Classification of nuclear reactions / Fission

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Fission Generalities

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Nuclear fission Decay process in which an unstable nucleus splits into two fragments of comparable mass.

1932: discovery of neutrons

1939: official discovery by Otto Hahn and Fritz Strassmann → fission of ^{235}U

↳ Lise Meitner! ($_{109}Mn$)

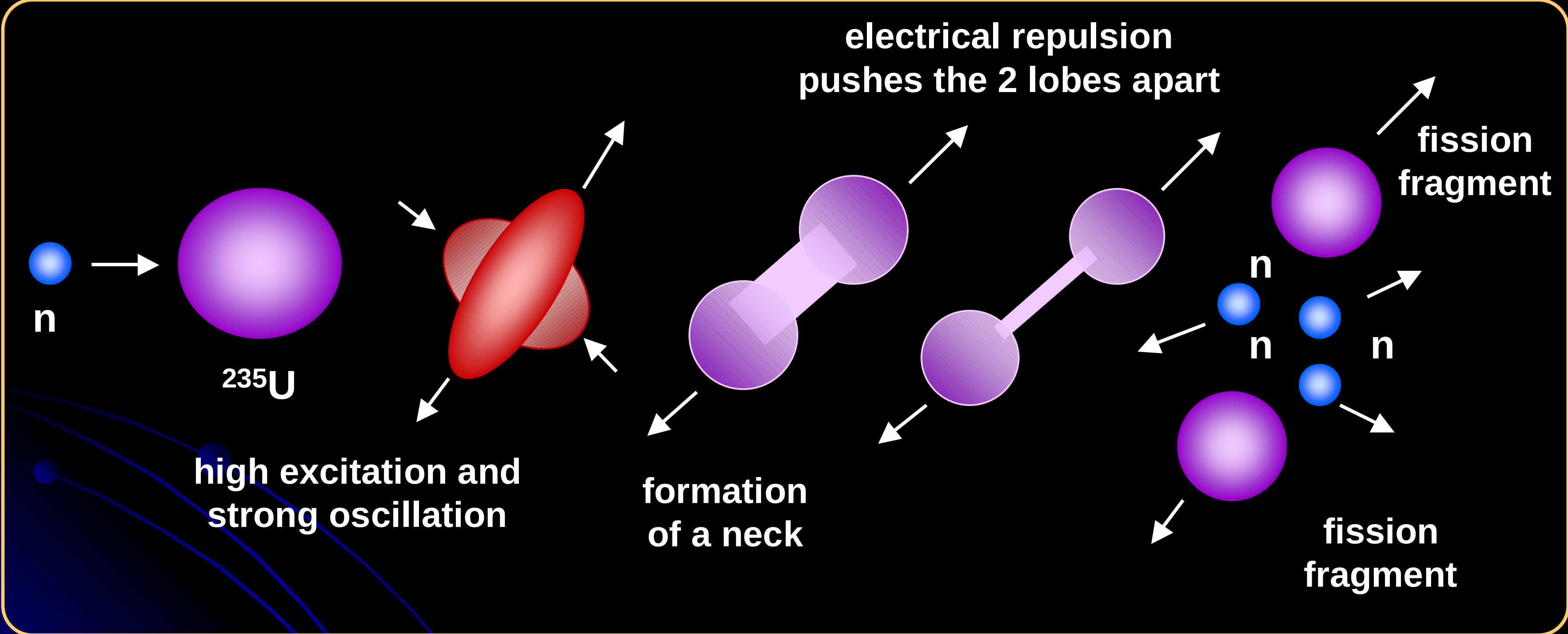
1942: first "chain reacting pile" (E. Fermi)

1945: first nuclear explosion in Alamogordo (New Mexico, USA)

1972: discovery of Oklo (Gabon): unique natural nuclear reactor (1.8 10^6 y ago)
→ very abnormal isotopic ratios of $^{235}U/^{238}U$ in uranium ores

Fission --- liquid drop picture

Fission can be qualitatively understood on the basis of the liquid-drop model



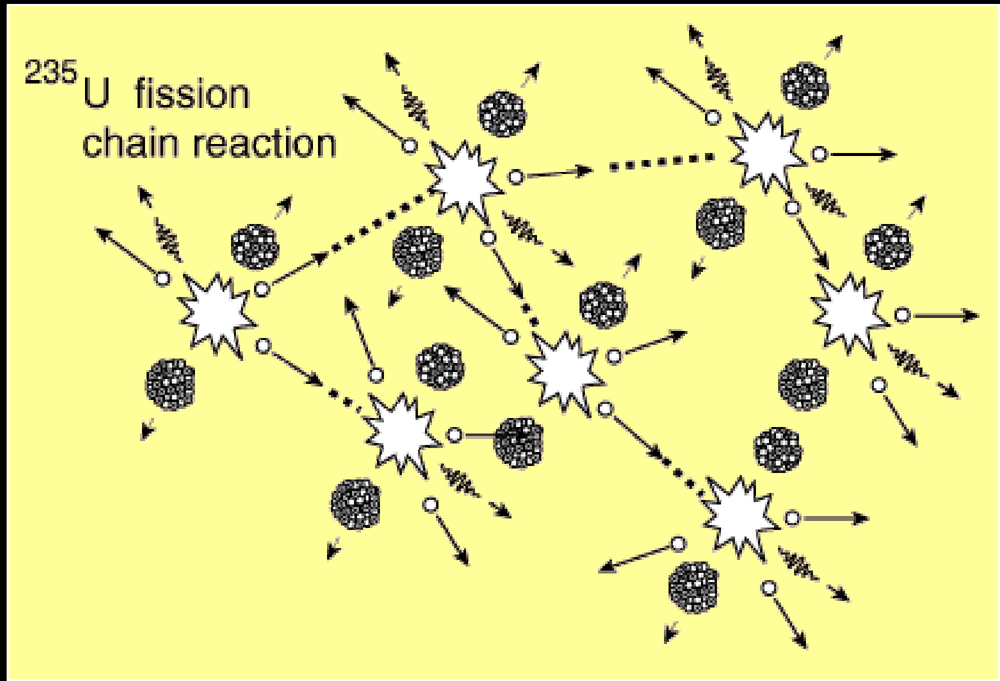
Note: fission liberates about 200 MeV per atom!

Fission --- chain reactions

Chain reactions

If at least one neutron from each fission strikes another ^{235}U nucleus and initiates fission, then the chain reaction is sustained.

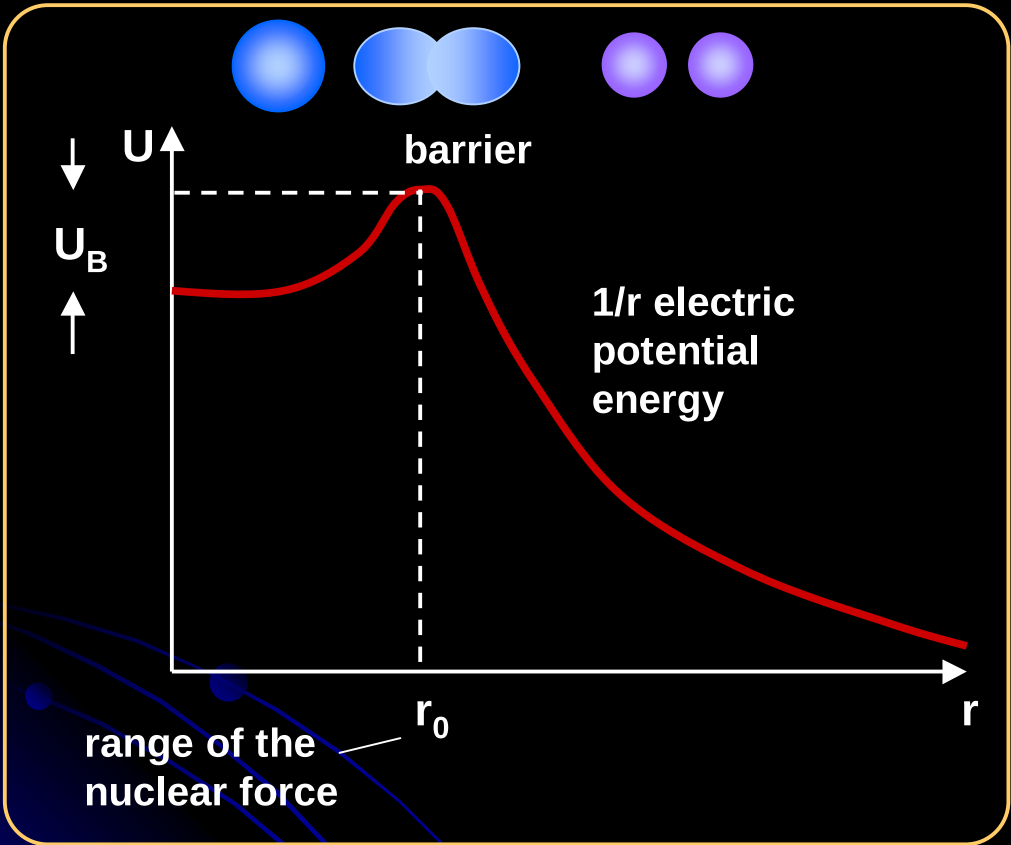
If the reaction will sustain itself, it is said to be "critical", and the mass of ^{235}U required to produced the critical condition is said to be a "critical mass". A critical chain reaction can be achieved at low concentrations of ^{235}U if the neutrons from fission are moderated in water to lower their speed, since the probability for fission with slow neutrons is greater.



A fission chain reaction produces intermediate mass fragments which are highly radioactive and produce further energy by their radioactive decay. Some of them produce neutrons, called delayed neutrons, which contribute to the fission chain reaction.

Fission barrier

Fission barrier



Fission occurs if there is an excitation energy greater than U_B or an appreciable probability for tunneling through the potential energy barrier.

Spontaneous fission occurs via a quantum mechanical tunneling through the fission barrier.

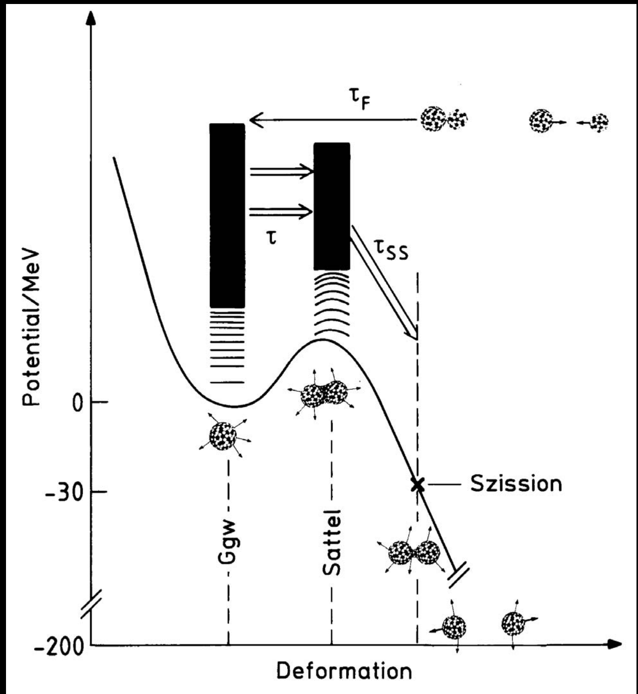
Fissibility parameter:

$$x = Z^2/A$$

Spontaneous fission is possible only for elements with $A \geq 230$ and $x \approx 45$.

Ground states spontaneous fission half-lives for

^{235}U: $(9.8 \pm 2.8) \times 10^{18}$ y	^{238}Pu: $(4.70 \pm 0.08) \times 10^{10}$ y	^{256}Fm: 2.86 h
^{238}U: $(8.2 \pm 0.1) \times 10^{15}$ y	^{254}Cf: 60.7 y	$^{260}_{106}$Sg: 7.2 ms



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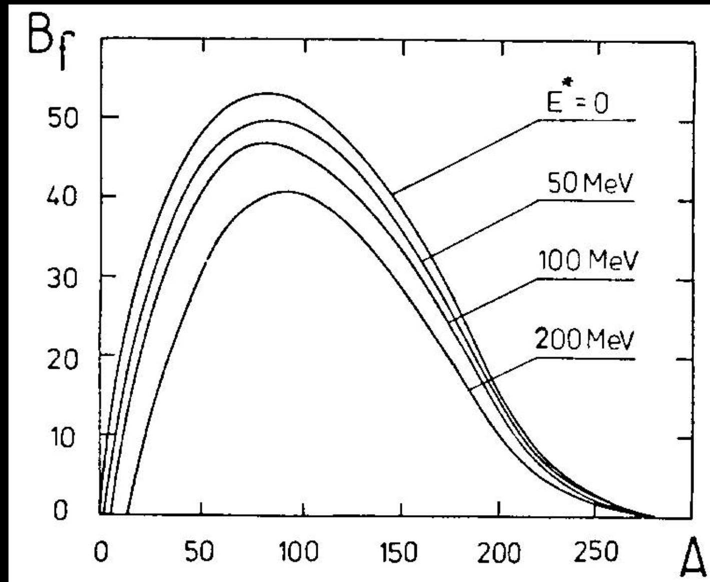
Fission -LDM



Binary splitting of excited nucleus: analog to liquid drop, surface tension is responsible for inner forces acting on surface nucleons

→Fission consequence of deformation – repelling electrostat. Coulomb forces on protons overbalance short ranging attractive nuclear forces

ground-state-deformed nucleus in min. of potential, increase of potential with deformation towards the saddle point (surface energy of the nucleus increases)

Beyond saddle point potential declines due to decreasing Coulomb repulsion until Szission point is reached

B_f difference between Ggw and saddle

Maximum of B_f at A ≈ 90

With increasing E* B_f declines because due to the expansion of nucleus at high E* surface energy decreases faster than Coulomb energy

B_f function of angular momentum of nucleus because additional rotational energies disperse nucleus (rotating LDM)

competition between fission and particle emission by statistical models according to the ratio of decay widths Γ_n and Γ_f

$$\frac{\Gamma_n}{\Gamma_f} = \frac{4A^{2/3} a_f (E^* - B_n)}{C_0 a_n [2a_f^{1/2}(E^* - B_f)^{1/2} - 1]} \exp\left(2a_n^{1/2}(E^* - B_n)^{1/2} - 2a_f^{1/2}(E^* - B_f)^{1/2}\right)$$

B_f, E^* and B_n being the height of the fission barrier, the excitation energy and the binding energy of the neutron, a_n and a_f the level density parameters of the ground state and at the saddle point after the emission of a neutron

fissility is given by

$$\chi = \frac{E_c^0}{2E_s^0} = \frac{Z^2/A}{50.883(1 - 1.7826 I^2)} \quad \text{with } I = (N - Z)/A$$

E_c^0, E_s^0 Coulomb and surface energy of the nucleus in the ground state, Z, N, A the atomic, neutron and mass numbers

Energy dependence of (n,f) cross sections

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Case of ^{235}U and ^{237}Nb

thermal neutrons

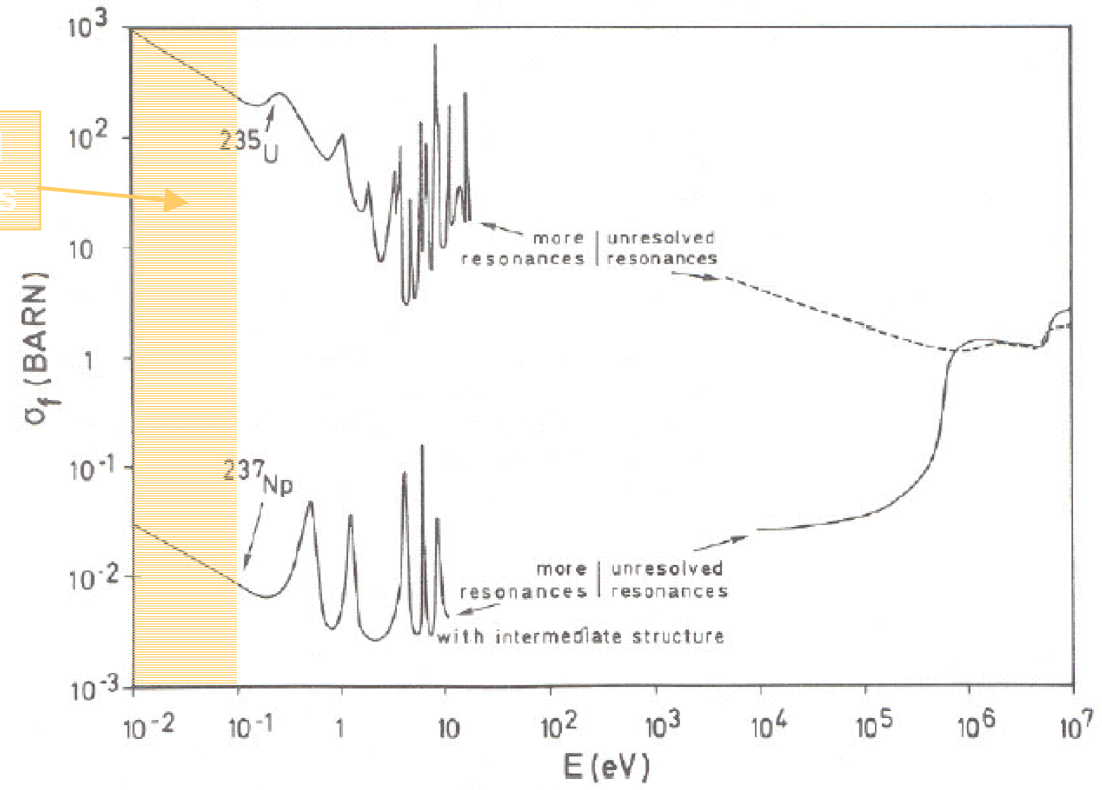


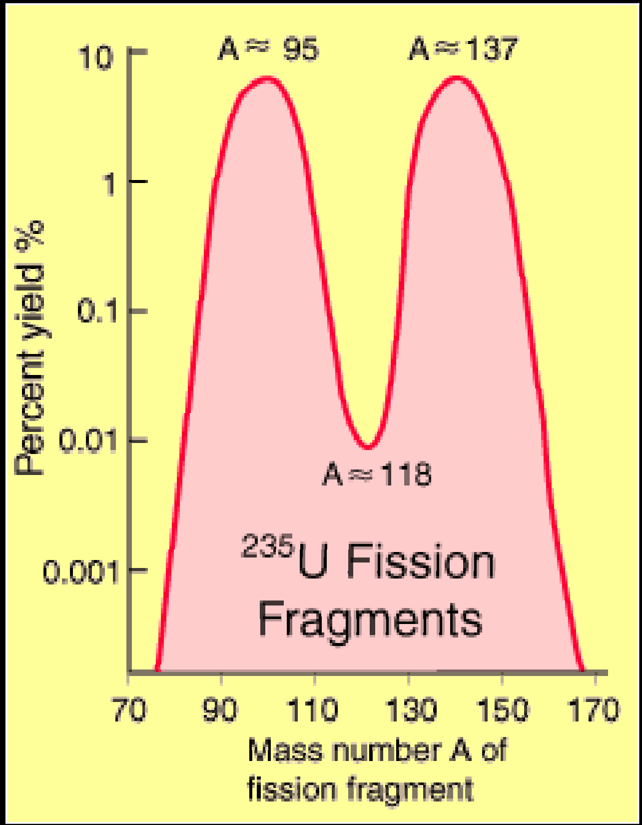
FIGURE 2. The neutron-induced fission cross section of ^{235}U and ^{237}Np. (After Wagemans.[6])

^{235}U:	**neutron binding energy > maximum fission barrier → large cross section**
^{237}Nb:	**neutron binding energy < maximum fission barrier → small cross section**

↳ when excitation energy E* > maximum fission barrier → sharp rise of σ_f

Fission --- mass distribution

When ^{235}U undergoes fission, the average of the fragment mass is about 118, but very few fragments near that average are found. It is much more probable to break up into unequal fragments, and the most probable fragment masses are around mass 95 and 137. Most of these fission fragments are highly unstable, and some of them such as ^{137}Cs and ^{90}Sr are extremely dangerous when released to the environment.



$^{235}U + n \rightarrow {}^{236}U^* \rightarrow {}^{140}Xe + {}^{94}Sr + 2n$

^{140}Xe	^{94}Sr
$T_{1/2}$ = 14s ↓ β	β ↓ 75s
^{140}Cs	^{94}Y
64s ↓ β	β ↓ 19m
^{140}Ba	^{94}Zr
13d ↓ β	
^{140}La	
40h ↓ β	
^{140}Ca	

Asymmetric mass splittings at low E* cannot be explained by LDM ! Shell effects...

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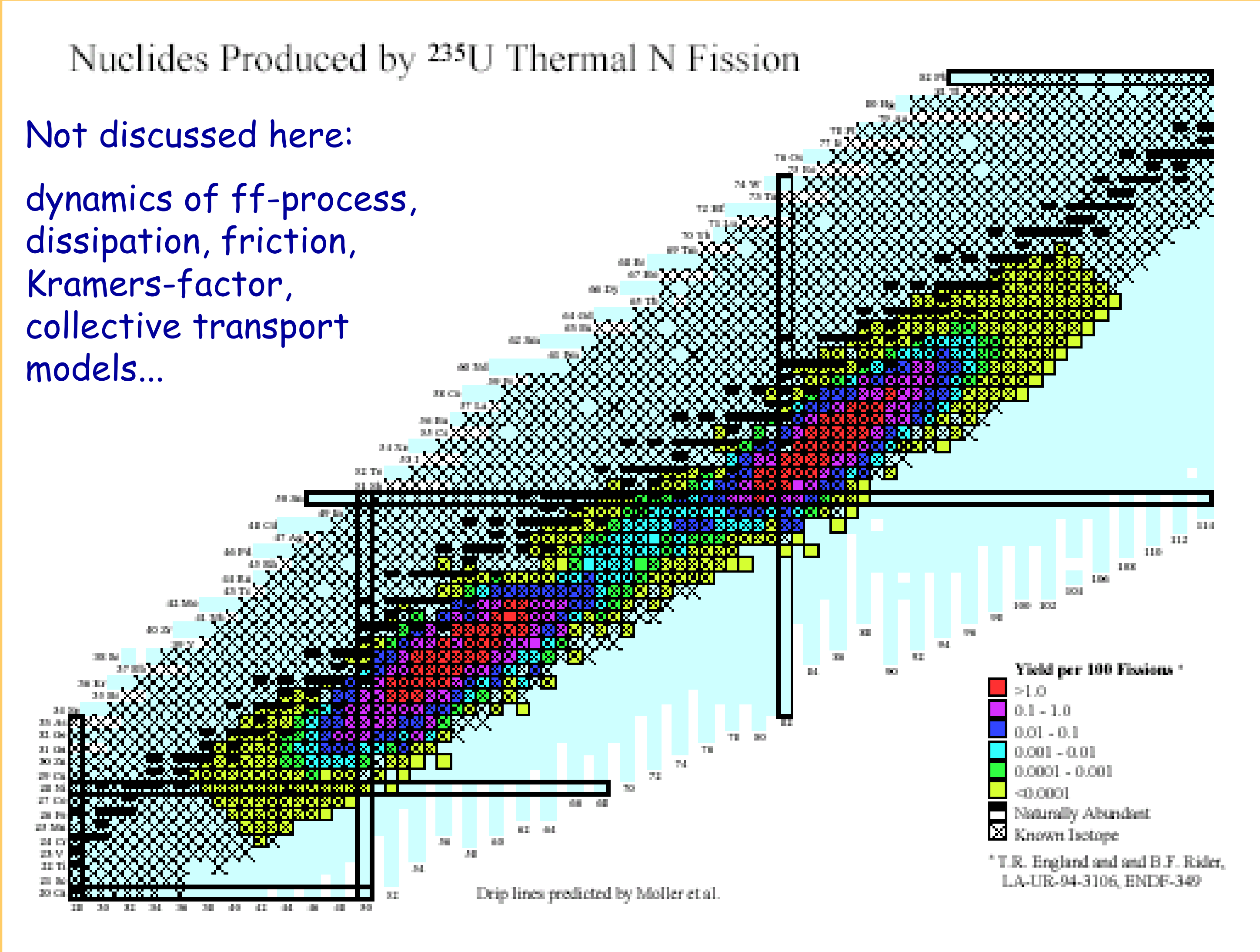
Fission --- mass distribution



Not discussed here:

dynamics of ff-process, dissipation, friction, Kramers-factor, collective transport models...