Induced fission

Induced fission of nuclei occurs when a nucleus captures a low energy neutron receiving enough energy to climb the fission barrier.

e.g. $$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow X^* + Y^* \rightarrow X + Y + \kappa n$$

$\kappa \sim 2.4$

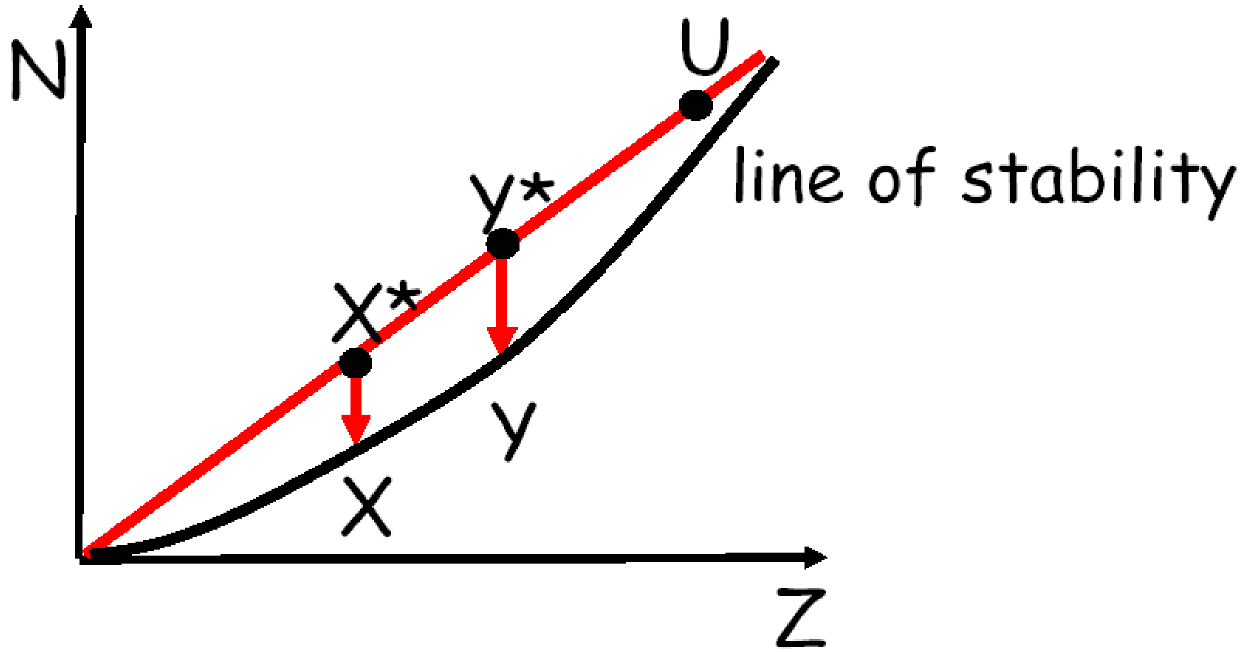
prompt neutrons

If excitation energy > fission activation energy, fission will occur for zero energy neutrons

$\rightarrow$ thermal neutrons.

Prompt and delayed neutrons

- Fragments tend to have same Z/N ratio as parent → neutron rich nuclei which emit <u>prompt neutrons</u> (10^{-16}s)



X,Y β decay more slowly → <u>delayed n emission</u> (~1 delayed n/100 fissions)

fission chain reaction

- per fission 2–3 free neutrons are generated within ~ 10^{-14} s
  -> *prompt neutrons*
- neutron emission after β–decay -> *delayed neutrons*
- small fraction of approximately 0.65% of all neutron emission is delayed
- very important to control self sustained chain reaction in nuclear reactor

A chain reaction can be sustained is at least 1 n/fission induces another fission process.

Define k = number of neutrons from one fission which induce another

Reactors →	$k = 1$	critical
	$k < 1$	subcritical
	$k > 1$	supercritical

Heavy nuclei, breeding

Heavy fissile nuclei and natural abundance

^{232}Th: Z = 90, N = 142

^{234}U: Z = 92, N = 142, (0,0055%)

^{235}U: Z = 92, N = 143, (0,72%)

^{238}U: Z = 92, N = 146, (99.2745%)

- Nuclei with odd neutron number are fissile, cross sections of (n,f) reaction with thermal neutrons are very high.

Breeding of fissile material

- Nuclei with odd neutron number can be produced by n-capture of thermal neutron with even n-number in reactor -> ‚breeding'.

Via n-capture reaction an odd n-number nucleus is formed.

example: $^{238}U(n,\gamma)\,^{239}U$, $^{239}U \xrightarrow{\beta^-} {}^{239}Np$, $^{239}Np \xrightarrow{\beta^-} {}^{239}Pu$

- Natural fission fuel for conventional fission reactor is ^{235}U.

Chain reaction, critical mass

Isotop	critical mass* in kg	
^{235}U	22,8 kg	highly enriched, enrichment from 0,72 % to > 90%
^{233}U	7,5 kg	obtained from n-capture or breeding of ^{232}Th
^{239}Pu	5,6 kg	obtained from n-capture or breeding of ^{238}U

*critical mass for a spherical configuration and a neutron reflector

Critical mass: mass value which is needed to sustain a chain reaction of fission.

The critical mass of an arbitrarily shaped fissile amount of material is mainly determined by ratio of surface area to volume.

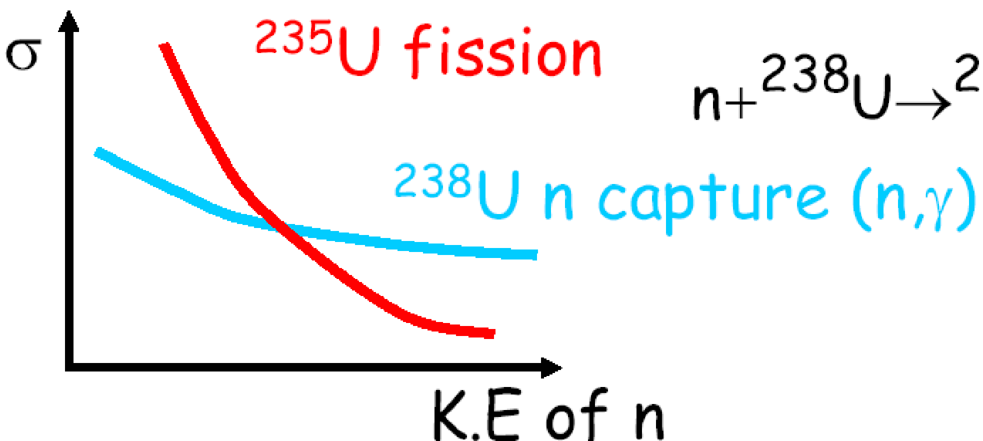
Important is also surrounding material. Neutron reflecting and not absorbing material favours chain reaction.

fission reactors

Fission Reactors

For reactors want a steady energy release, exactly critical (k = 1).

- A moderator slows neutrons via elastic collisions (large energy transfer). Requires a light nucleus (e.g. ^{12}C).
- Problem : Natural U (99.3% ^{238}U, 0.7% ^{235}U) and n capture cross-section large for ^{238}U



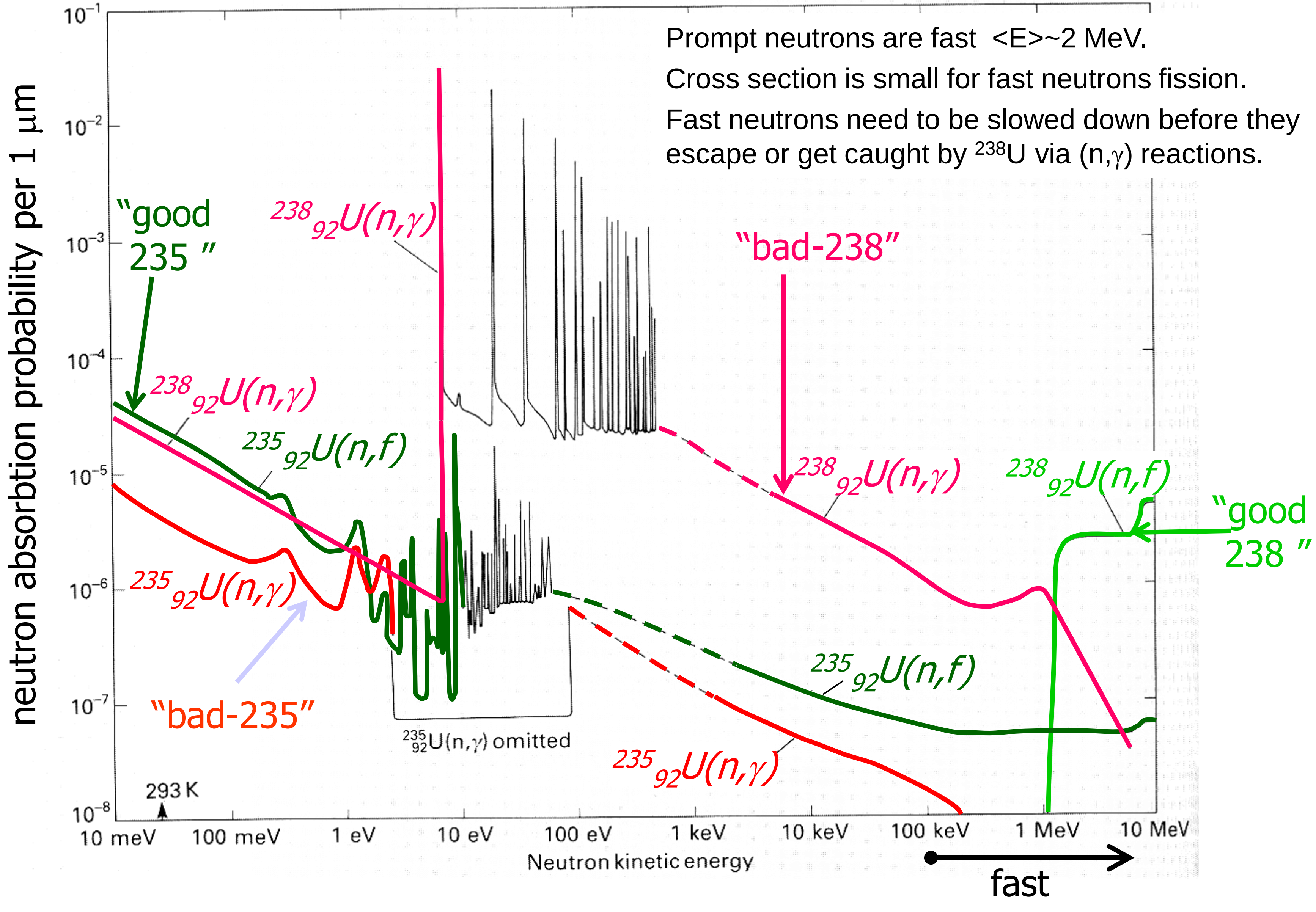
$$n + {}^{238}U \rightarrow {}^{239}U^{*} \rightarrow {}^{239}U + \gamma$$

Neutron capture of ^{235}U and ^{238}U

Prompt neutrons are fast <E>~2 MeV.

Cross section is small for fast neutrons fission.

Fast neutrons need to be slowed down before they escape or get caught by ^{238}U via (n,γ) reactions.



fission reactors

Need to thermalise fast neutrons away from ^{238}U to avoid capture (i.e. in rods of ^{12}C).

- Control of reaction rate

  Control number of neutrons by absorption (e.g. ^{113}Cd rods).

  Typical time between fission and daughter inducing another fission ~10^{-3} s.

  → Mechanical control of rods in times « seconds not possible.

reactors

What happens if no control of neutrons ?

$$N(t+dt) = N(t) + (k-1)N(t)\frac{dt}{\tau}$$

$$dN = (k-1)N\frac{dt}{\tau}$$

$$\int_{N(0)}^{N(t)} \frac{dN}{N} = \int_0^t (k-1)\frac{dt}{\tau} \quad \rightarrow \quad \underline{N(t) = N(0)e^{(k-1)t/\tau}}$$

where N(t) is the number of neutrons at time t

(k-1) is the % change in number of neutrons in 1 cycle

τ mean time for 1 cycle ~10^{-3} s (fission $\rightarrow$ fission)

reactors

e.g. k =1.01, τ = 0.001s, t = 1s

$$\frac{N(t)}{N(0)} = e^{0.01/0.001} = e^{10}$$

(22,000 in 1s)

N.B. U reactor will not explode if it goes supercritical. As it heats up, K.E. of neutrons increases and fission cross section drops. Reactor stabilizes at a very high temperature

$\rightarrow$ meltdown

Solution is to make use of delayed n emission.

(delay ~ 13 s)

Design reactor to be subcritical to prompt n and use delayed n to take it to critical.