distributions of fission fragments of low- and high-energy fission of Fm, No, and Rf isotopes

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


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

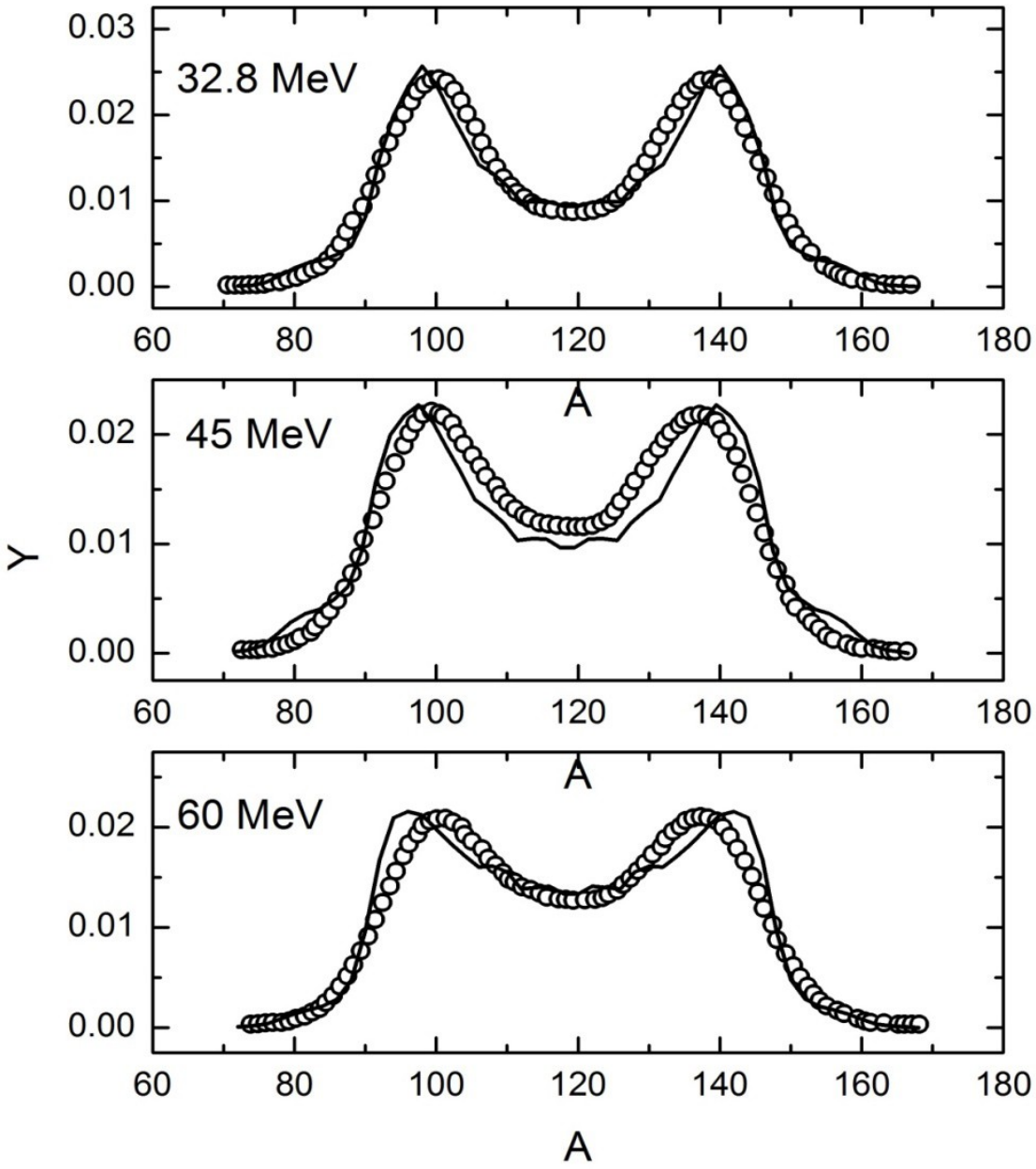
General opinion:

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 (60 MeV) 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 + ^{238}U

Statistical Scission-point Model

or

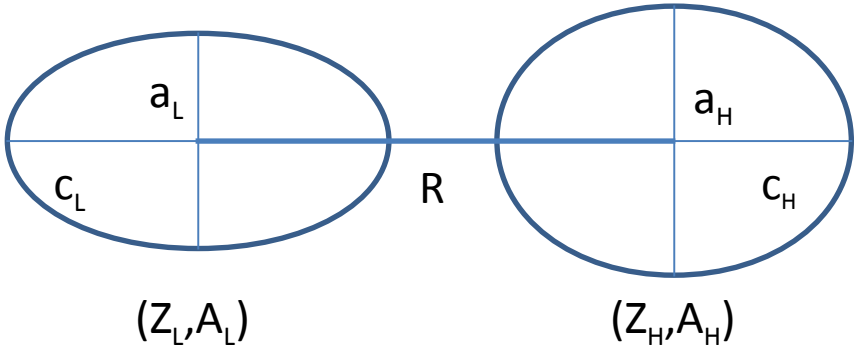
Cluster model of fission

- 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

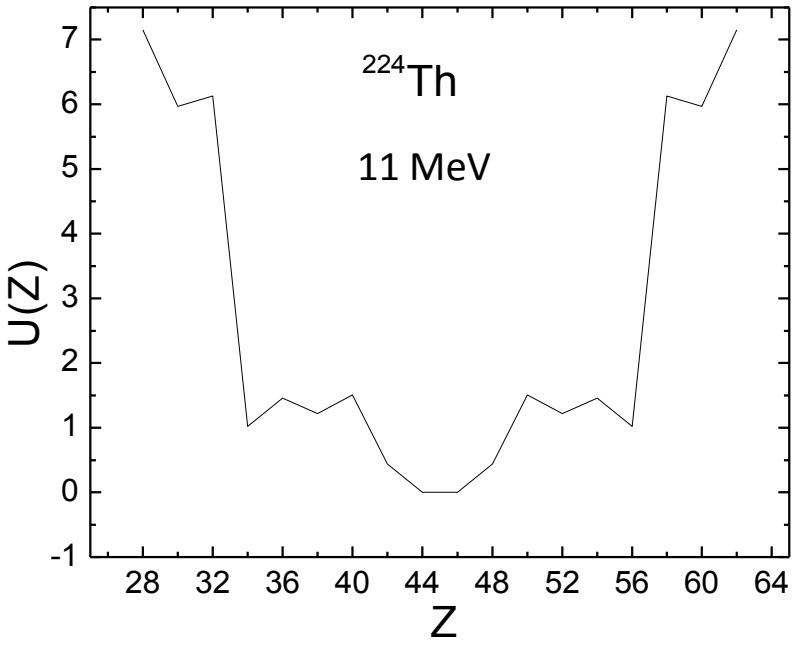
Coordinates Z_i, A_i, β_i (I = L, H), *R completely describe the geometry of system*



- ***Total Potential Energy*** :

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

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

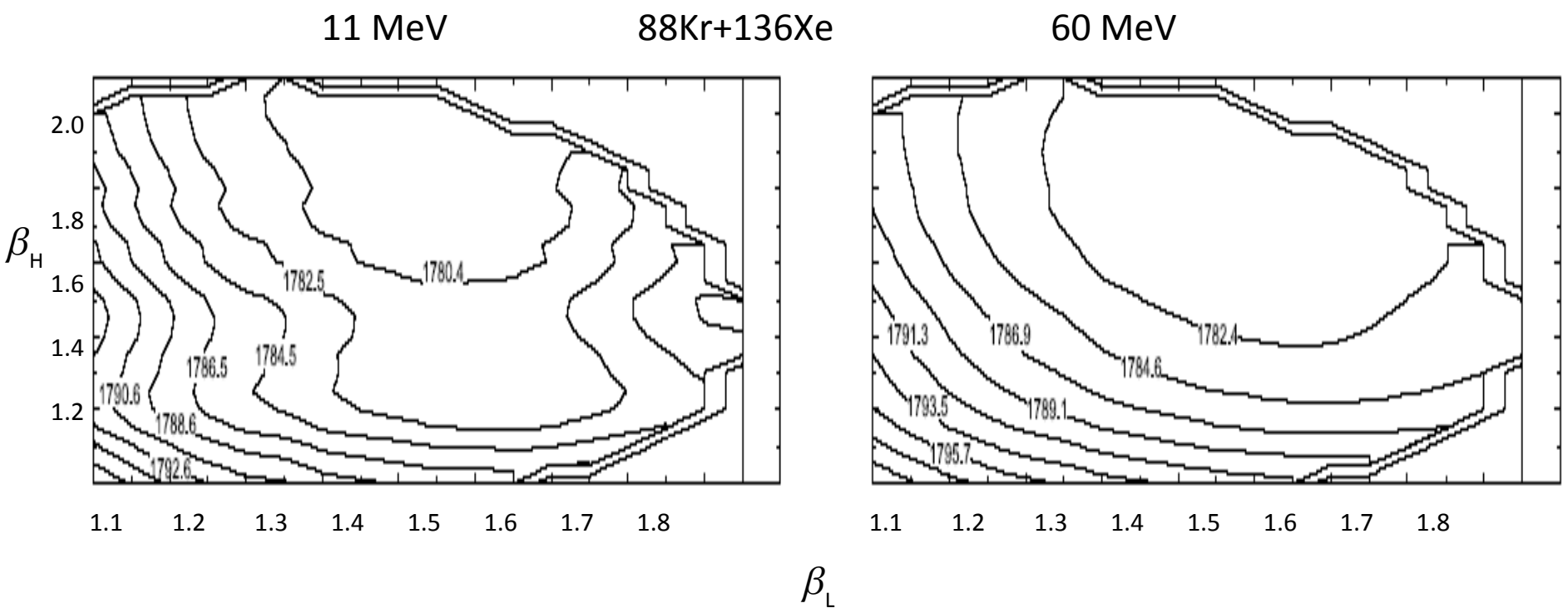


Minima in potential are result of interplay between liquid-drop, interaction, and shell correction energies

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

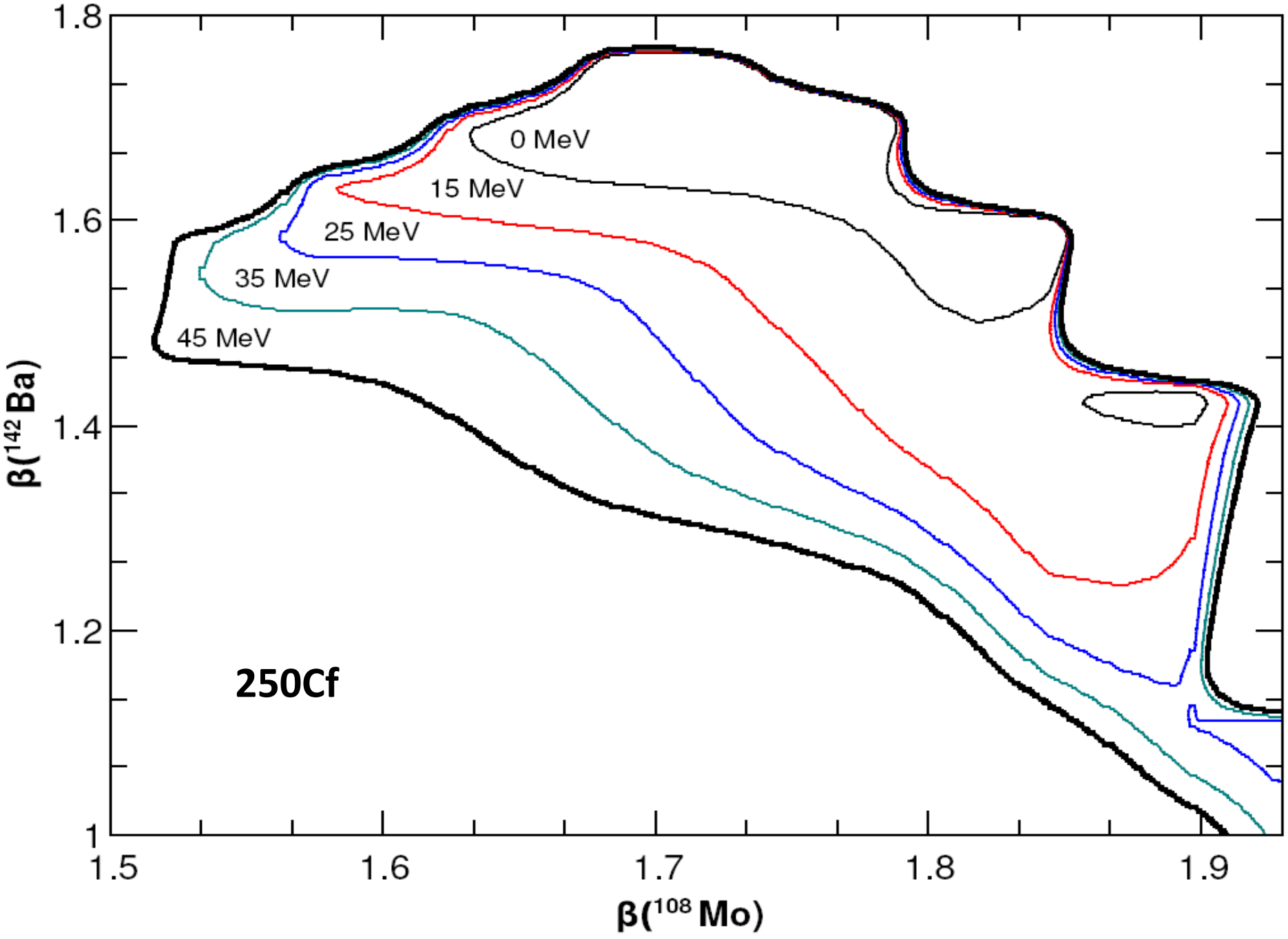
Yields:

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

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

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

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


0 MeV
15 MeV
25 MeV
35 MeV
45 MeV
250Cf
β(142 Ba)
β(108 Mo)
1.8
1.6
1.4
1.2
1
1.5
1.6
1.7
1.8
1.9

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

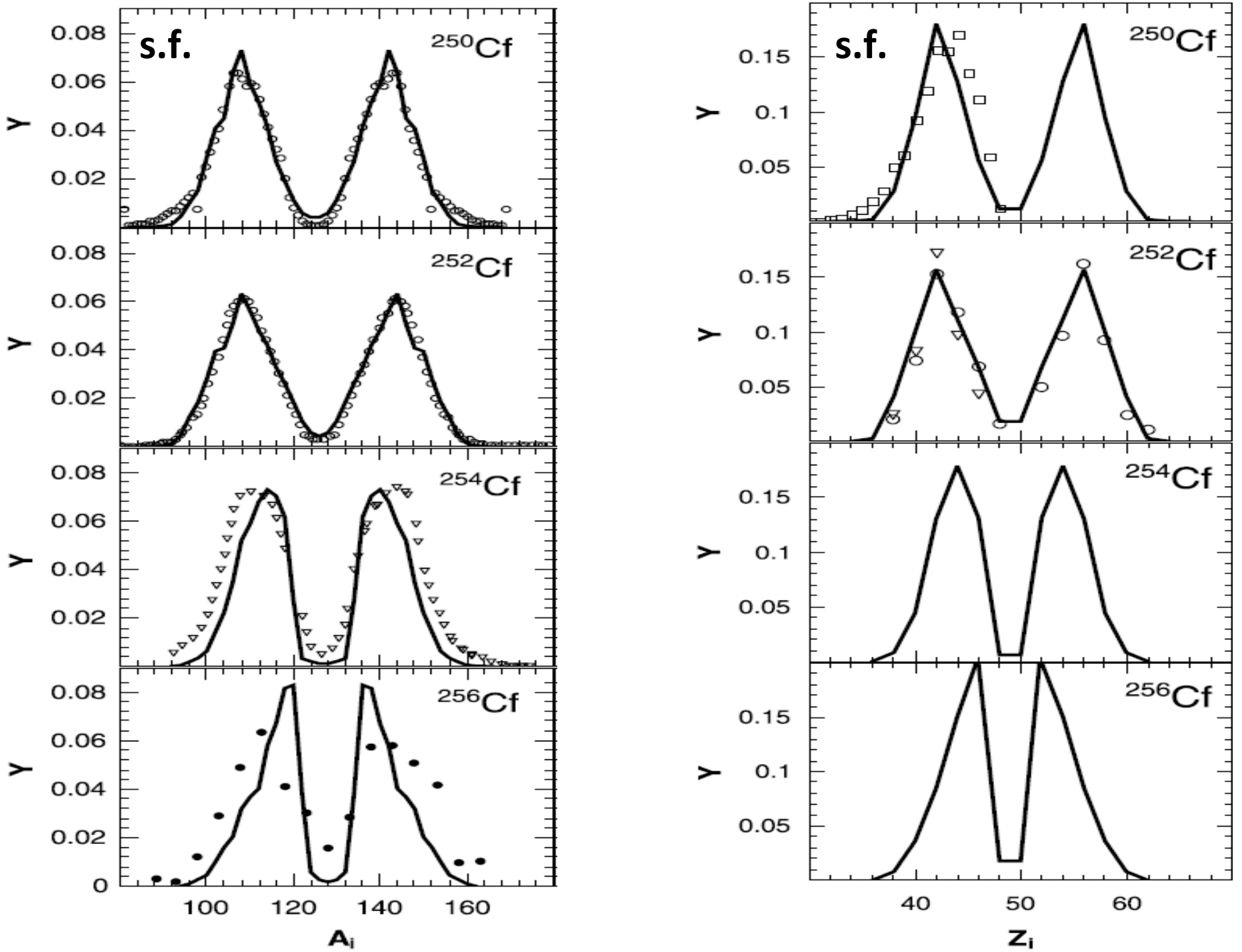
If two minima are close in energy, higher yield stems from (β_L, β_H). shallower minimum, lower yield emerges from abrupt-narrow minimum

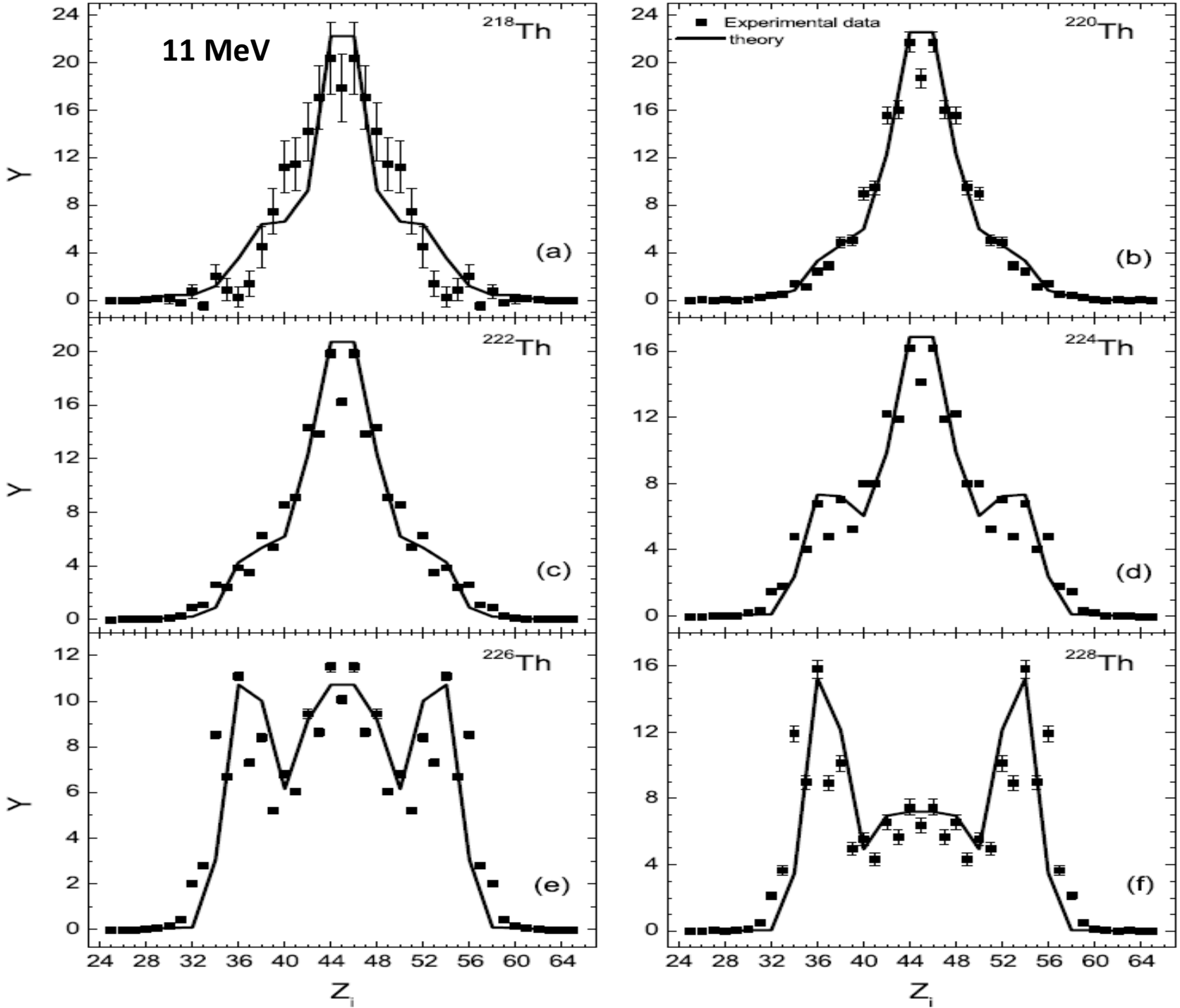
Results

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

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

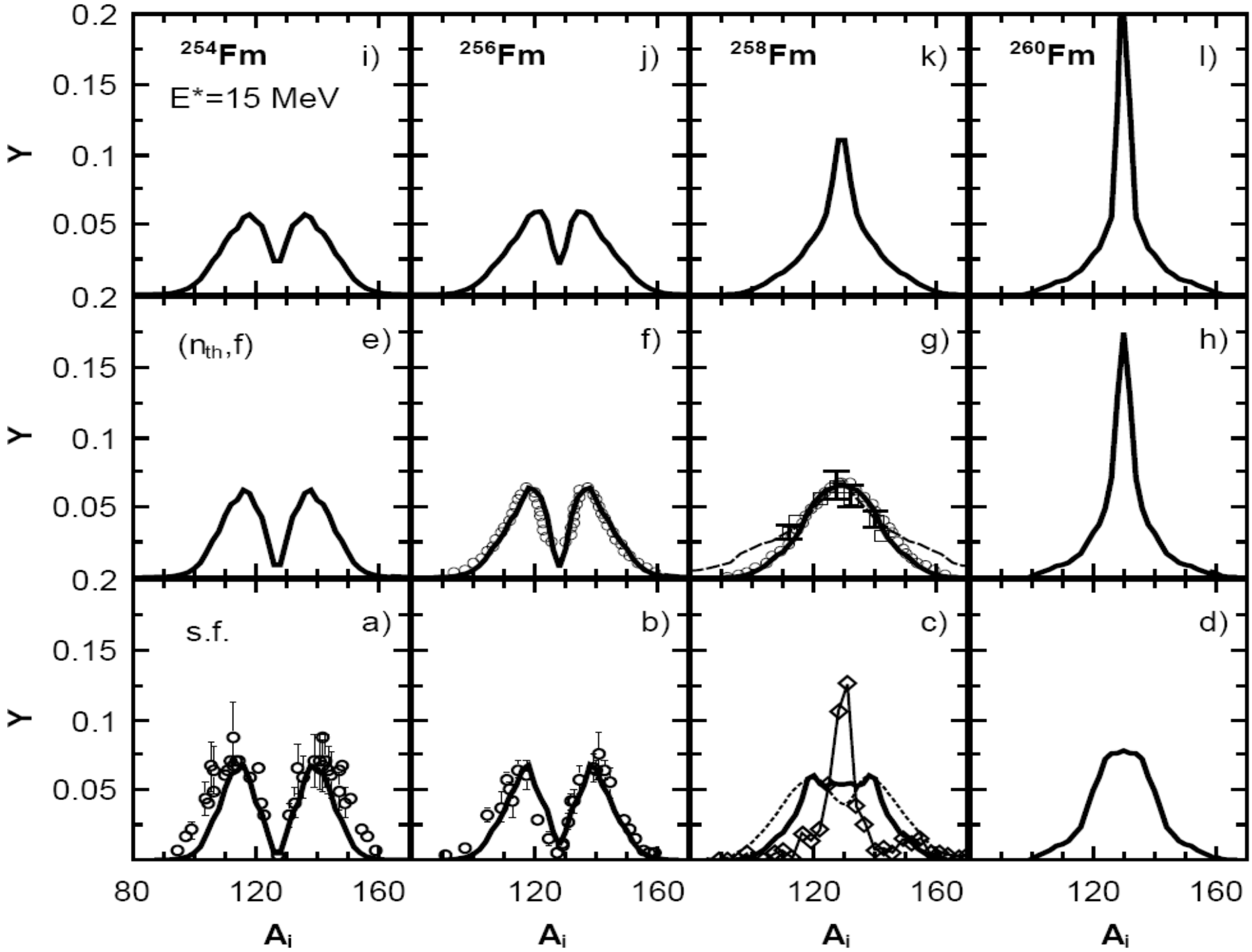
3. Fission of Heavy Actinides (**Fm, No, Rf**) at low & high excitation energy and zero spin

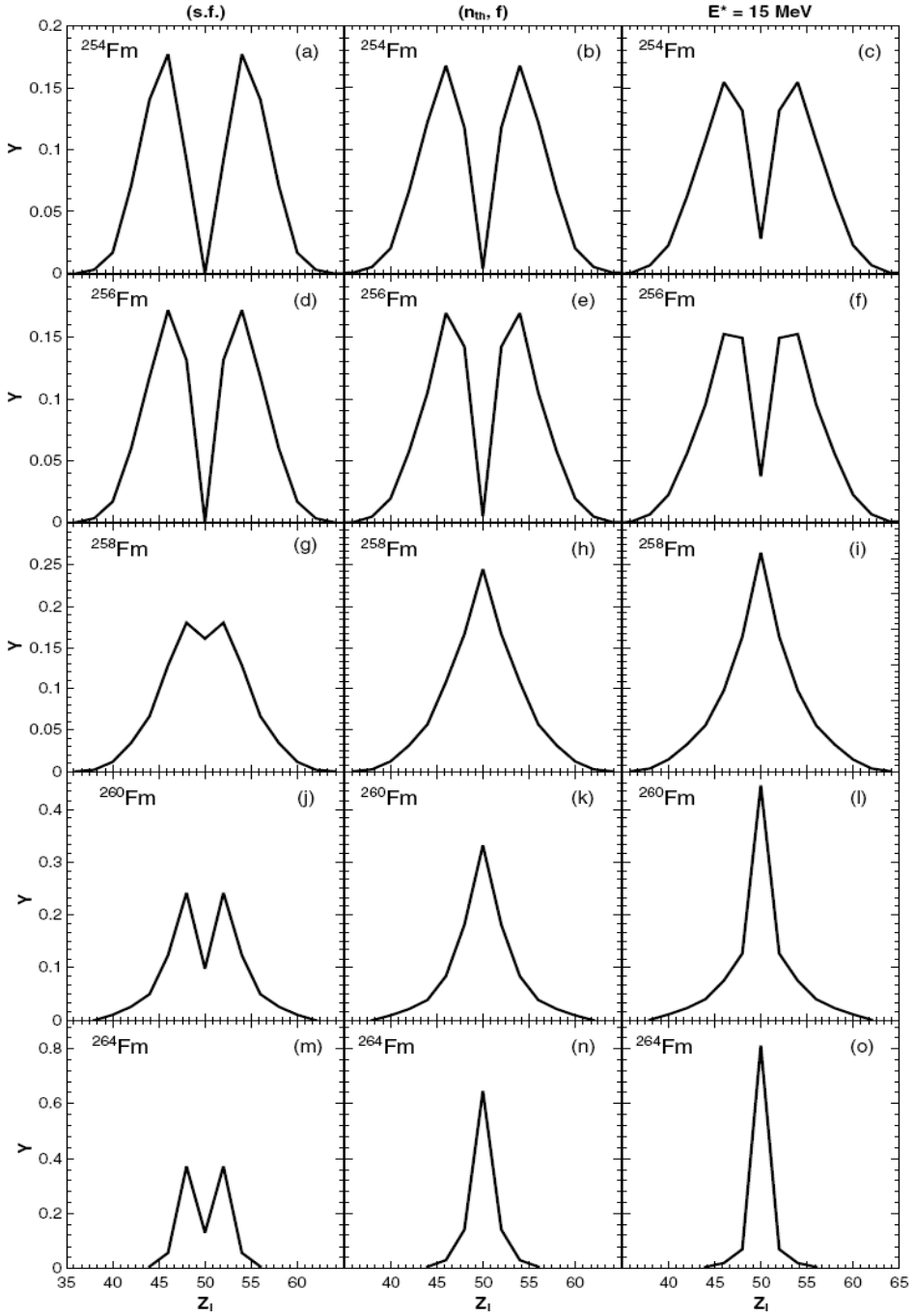

s.f.
^{250}Cf
^{252}Cf
^{254}Cf
^{256}Cf
Y
A_i
Z_i

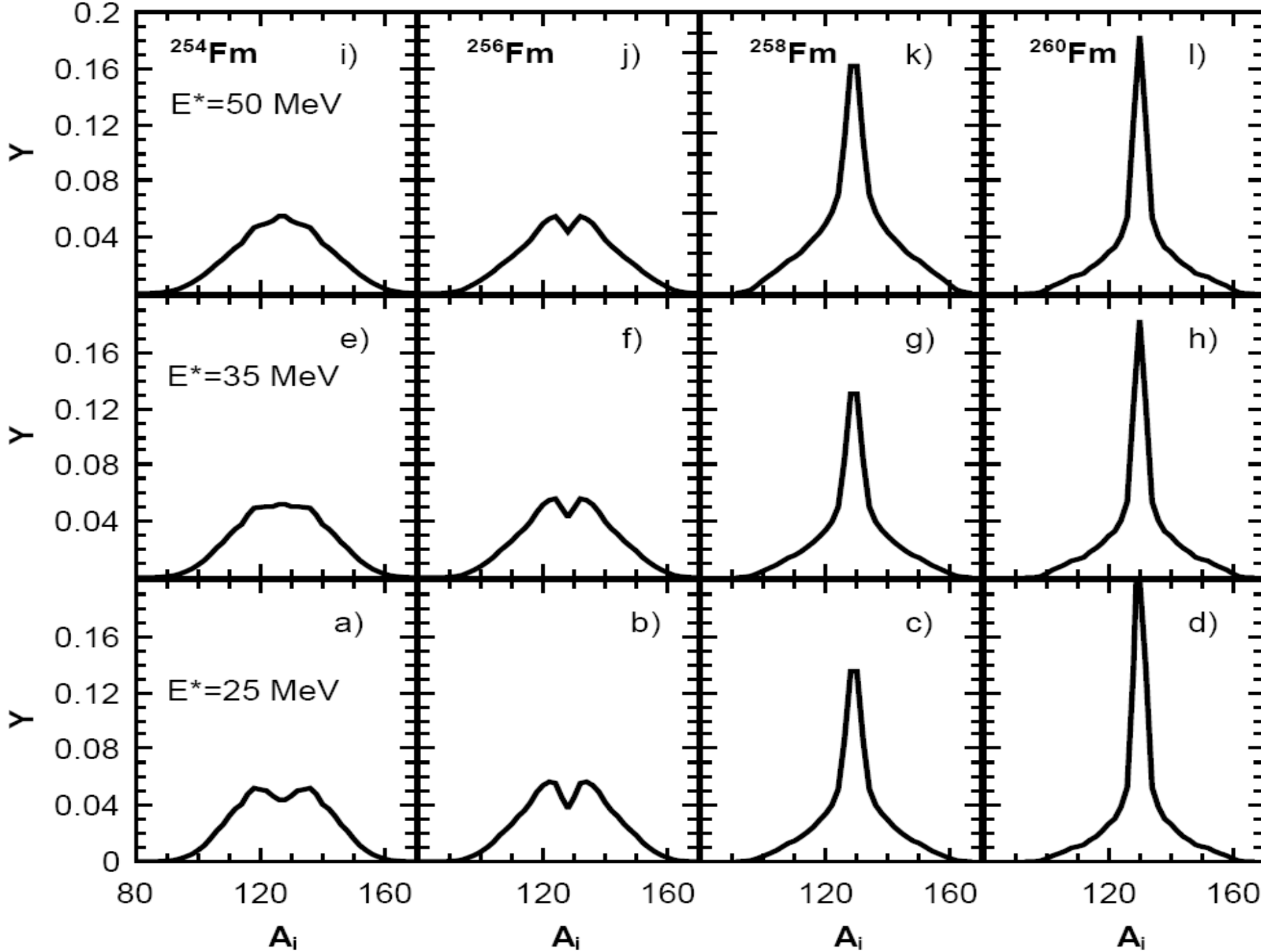

11 MeV
Experimental data
theory
^{218}Th
^{220}Th
^{222}Th
^{224}Th
^{226}Th
^{228}Th
(a)
(b)
(c)
(d)
(e)
(f)
Y
Z_i

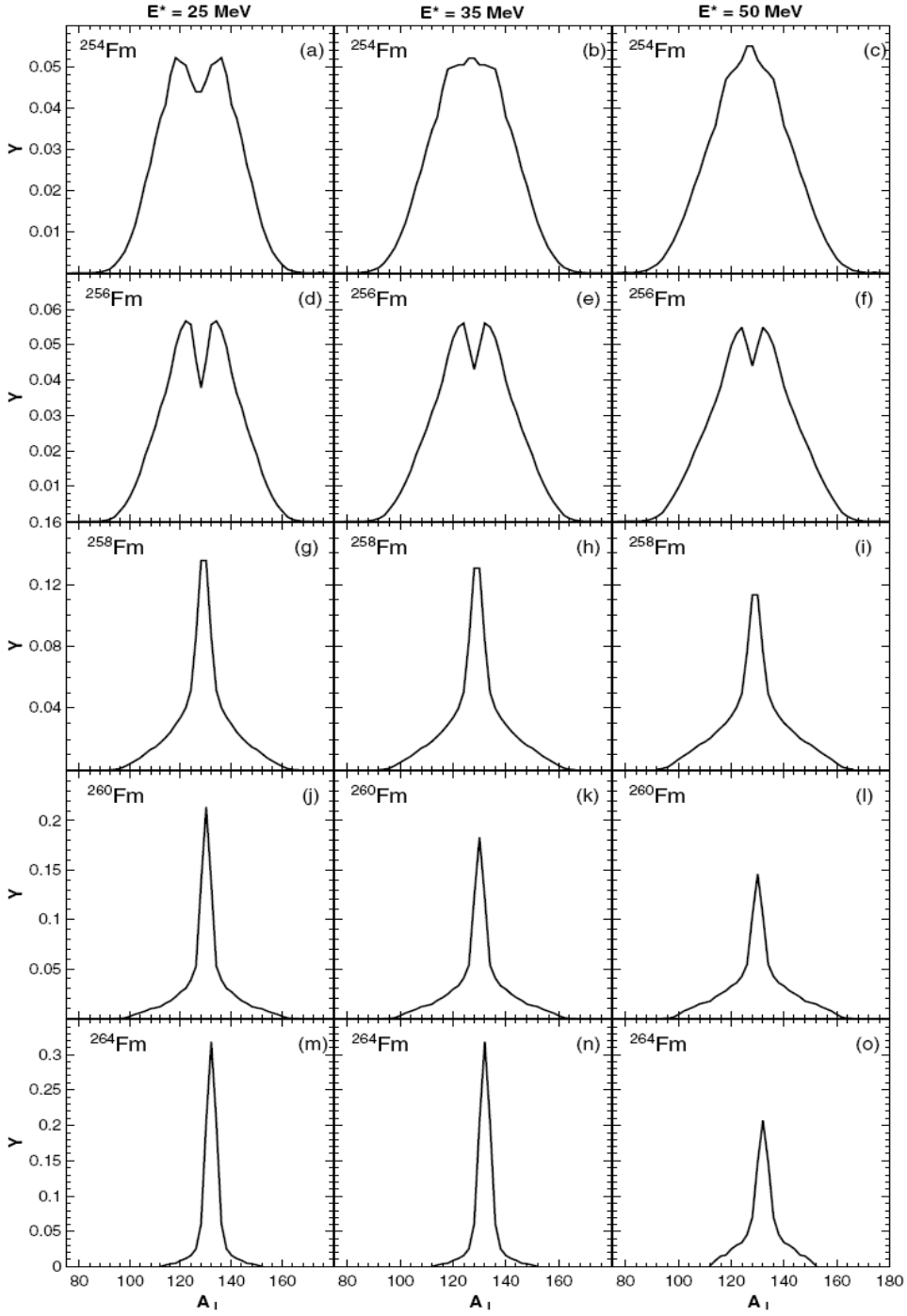
The change of charge/mass-yields with increasing isospin or excitation energy is related to the change of PES at scission point

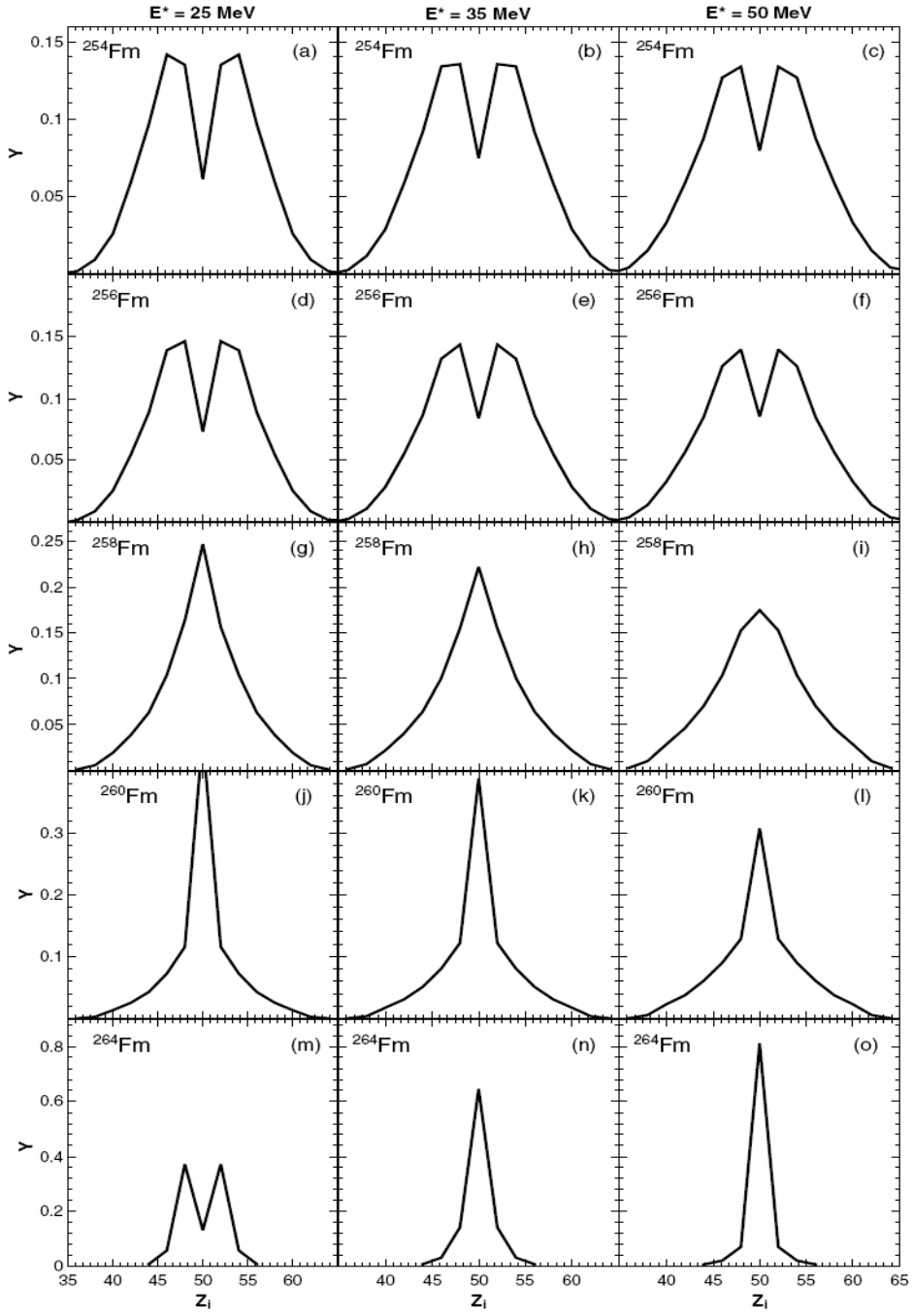
Fission of heavy actinides


^{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


(s.f.)
(n_th, f)
E* = 15 MeV
254Fm (a)
254Fm (b)
254Fm (c)
256Fm (d)
256Fm (e)
256Fm (f)
258Fm (g)
258Fm (h)
258Fm (i)
260Fm (j)
260Fm (k)
260Fm (l)
264Fm (m)
264Fm (n)
264Fm (o)
Y
Z_I

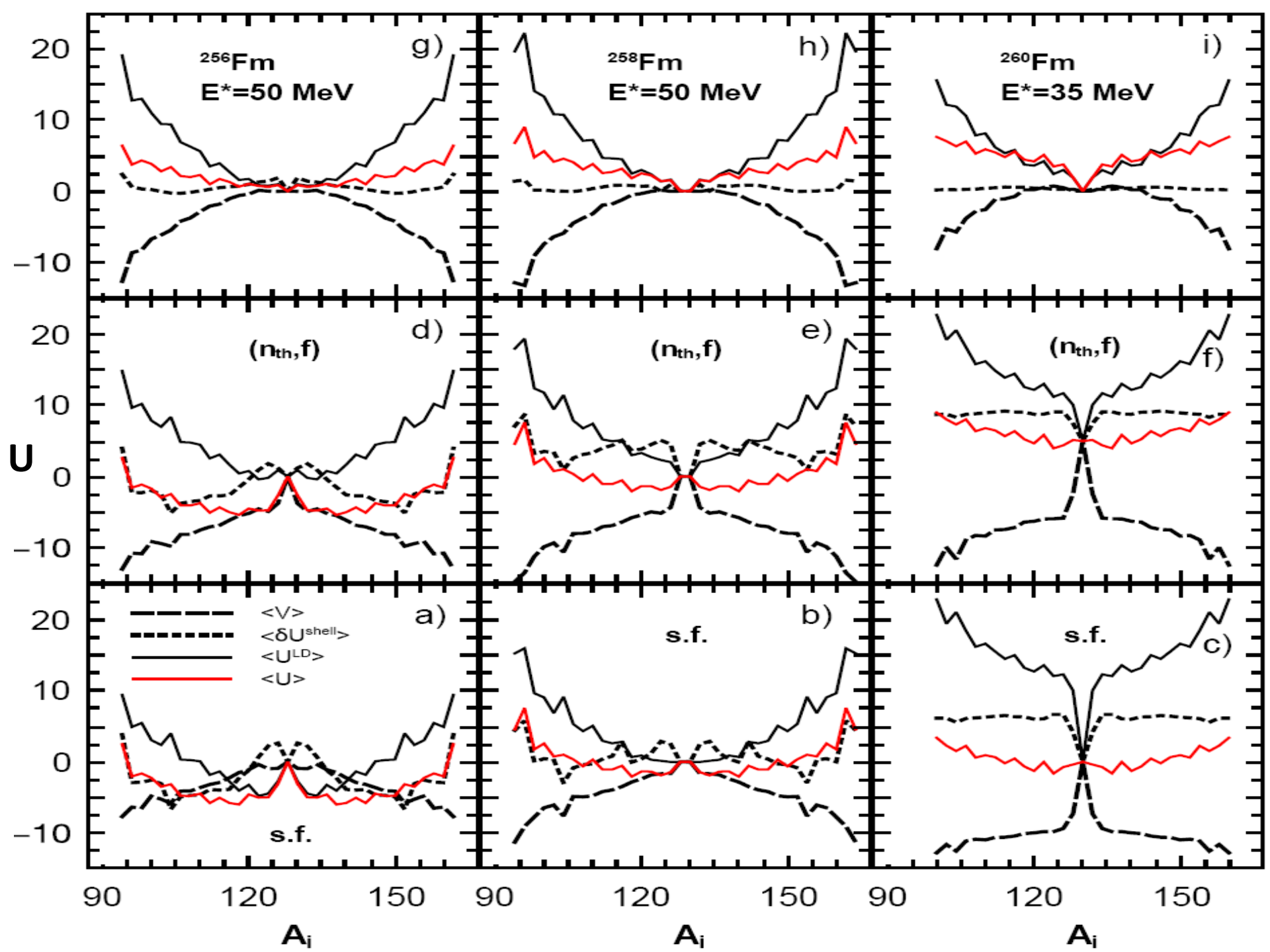

^{254}Fm
i)
E*=50 MeV
^{256}Fm
j)
^{258}Fm
k)
^{260}Fm
l)
e)
E*=35 MeV
f)
g)
h)
a)
E*=25 MeV
b)
c)
d)
Y
0.2
0.16
0.12
0.08
0.04
0
80
120
160
A_i


E* = 25 MeV
E* = 35 MeV
E* = 50 MeV
^{254}Fm
(a)
(b)
(c)
^{256}Fm
(d)
(e)
(f)
^{258}Fm
(g)
(h)
(i)
^{260}Fm
(j)
(k)
(l)
^{264}Fm
(m)
(n)
(o)
Y
A$_1$


E* = 25 MeV
E* = 35 MeV
E* = 50 MeV
254Fm (a)
254Fm (b)
254Fm (c)
256Fm (d)
256Fm (e)
256Fm (f)
258Fm (g)
258Fm (h)
258Fm (i)
260Fm (j)
260Fm (k)
260Fm (l)
264Fm (m)
264Fm (n)
264Fm (o)
Y
Zi

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**

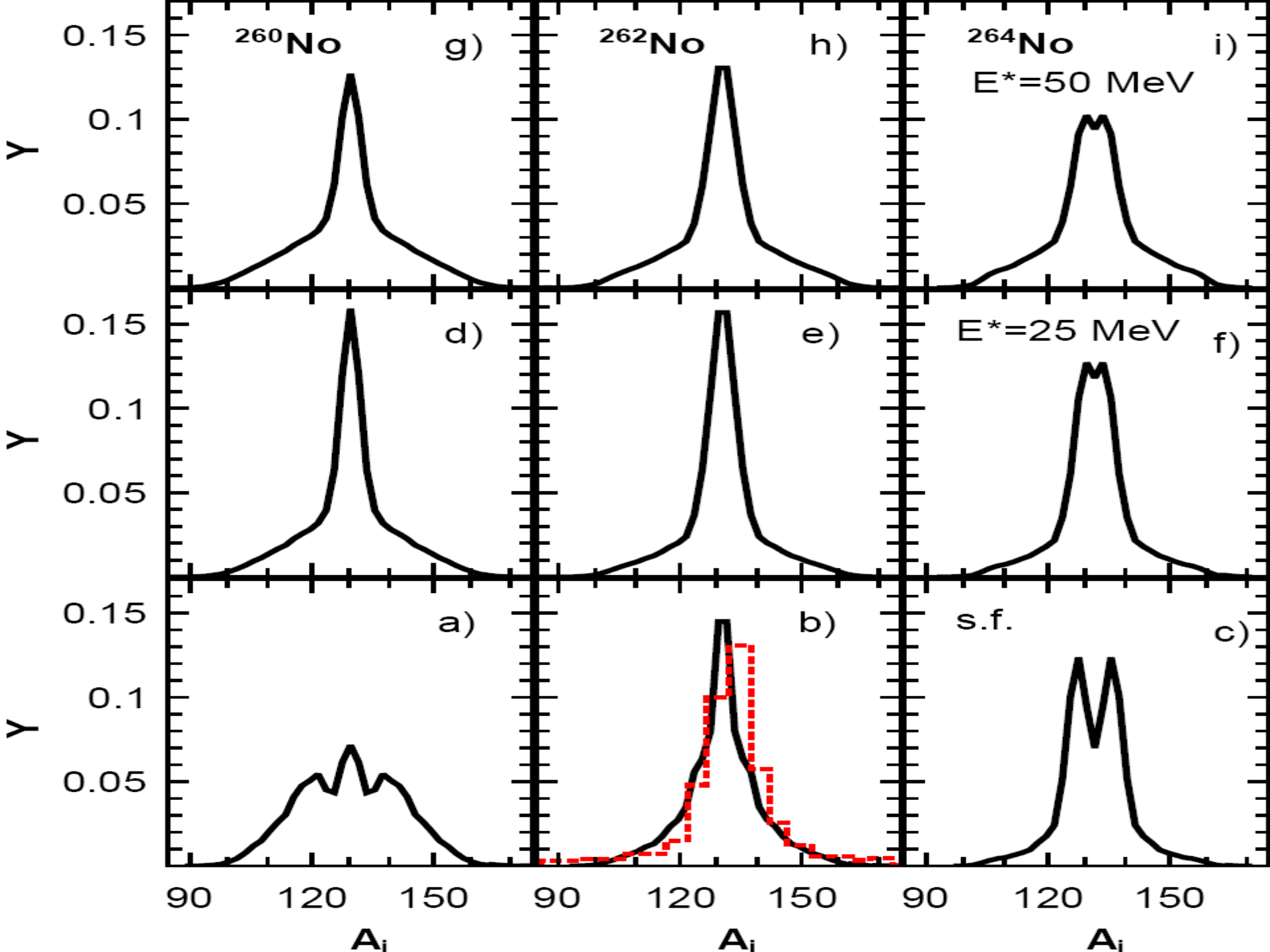

g)
^{256}Fm
E*=50 MeV
h)
^{258}Fm
E*=50 MeV
i)
^{260}Fm
E*=35 MeV
d)
(n$_{th}$,f)
e)
(n$_{th}$,f)
f)
(n$_{th}$,f)
a)
<V>
<δU^{shell}>
<U^{LD}>
<U>
s.f.
b)
s.f.
c)
s.f.
U
A$_i$
A$_i$
A$_i$
20
10
0
−10
90
120
150

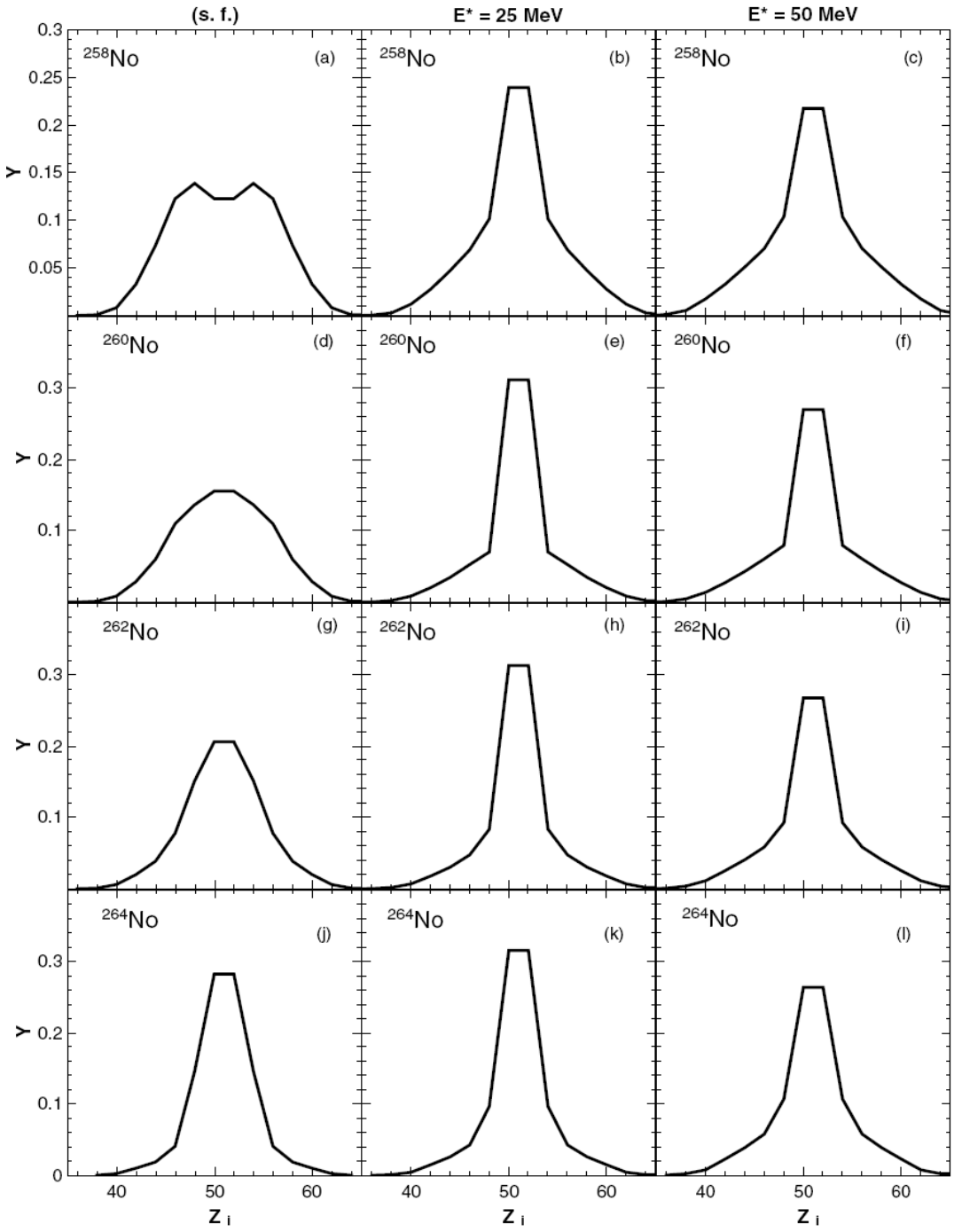
Minima in potential or Maxima in yields are result of interplay between liquid-drop, interaction, shell correction energies.

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.


^{260}No
g)
^{262}No
h)
^{264}No
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
A_i

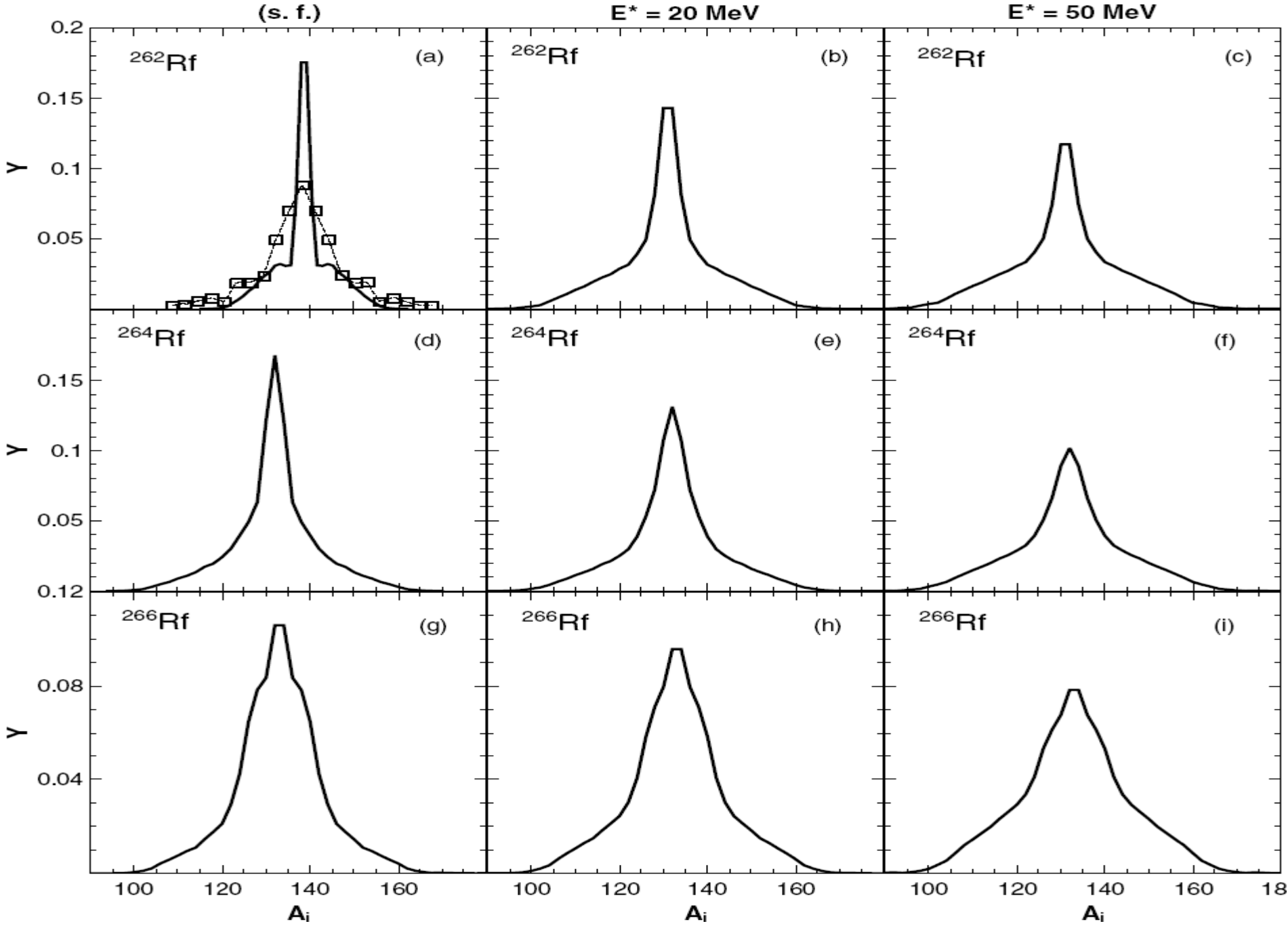

(s. f.)
E* = 25 MeV
E* = 50 MeV
^{258}No
(a)
^{258}No
(b)
^{258}No
(c)
^{260}No
(d)
^{260}No
(e)
^{260}No
(f)
^{262}No
(g)
^{262}No
(h)
^{262}No
(i)
^{264}No
(j)
^{264}No
(k)
^{264}No
(l)
Y
Z i
0
0.05
0.1
0.15
0.2
0.25
0.3
40
50
60

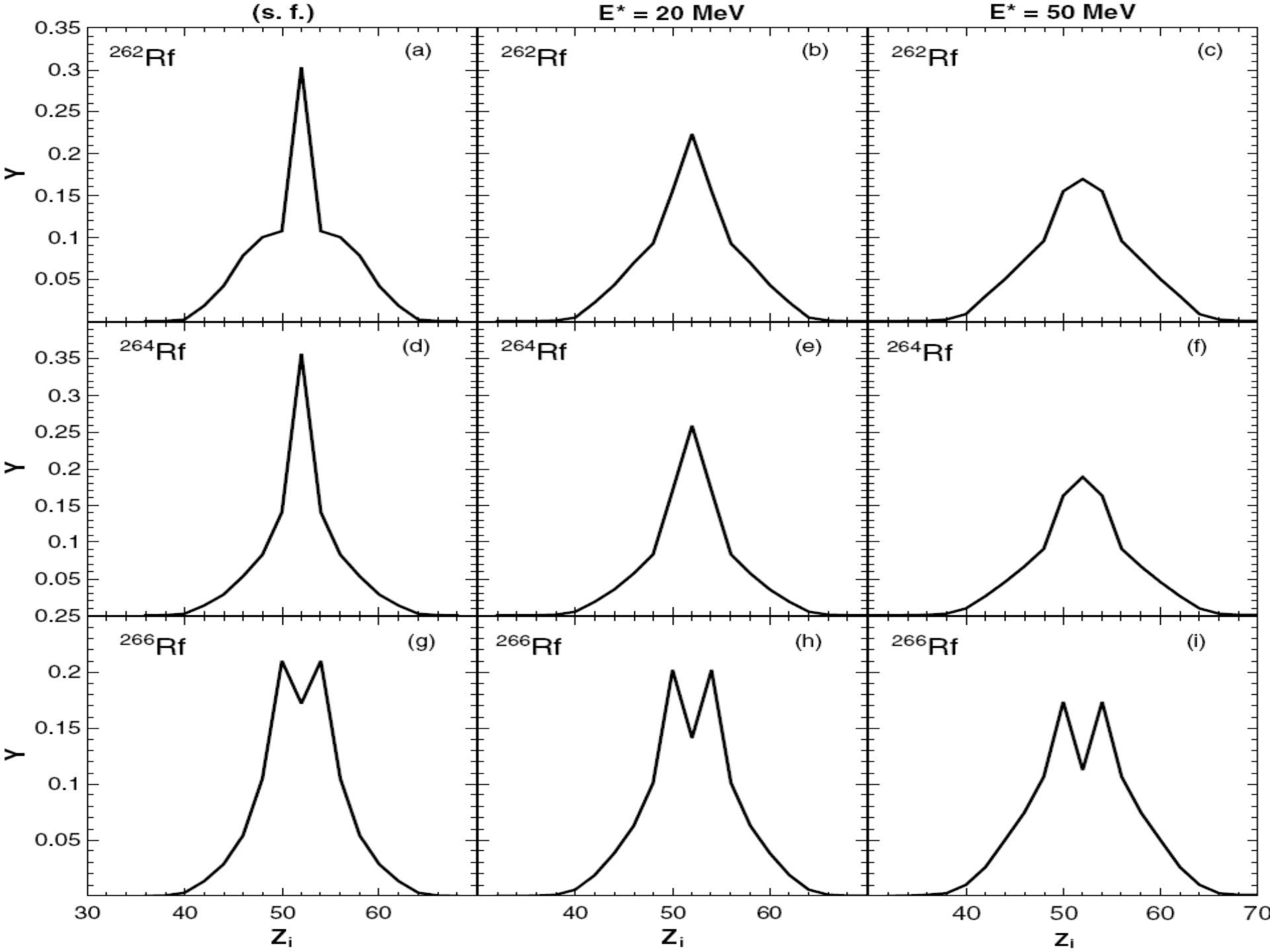
Saturation effect

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
^{262}Rf
(a)
^{262}Rf
(b)
^{262}Rf
(c)
^{264}Rf
(d)
^{264}Rf
(e)
^{264}Rf
(f)
^{266}Rf
(g)
^{266}Rf
(h)
^{266}Rf
(i)
Y
A_i
0.2
0.15
0.1
0.05
0.12
0.08
0.04
100
120
140
160
18


(s. f.)
E* = 20 MeV
E* = 50 MeV
^{262}Rf
(a)
^{262}Rf
(b)
^{262}Rf
(c)
^{264}Rf
(d)
^{264}Rf
(e)
^{264}Rf
(f)
^{266}Rf
(g)
^{266}Rf
(h)
^{266}Rf
(i)
Y
Z_i

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, ^{260}Fm(sf), ^{260}No(sf), ^{266}Rf(sf)**

Thank You For Your Attention !