Fission of Transactinide Elements Described in Terms of Generalized Cassinian Ovals: Fragment Mass and Total Kinetic Energy Distributions

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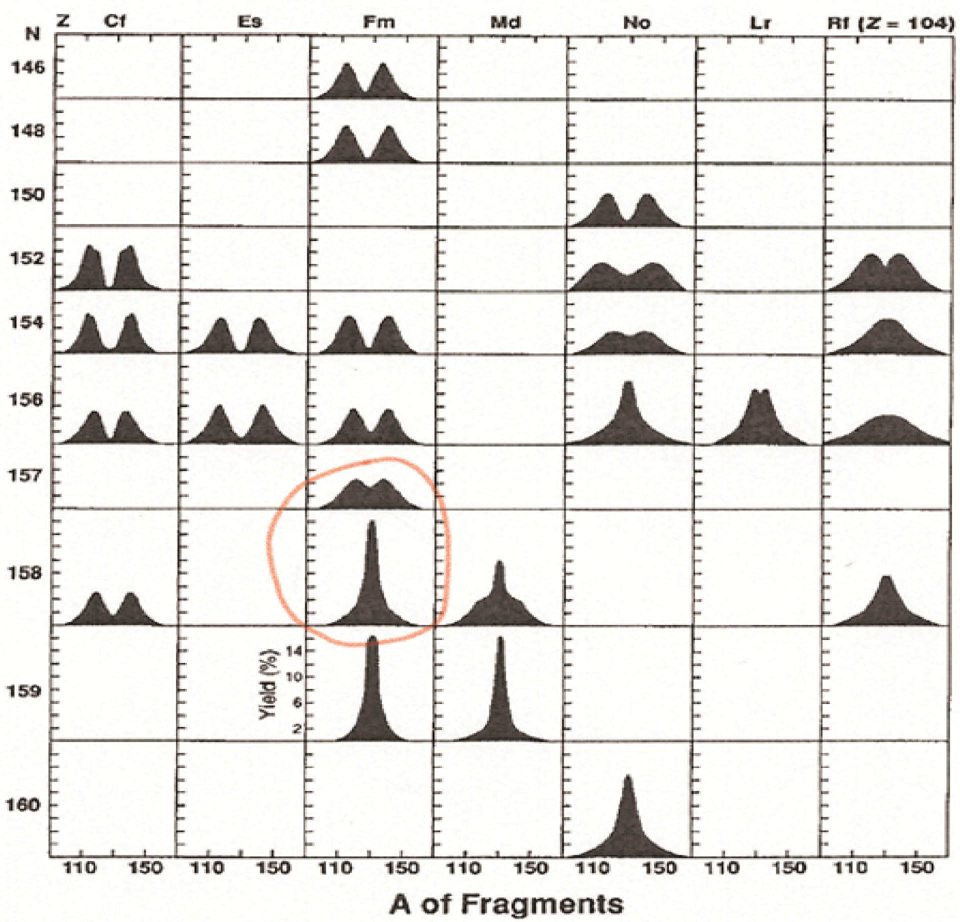
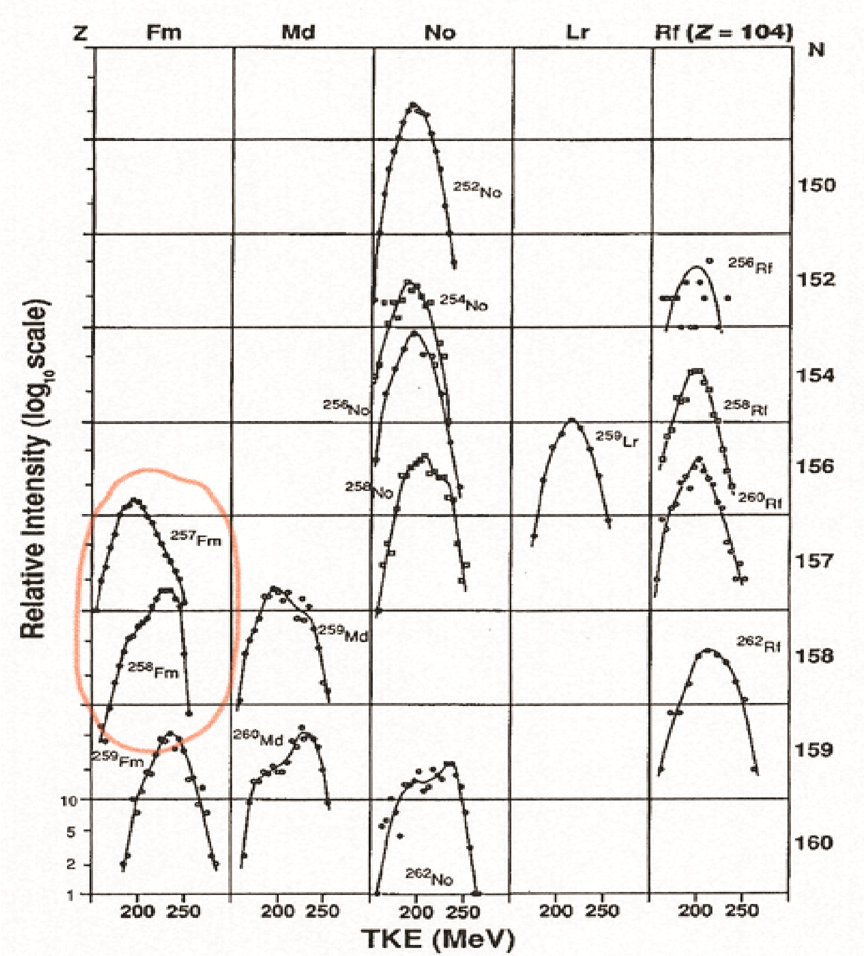
Known mass and TKE distributions for SF of trans-actinide isotopes

(from M.R Lane et al. PRC 53 (1996) 2893)





Basic ingredient: potential energy of deformation calculated using the microscopic-macroscopic approach (Liquid-Drop model + Strutinsky shell correction)

$$E_{def}(\textit{shape}) = E_{LD}(\textit{shape}) + E_{shell}(\textit{shape})$$

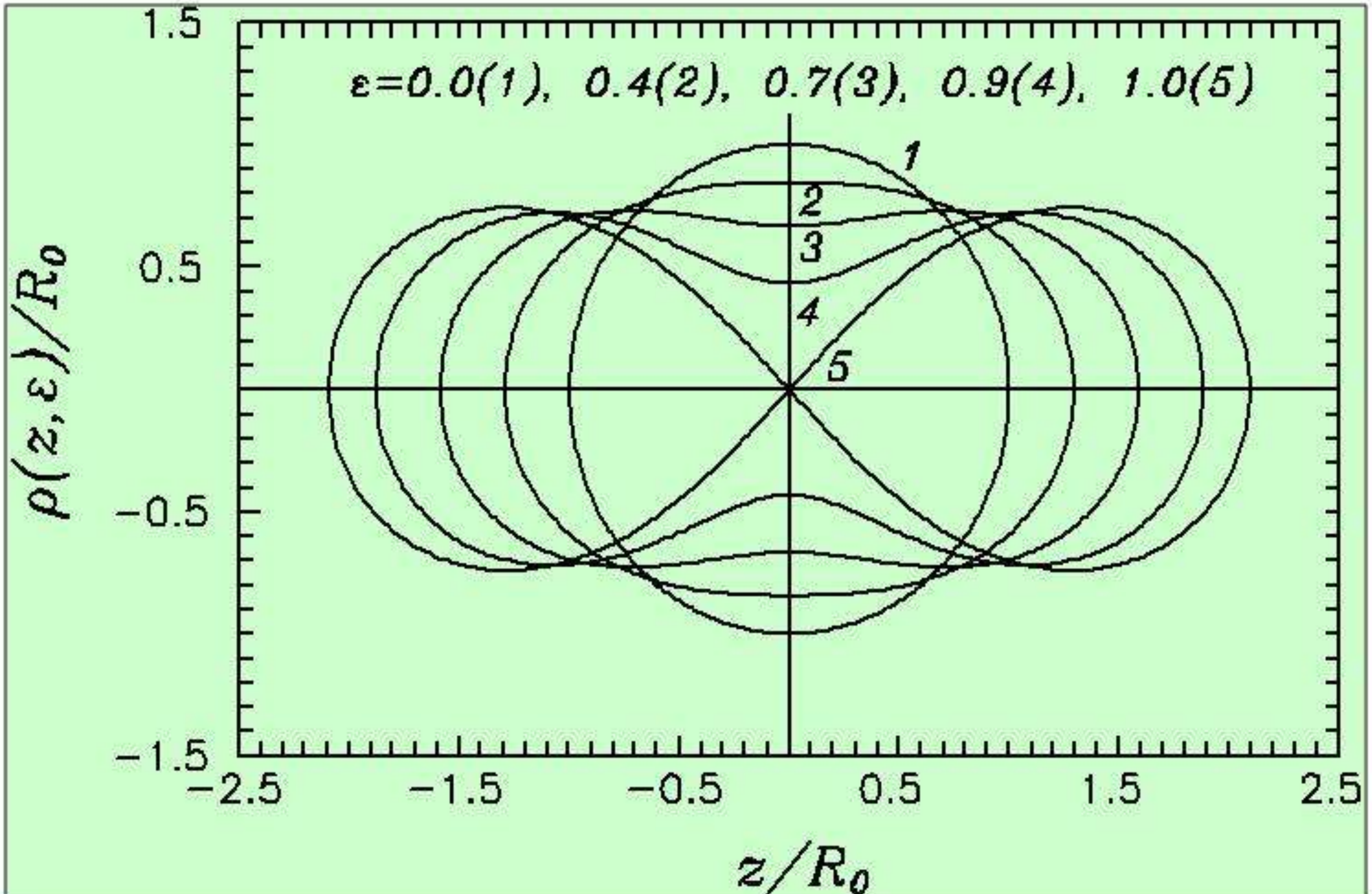
Shape parametrization: expansion of the Cassinian ovals in series of Legendre polynomials

$$R(x) = R_0 / c[1 + \sum_n \alpha_n P_n(x)]$$

R_0 is the radius of the spherical nucleus, α_n are the shape parameters and $c = (V/V_0)^{1/3}$ assures the volume conservation.

(R,x) is an orthogonal coordinate system convenient to describe the shape of a fissioning nucleus close to the scission point (V. V. Pashkevich 1971)

Pure Cassini ovals are the basic lines of the lemniscate coordinate system



Obviously it is easier to describe a scission shape starting from curve no (5) than from no (1)

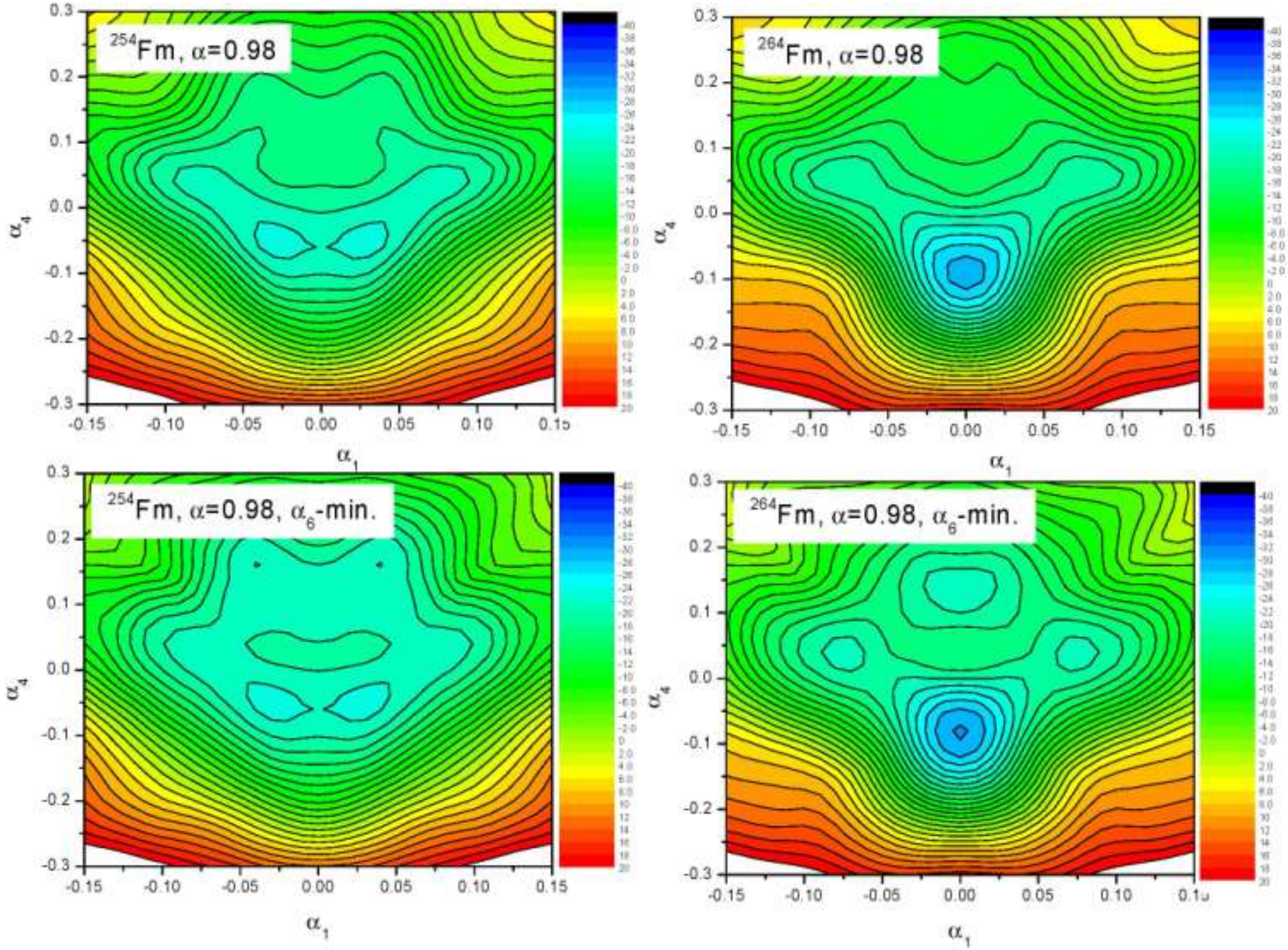
We introduce a new parameter α with the property that a shape with r_{neck} =0 has always α=1 , irrespective of the values of α_n

$$\alpha(\alpha_n) = \frac{z_L^2 + z_R^2 - 2\rho}{z_L^2 + z_R^2 - 2\rho}$$

Where z_L (z_R) is the coordinate of the left (right) tip of the nuclear shape and $\rho = r^2_{neck}$. Values slightly lower than 1 correspond to two fragments connected by a thin neck.

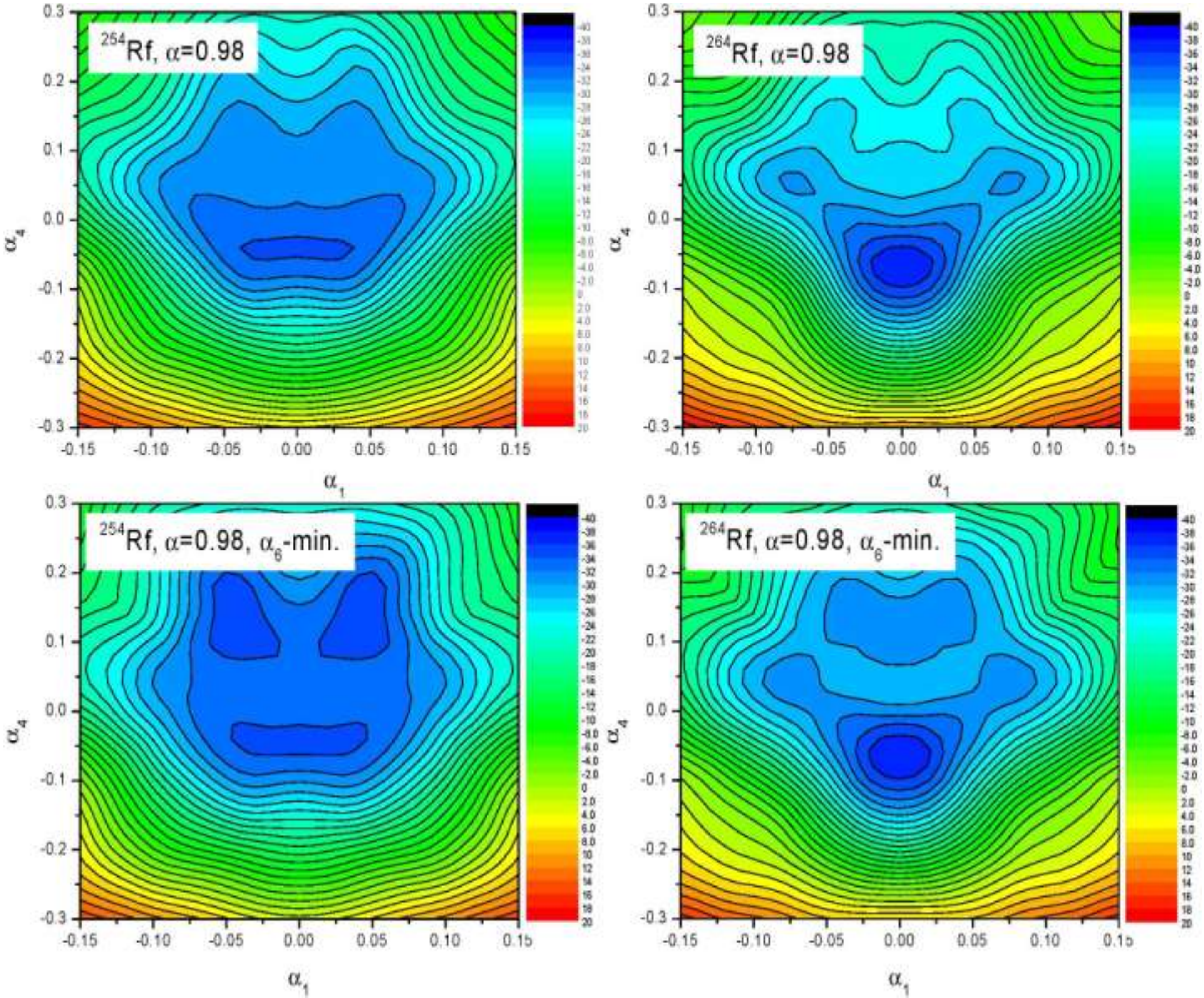
We approximate the scission line by α = 0.98

Potential energy surfaces: we study the influence of α_1 (mass asymmetry) and α_4 [acting on the quadrupole elongation of each fragment makes the scission shape more compact (α_4<0) or more elongated (α_4 >0)]. In addition we minimize with respect to α_6 .



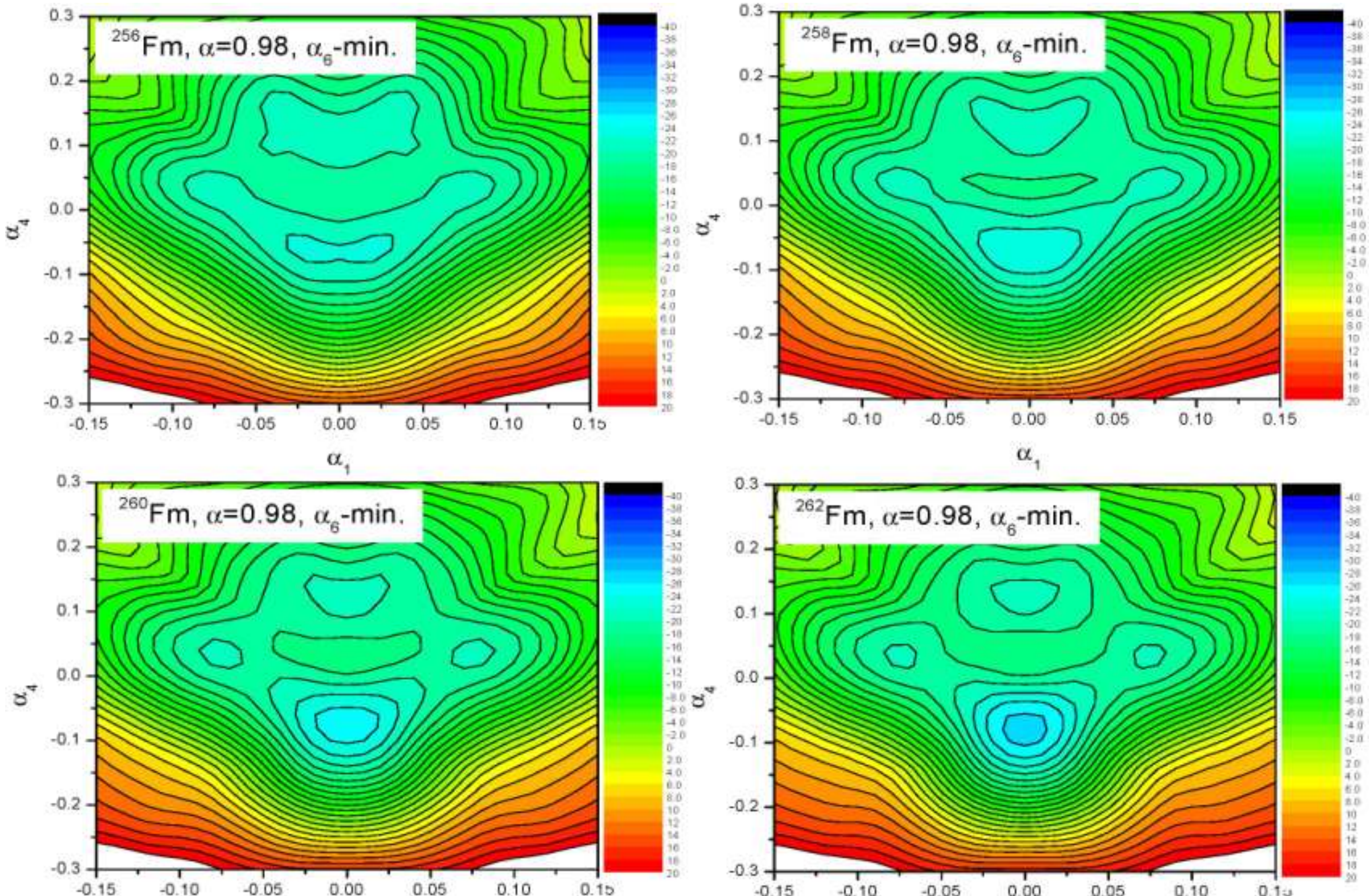
Upper part: minima are found in the negative (compact) α_4 plane: broad-asymmetric for A=254 and narrow-symmetric for A=264. Slightly elongated, mass-asymmetric shallower minima are also visible.

Lower part: the inclusion of α_6 makes new minima to appear in the positive (elongated) α_4 plane: again asymmetric for A=254 and symmetric for A=264. The shallow minima are now more pronounced.



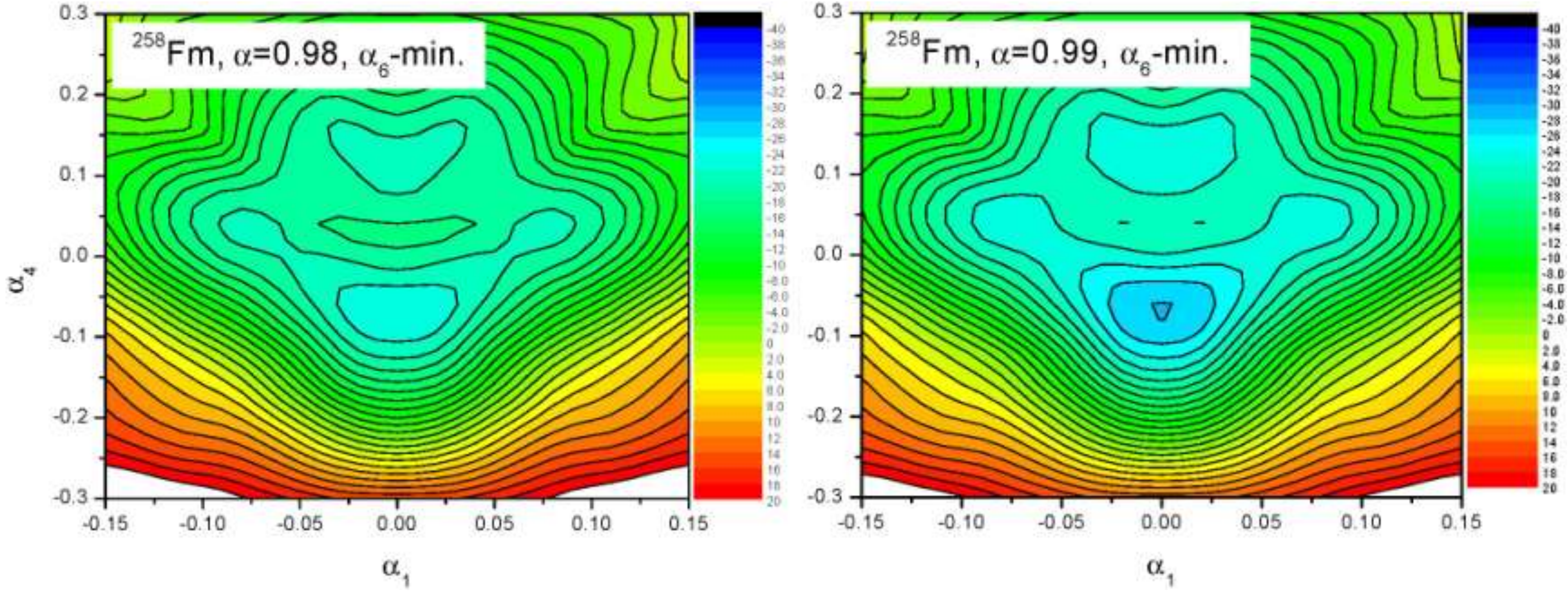
Rf isotopes are qualitatively similar with Fm. The dominance of the blue nuances are due to the lower energy of the scission configuration with respect of the macroscopic ground state in Rf (as compared with Fm).

Evolution of the potential energy surfaces from ^{256}Fm to ^{262}Fm. Although the 3 minima have different relative intensities, they are always present.



The minima corresponding to elongated shapes (both mass symmetric and asymmetric) do not vanish closer to zero-neck shapes

(α = 0.99, i.e. r_{neck} = 1.05 fm)



Mass distribution of the fission fragments

Supposing statistical equilibrium for the collective degrees of freedom normal to the fission direction, the distribution of each point (α_1,α_4) on the previous surfaces is due to thermal fluctuations:

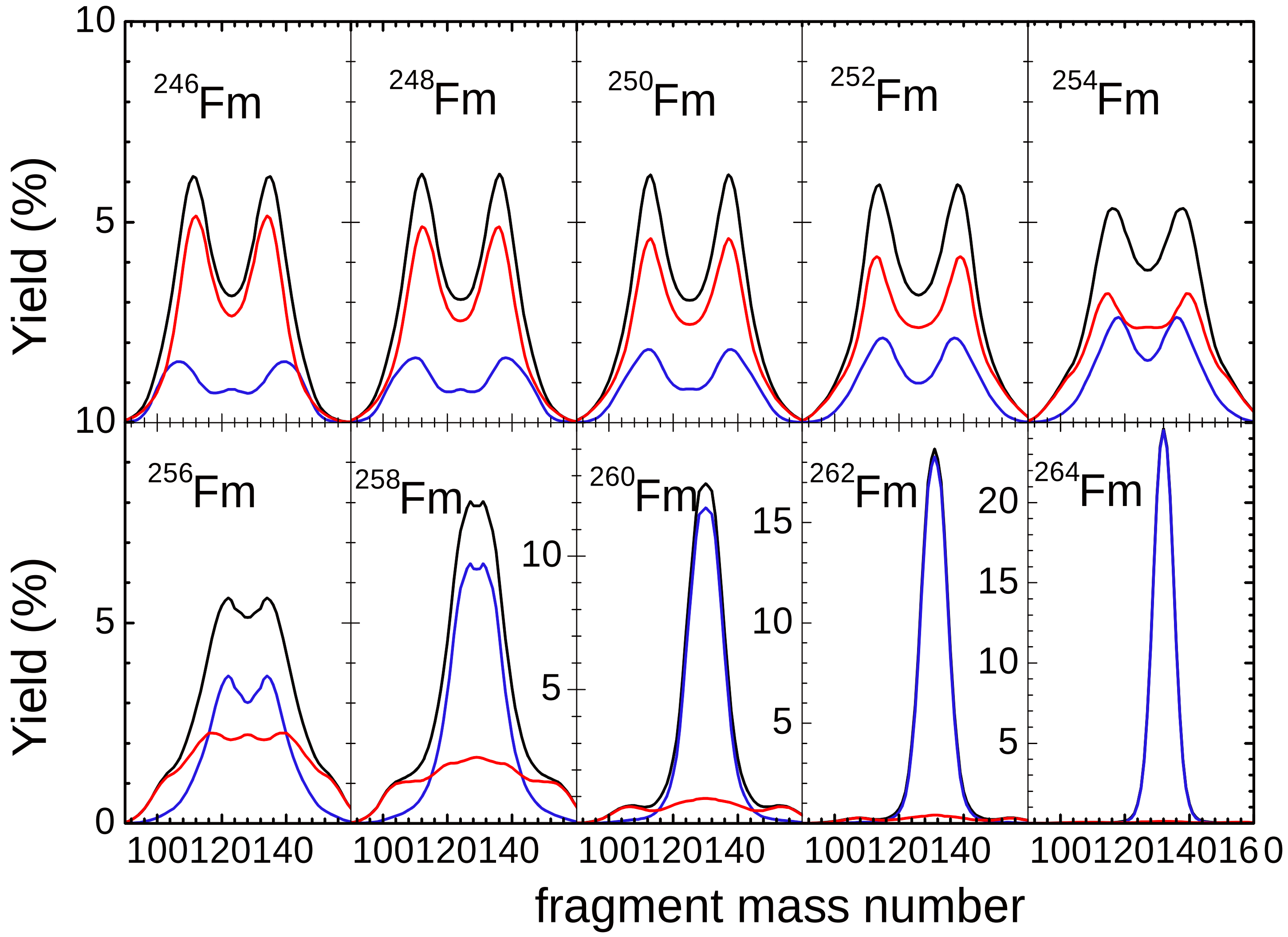
$$P(\alpha_1, \alpha_4) \propto e^{-E_{def}(\alpha_1, \alpha_4)/T_{coll}}$$

with T_{coll} =1.5 MeV.

Projecting on the α_1 –axis one obtains the total yield:

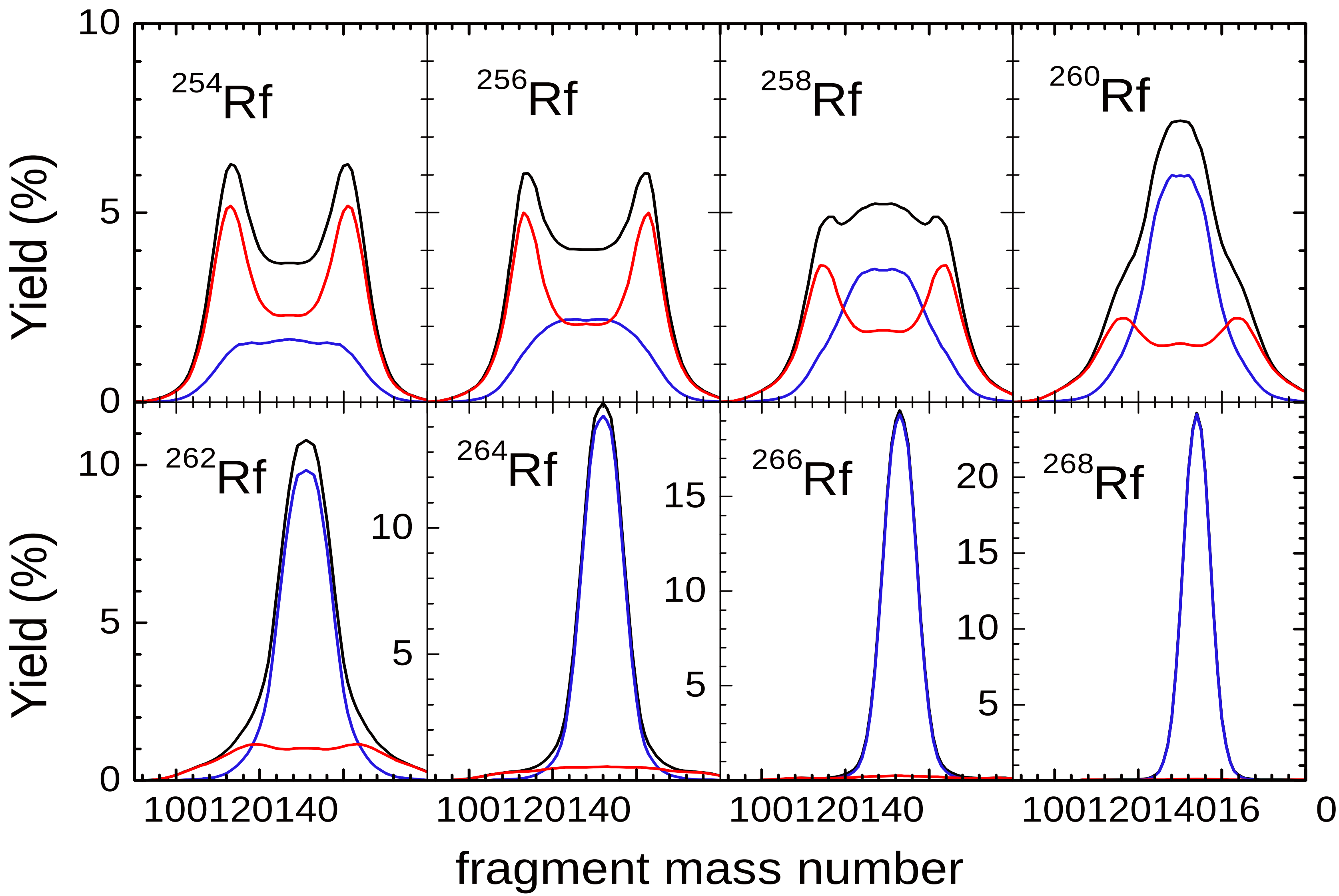
$$Y(\alpha_1) = \sum_i P(\alpha_1, \alpha_{4i}) / \sum_j (\sum_i P(\alpha_{1j}, \alpha_{4i}))$$

The shape parameter α_1 determines the mass asymmetry $\eta = (A_F^H - A_F^L)/A$. The mass distributions are calculated using the formulae from above.



Decomposition of the total mass distribution (black) into two fission modes: one compact (blue) (α_4<0) and one elongated (red) (α_4>0) . An interesting double inversion of these two modes occurs with increasing mass A:

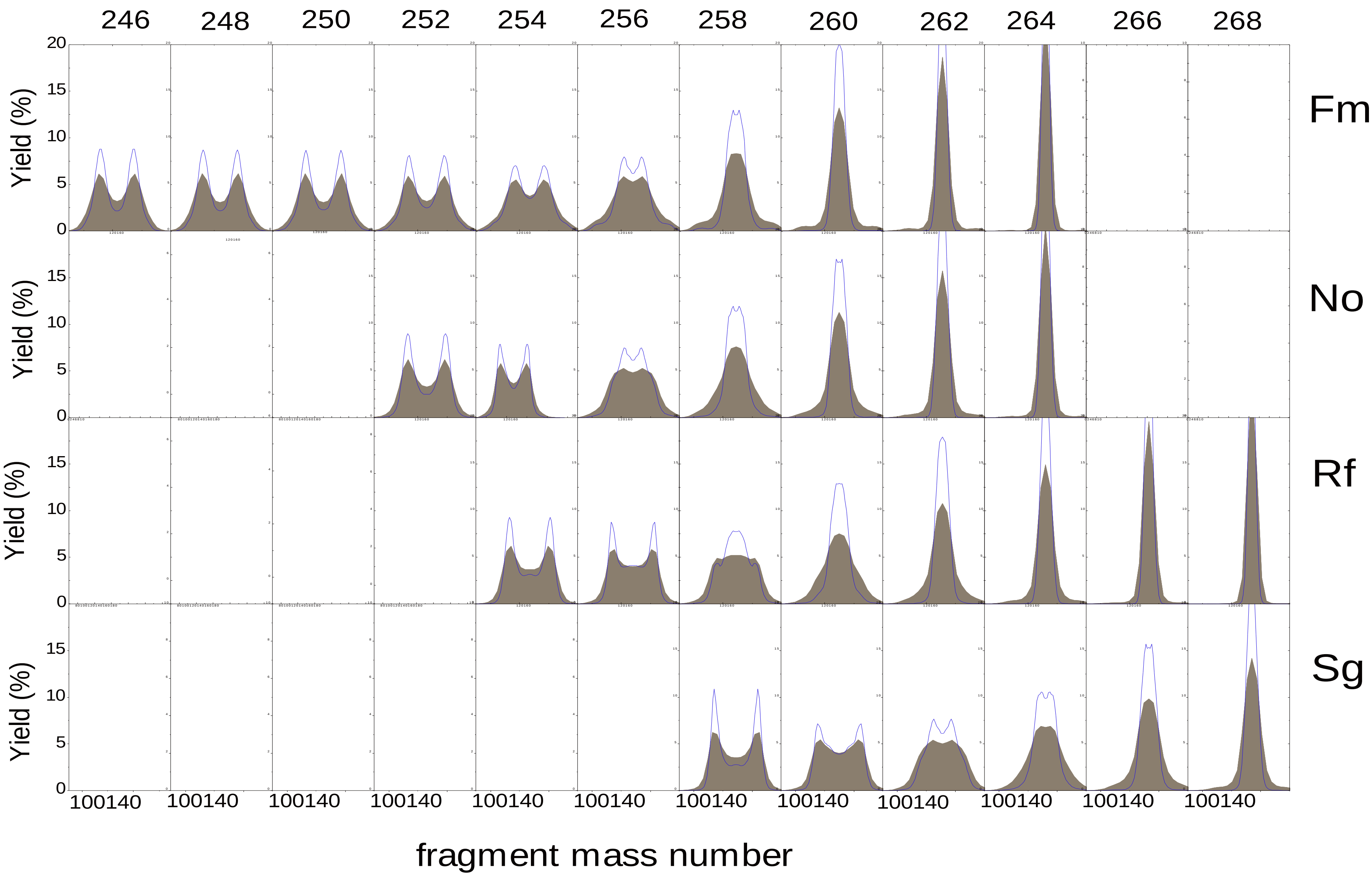
The blue curve gradually replaces the red curve as dominant mode and at the same time it (the compact mode) evolves from asymmetric to symmetric mass division.



The inversion point (when the compact –symmetric mode becomes dominant) in Rf isotopes is at A=261 as compared with A=259 in Fm isotopes.

Fission fragment mass distributions for isotopes of Fm, No, Rf and Sg chosen around the transition point from asymmetric to symmetric fission.

Results with T_{coll} =0.75 MeV are also presented (blue curves) for comparison.



The agreement with data is only qualitative in the sense that the transition from symmetric to asymmetric fission is not as sharp as observed.

Total kinetic energy of the fission fragments

For each shape defined by (α_1,α_4) one calculates D_{cm} and estimates the Coulomb repulsion of the nascent fragments in the point charge approximation:

$$E_{coul}^{int} = e^2 Z_L \times Z_H / D_{cm} = TKE$$

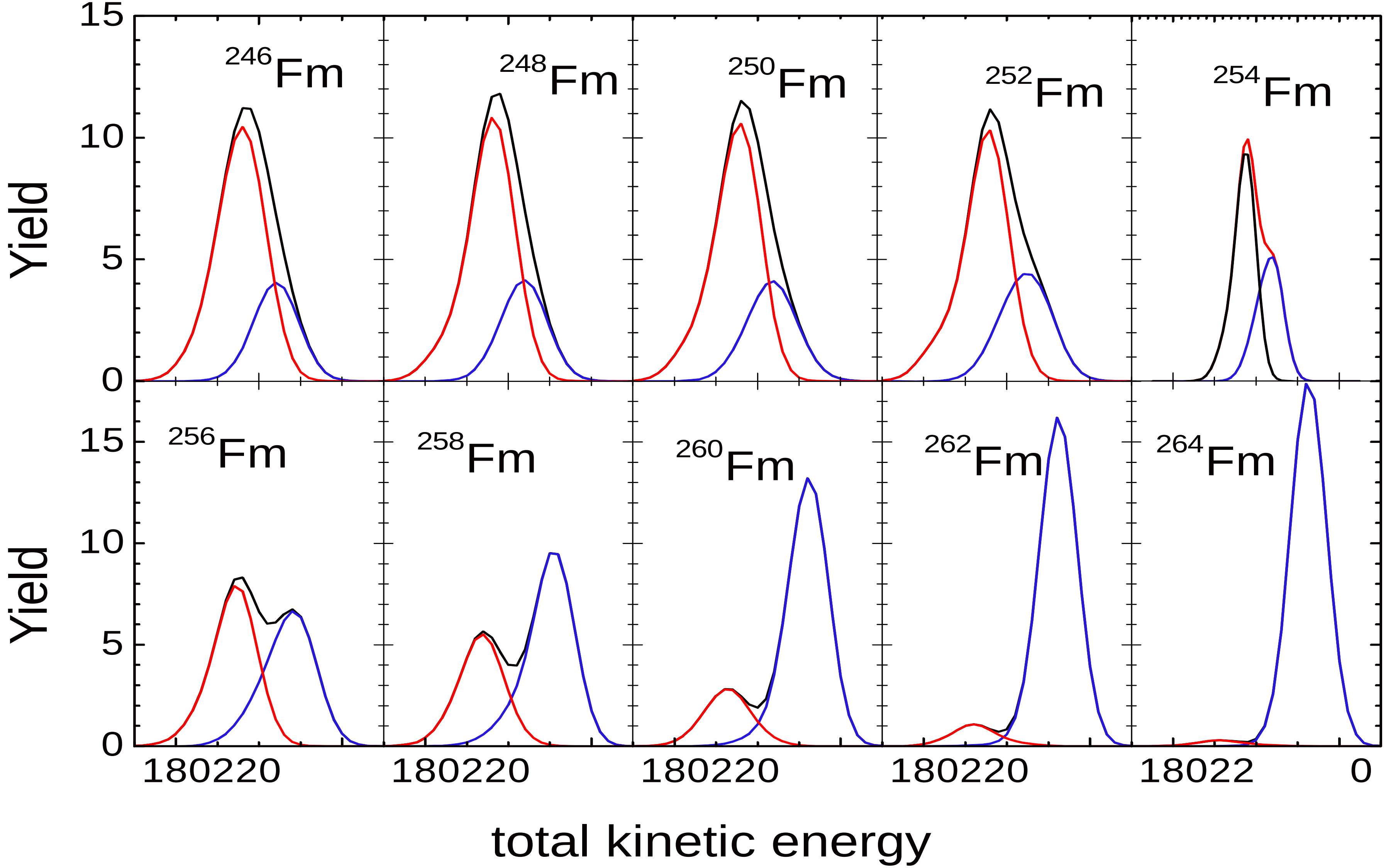
if one neglects the pre-scission kinetic energy.

It is therefore a lower limit for TKE.

The TKE distribution can be calculated using

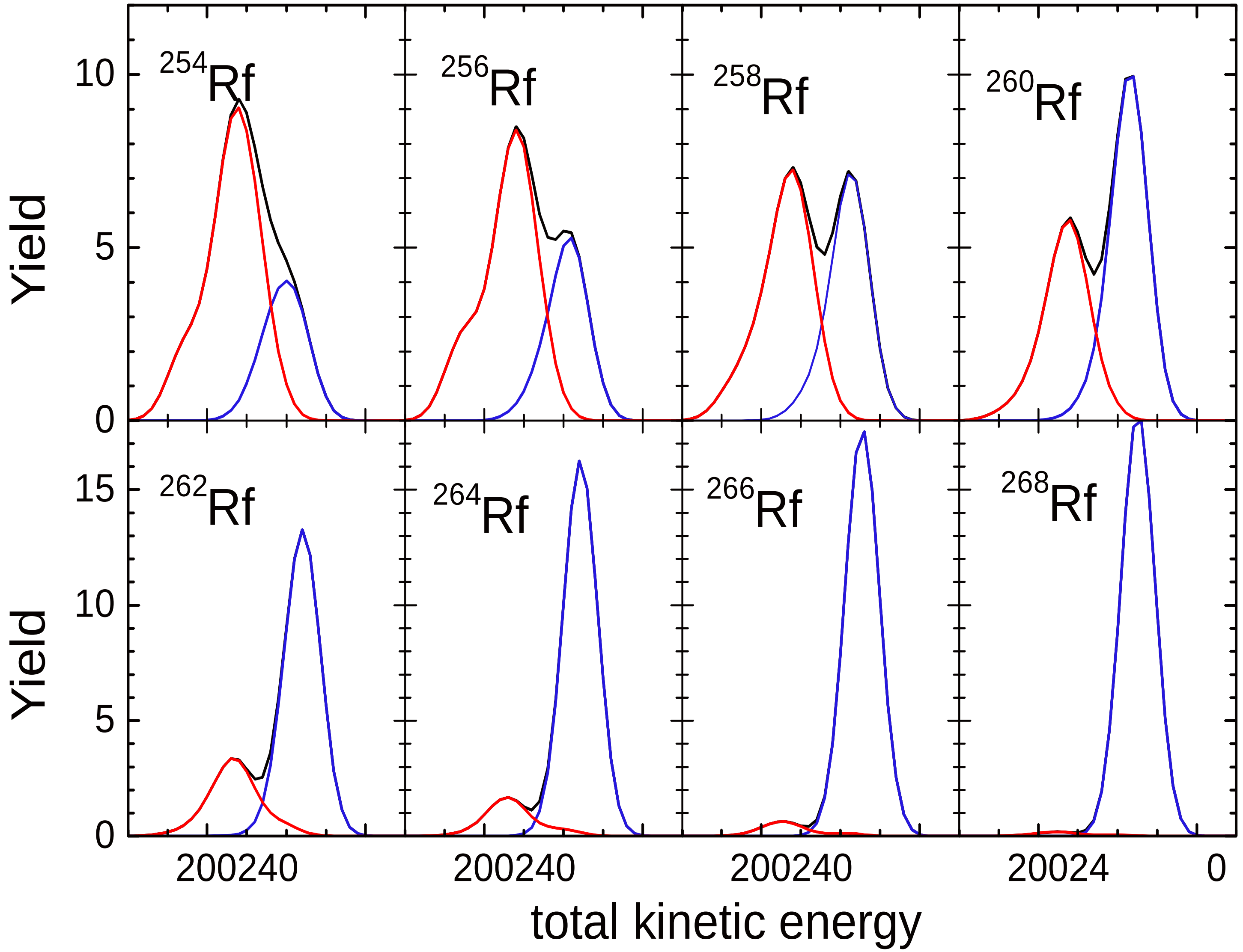
$$Y(TKE) = \sum_j \sum_i P(\alpha_1 j, \alpha_{4i}) \times exp[-(TKE_{ij} - TKE)^2 / \Delta^2] / (\Delta\sqrt{2})$$

It accounts for the finite energy resolution through the parameter Δ that was chosen 6 MeV corresponding to an experimental resolution with a FWHM = 5 MeV.



As a consequence of the fission-mode inversion discussed previously, we observe, with increasing mass A of the fissioning nucleus, a transition from a TKE distribution that deviates from a Gaussian in the high energy part of the spectrum to one that deviates on the low energy part.

At the same time the energy difference between the two peaks increases with A reaching 20 MeV for the heaviest isotopes. For ^{258}Fm the measured value is 25 MeV. So again the agreement is only qualitative.



For Rf isotopes the yields of the two modes become comparable at A=258 as compared to A=256 for Fm isotopes. It is another indication that the transition point is displaced to higher masses with increasing atomic number Z.

Concluding remarks

The main properties of the fission fragments in low-energy fission of even-even transactinide elements are estimated in the frame of a scission-point model. The scission shapes are defined in terms of generalized Cassini ovals. It is this choice that enables us to successfully describe, with only 3 parameters, the transitions observed in these series of isotopes, when the atomic mass A increases:

1)From a mass asymmetric to a mass symmetric fission.

2)From a TKE distribution that deviated from a Gaussian in the higher energy part of the spectrum to a distribution that deviates from a Gaussian in the lower energy part.

At the origin of these transitions is a double inversion of the two main fission modes involved that occurs with increasing A. The existence of this inversion was clearly demonstrated for the first time.

The agreement with experimental data is *a fortiori* qualitative.

The macroscopic-microscopic model used averages over neighbouring nuclei. Therefore sharp transitions from one nucleus to another cannot be reproduced. Moreover dynamical effects are not included.