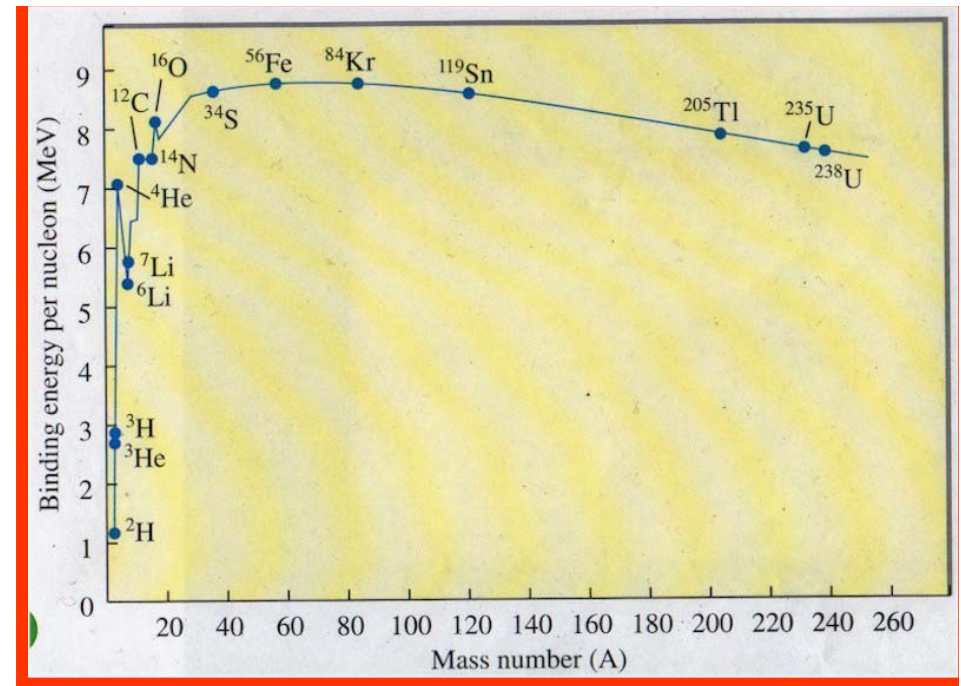


Nuclear fission

- Fission: what is it?
- The main steps toward nuclear energy
- How does fission work?
- Chain reactions

What is nuclear fission?

- Nuclear fission is when a nucleus break into two or more nuclei.
- This process yields a net energy gain when the initial nucleus is heavy enough.



- Consider the possibility that $A \rightarrow A_1 + A_2$. The mass of A is given by:

$$M(A)c^2 = (Z_1 + Z_2)m_p c^2 + (N_1 + N_2)m_n c^2 - E_b(A)$$

The binding energy of A, $E_b(A)$, for large A, is:

$$E_b(A) = A \varepsilon(A) = A_1 \varepsilon(A) + A_2 \varepsilon(A) < A_1 \varepsilon(A_1) + A_2 \varepsilon(A_2) \rightarrow$$

$$M(A)c^2 > M(A_1)c^2 + M(A_2)c^2$$

- In this case the reaction can occur spontaneously.
- When moving from U to A about 100, the energy gain per nucleon is about 1 MeV, so the typical energy gain from a U fission is about 200 MeV.



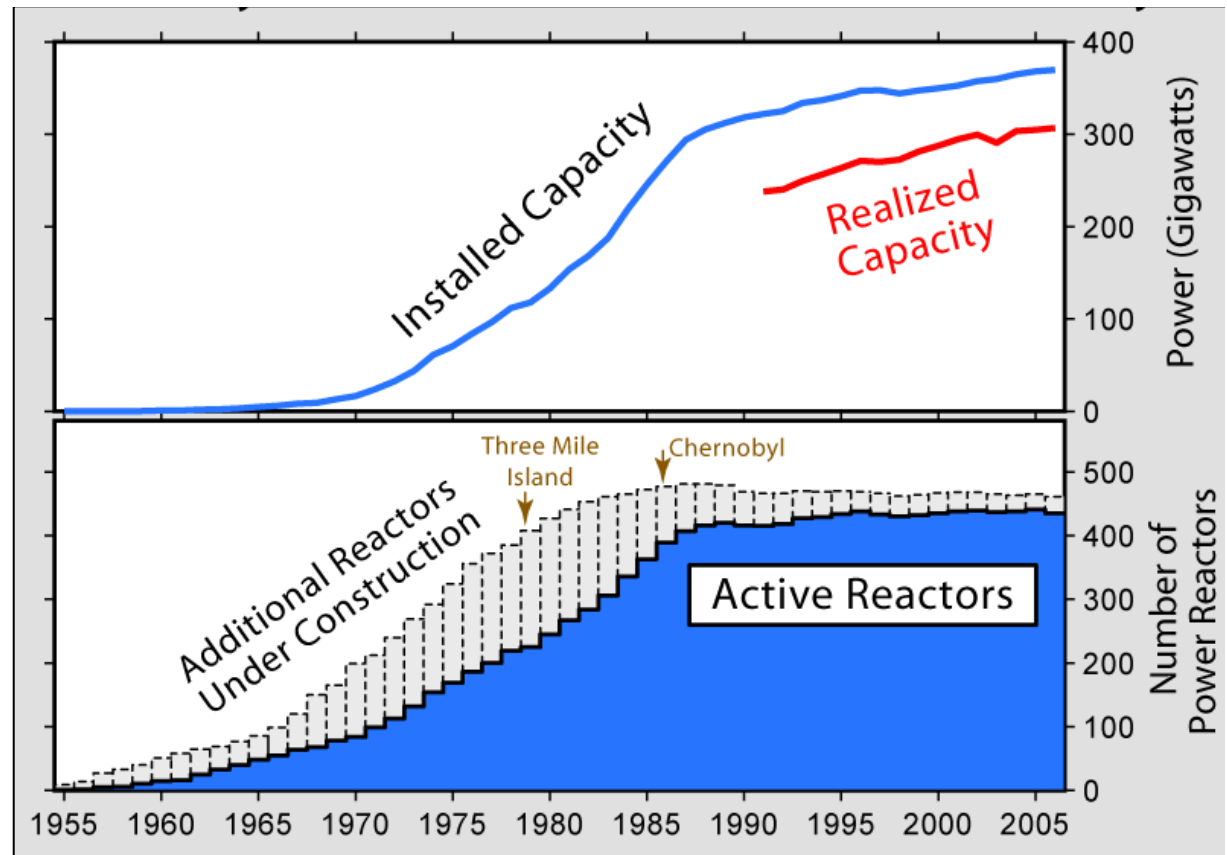
A little of history



- 1934 Ida Noddack mentions fission as an hypothesis for the non existence of long lived nuclei beyond $Z=92$**
- 1934 Fermi group produce nuclear transmutations by neutron bombardment, by means of (n,γ) and $n(\alpha)$ reactions. When U was bombarded, they obtained fission, but misinterpreted it.**
- 1938 Hahn and Strassman bombarded U and discovered Ba in the reaction products. Lise Meitner (a former assistant of Hahn, flown to Sweden for escaping the racial laws of nazist Germany)) and his nephew explain the experimental result as due to fission. In 1944 Hahn got the Nobel Prize**
- () Joliot-Curie's team in Paris discovered that secondary neutrons are released during uranium fission, thus making a nuclear chain-reaction feasible**
- 1942 Fermi and Szilard created the first man made reactor, Chicago Pile 1**
- 1945 The first “atomic” (fission) bomb was exploded in Alamogordo, and soon later in Hiroshima and Nagasaki**
- 1951 Electricity was generated from a nuclear reactor (100 kW) at Arco, Idaho**
- 1954 USSR's Obninsk Nuclear Power Plant became the world's first nuclear power plant to generate electricity for a power grid, and produced around 5 megawatts of electric power.**
- 1957 First nuclear powered submarine...**

History of the Global Nuclear Power Industry

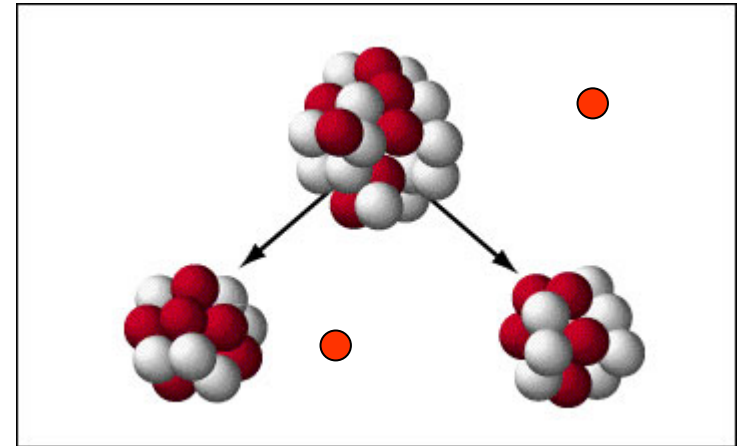
- All utility-scale reactors heat water to produce steam, which is then converted into mechanical work for the purpose of generating electricity or propulsion.



- In 2007, 14% of the world's electricity came from nuclear power, from some 440 nuclear reactors.
- Nuclear power accounts for 77% of electricity in France, 34.5% in Japan, 26% in Germany and 19% in US.
- More than 150 nuclear-powered naval vessels have been built, and a few radioisotope rockets have been produced.

Spontaneous Fission

- As discovered by Flyorov and Petrhak in 1940, Uranium nuclei, beside the dominant alpha decay mode, can also have spontaneous fission, into two fragments with A around 100.



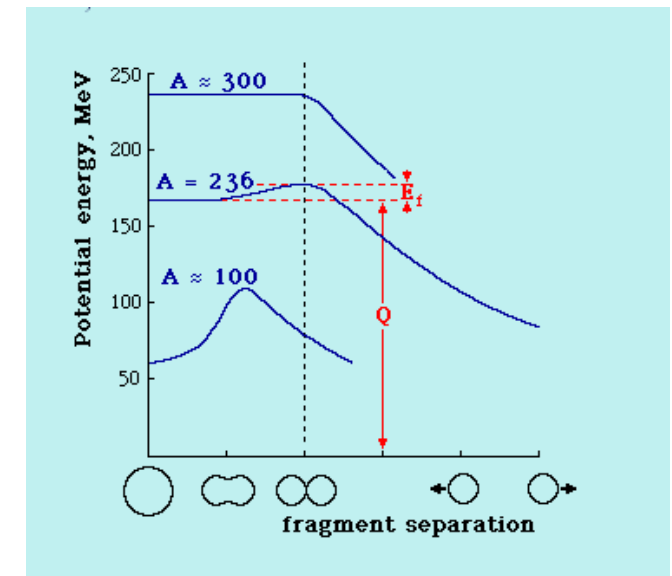
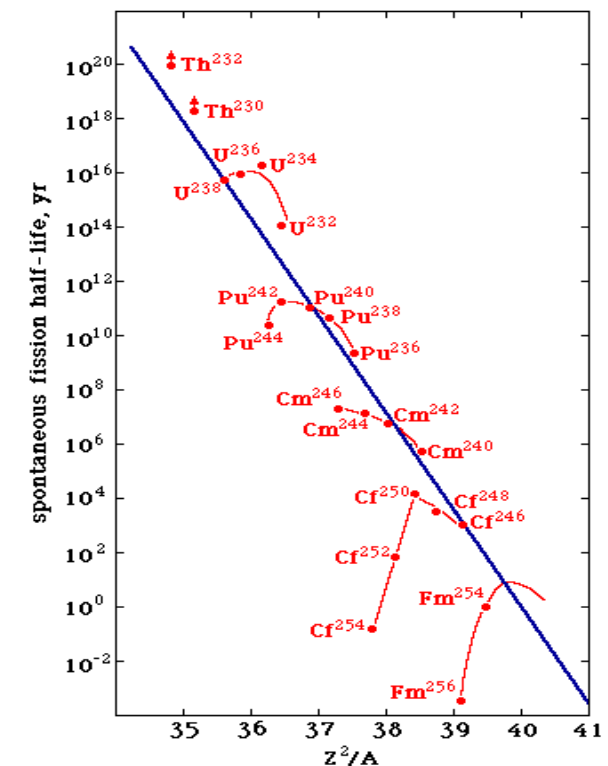
- In the liquid drop model, comparison between surface energy ($E_s = a_s A^{2/3}$) and Coulomb energy ($E_c = a_c Z^2/A^{1/3}$) shows that nuclei are unstable to fission for $Z^2/A > 18$, i.e. for nuclei heavier than ^{90}Zr .
- The Liquid Drop model can be used to estimate the energy release in fission. For ^{235}U it is about **200 MeV** per nucleus and it mostly comes from the coulomb energy. The energy released is approximately divided up as follows: Fragment kinetic energies 165 MeV, Prompt Neutrons 5 MeV Prompt gammas 7MeV, Radioactive decay fragments 25 MeV

Nuclide	Half-life	Fission prob. per decay (%)	Neutrons per fission
^{235}U	7.04×10^8 years	$7.0 \times 10^{-9} \%$	1.86
^{238}U	4.47×10^9 years	$5.4 \times 10^{-5} \%$	2.07

Spontaneous “Fission lifetimes”*

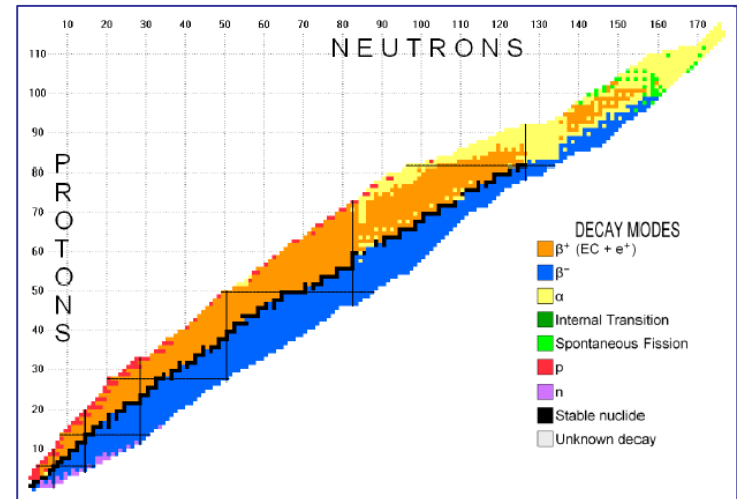
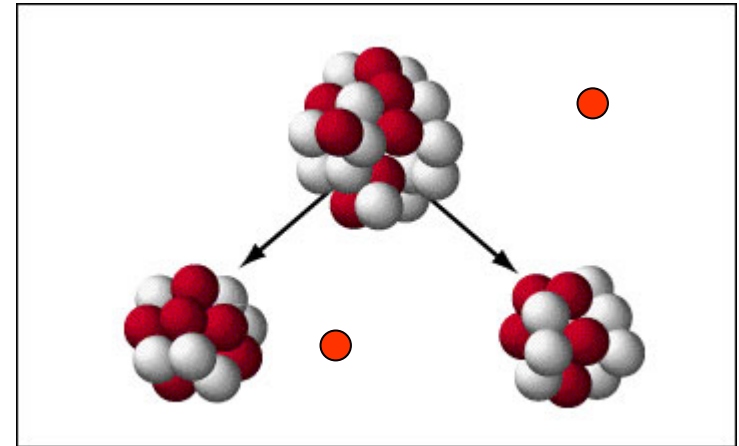
- They range from 10^{16} yr for ^{238}U to 10^{-2} yr for ^{256}Fm .
- Very much like for alpha decay, the process of fission is suppressed by the presence of a potential barrier.
- The figure below shows schematically the shape of the barrier as a function of the deformation or fragment separation for different values of the atomic mass number, **A**.
- Consider $^{238}\text{U} \rightarrow ^{145}\text{La} + ^{90}\text{Br} + 3\text{n}$, the fission rate is $3 \cdot 10^{24} \text{ s}^{-1}$ to be compared with decay rate of $5 \cdot 10^{18} \text{ s}^{-1}$. i.e the fission probability is $0.5 \cdot 10^{-6}$. This since heavy particles have to tunnel through a barrier.
- Alpha decay is a limiting case of fission

*They are defined as inverse of the fission decay rate



Neutrons from Spontaneous Fission

- We have already seen that in $^{238}\text{U} \rightarrow ^{145}\text{La} + ^{90}\text{Br} + 3n$ three neutrons are emitted.
- There are several channels for ^{238}U spontaneous fission, with an average neutron number of 2.07
- Neutron emission is a general feature of (spontaneous and induced) fission.
- At large A one has $N \gg Z$, in order to diminish Coulomb repulsion, whereas at low and intermediate A the stable nuclei have $Z \approx N$.
- So there is generally an excess of neutrons, which have to be emitted.



Nuclide	Half-life	Fission prob. per decay (%)
---------	-----------	-----------------------------

^{235}U	7.04×10^8 years	$7.0 \times 10^{-9} \%$
------------------	--------------------------	-------------------------

^{238}U	4.47×10^9 years	$5.4 \times 10^{-5} \%$
------------------	--------------------------	-------------------------

Neutrons per fission

1.86

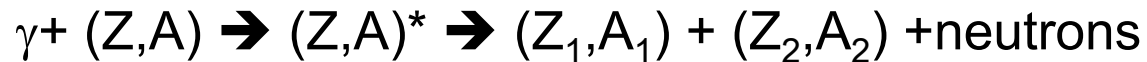
2.07

Induced Fission

- For inducing fission, one has to provide energy to the nucleus, so that its parts can overcome the fission barrier, or form a compound nucleus where the barrier is diminished or eliminated.

• In principle one can induce fission by :

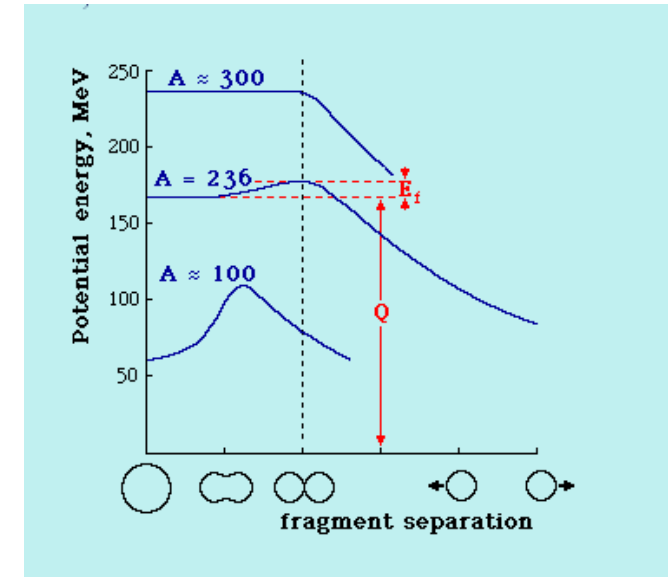
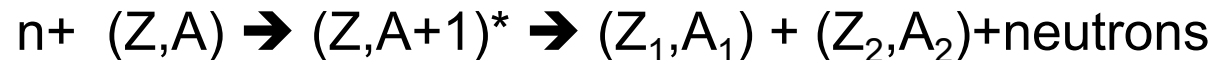
-**photofission**



-**proton induced fission**



-**neutron induced fission**



Nuclide	Half-life	Fission prob. per decay (%)	Neutrons per fission
^{235}U	7.04×10^8 years	$7.0 \times 10^{-9} \%$	1.86
^{238}U	4.47×10^9 years	$5.4 \times 10^{-5} \%$	2.07

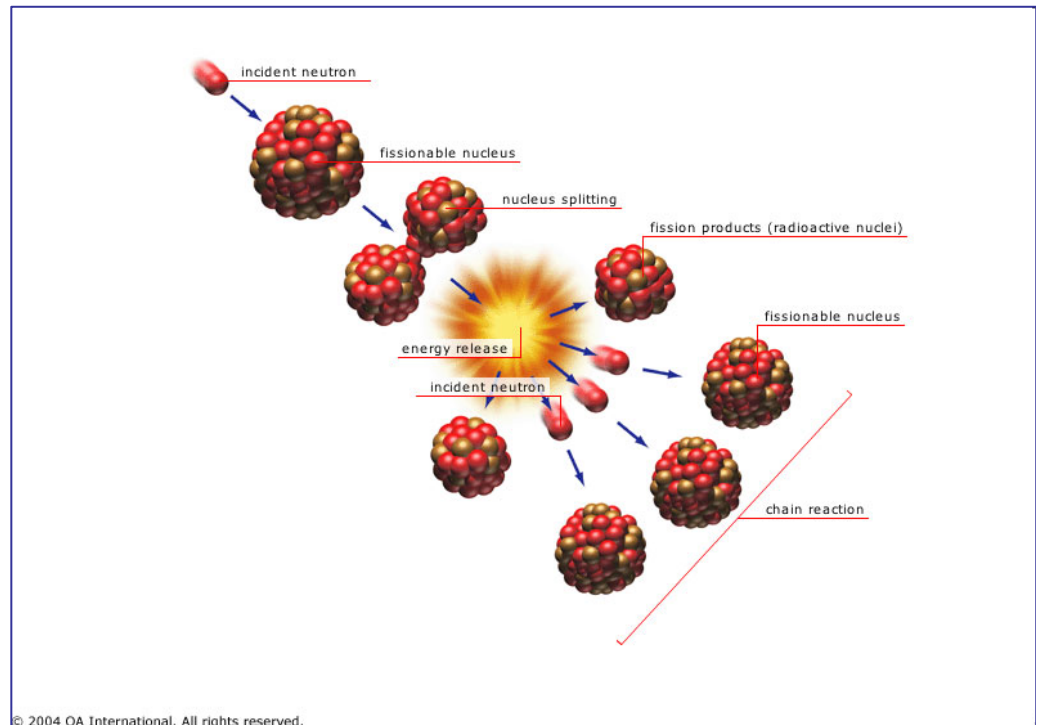
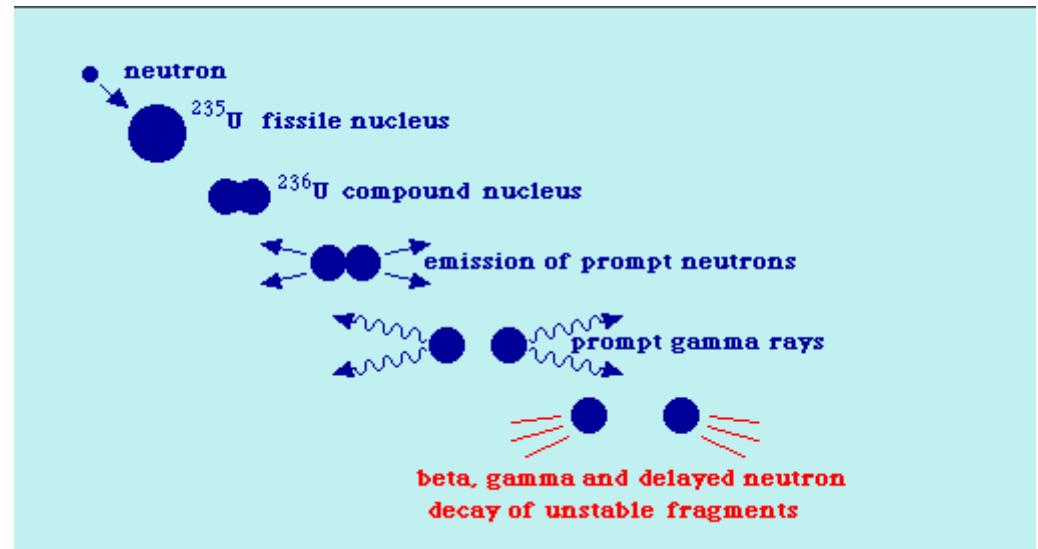
Neutron Induced Fission

- Neutron induced fission,
 $n + (Z, A) \rightarrow (Z, A+1)^* \rightarrow (Z_1, A_1) + n's$

is particularly effective for the following reasons:

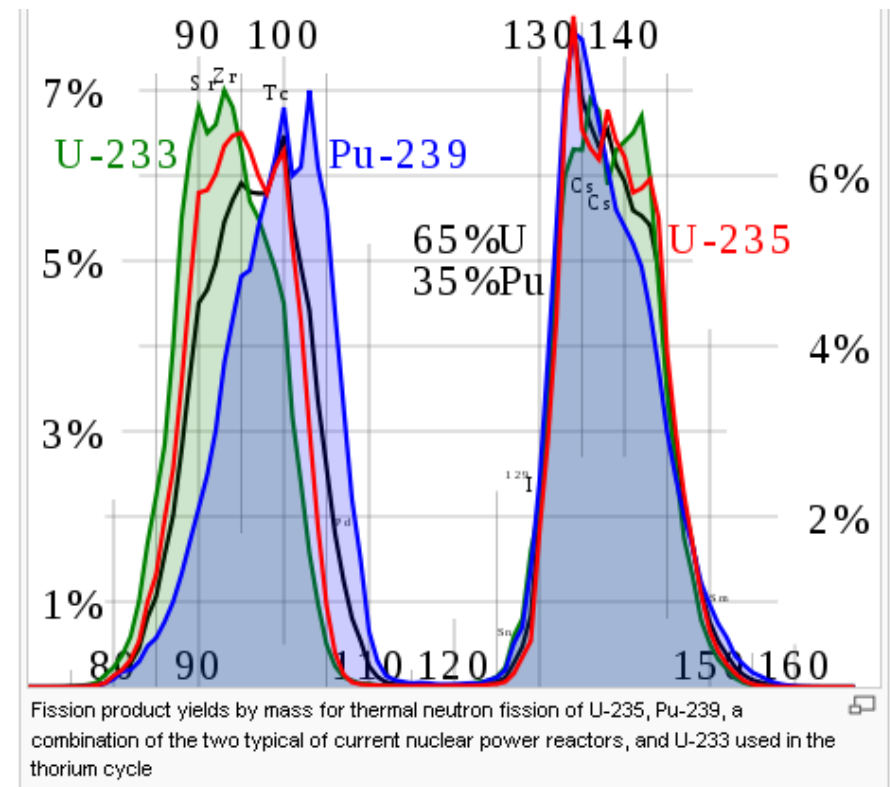
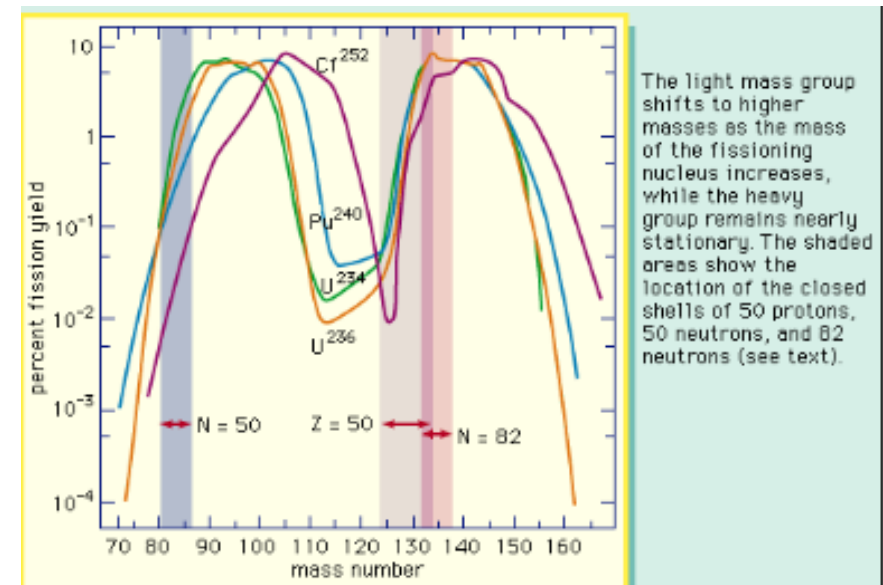
- 1) neutrons are penetrating,
- 2) slow neutrons cross sections are large, order 100-1000 barn at thermal energies (see later)
- 3) Neutrons are regenerated during fission

The induction of fission by neutron absorption and the subsequent emission of neutrons in the process of fission leads to the possibility of a **self sustaining** or **chain reaction**.



Fission fragments and fission products

- Fission fragments have a double bell distribution as a function of A.
- Note that they are unstable, as are neutron rich they decay towards stable nuclei by a chain of beta decays.
- This yields the so called “fission products”
- Some fifty per cent of fission products have decay times less than one year, the rest has lifetimes that can be as long as million years,



Neutrons from Fission

- One distinguishes two types neutrons from fission:

-prompt neutrons,

They are those accompanying
the two nuclear fragments,

e.g, the 2n in $^{235}\text{U} + n \rightarrow ^{93}\text{Rb} + ^{141}\text{Cs} + 2n$

In the case of ^{235}U , there are on the average 2.42 prompt neutrons

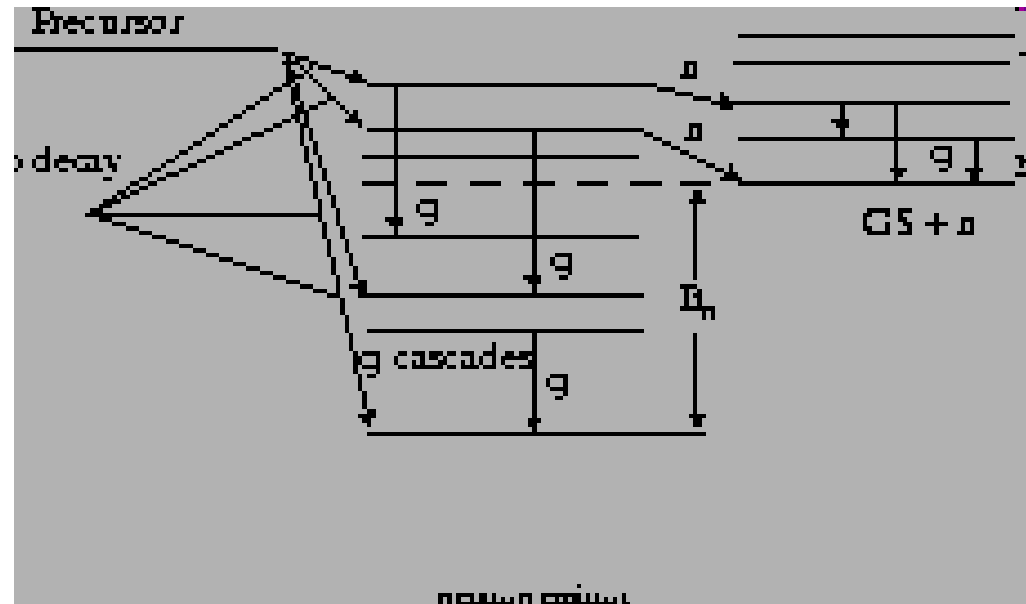
-delayed neutrons

These are associated with the beta decay of the fission products. Indeed, after prompt fission neutron emission the residual fragments are still neutron rich. They undergo a β decay chain. In some cases the available energy in the β decay is high enough for leaving the residual nucleus in such a highly excited state that neutron emission instead of gamma emission occurs.

(beta delayed neutron emission)

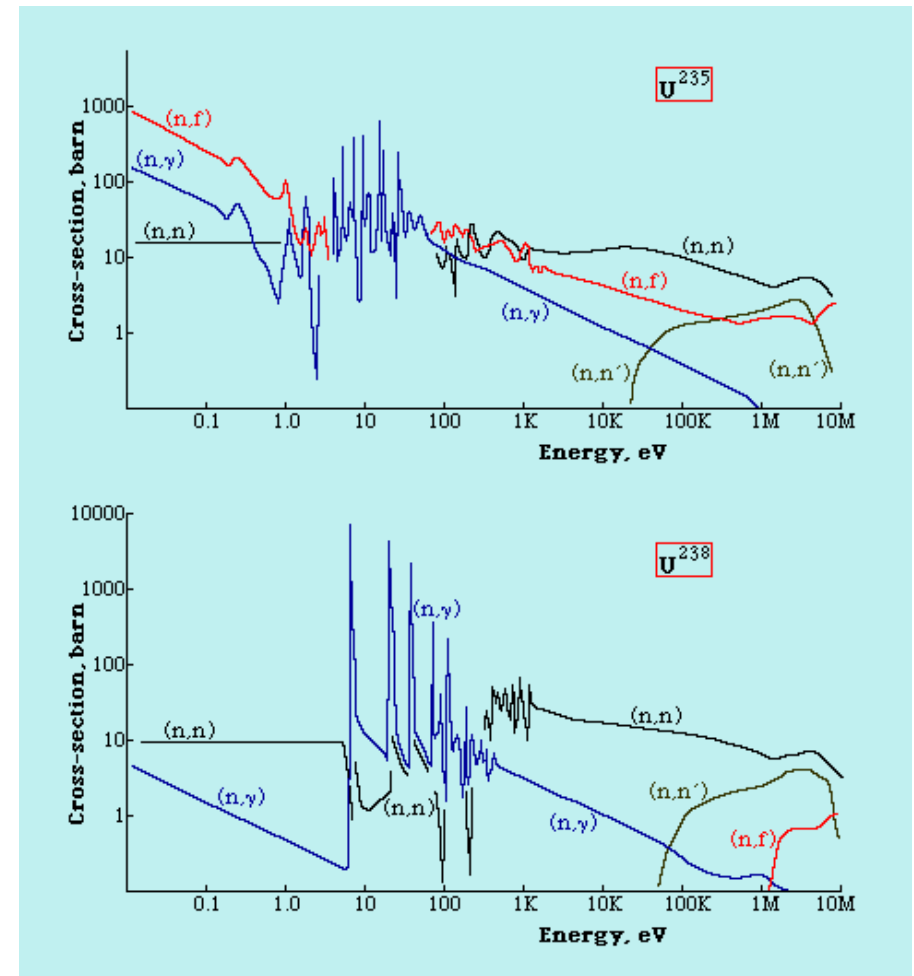
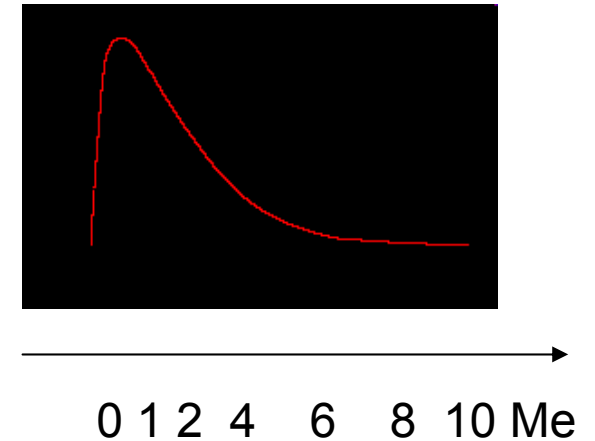
Delayed neutrons have delays of order seconds. They are about 1/100

fissions. Delayed neutrons are essential for the control of nuclear reactors



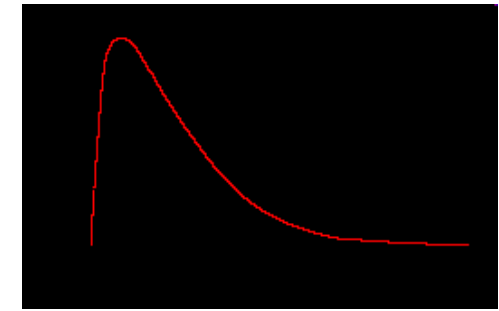
The fate of neutrons in Uranium (I)

- Natural uranium is an admixture of ^{235}U (presently 0.7%) and ^{238}U
- Neutrons emerging from fission have an energy spectrum peaked at about 1 MeV.
- Neutrons in Uranium can have several processes:
 - Elastic (n,n) and inelastic scattering (n,n')
 - Neutron capture (n, γ)
 - Fission (n,f)
- Elastic and inelastic scattering have the effect of slowing down neutrons
- Neutron capture removes neutron from the chain
- Only fission can reproduce neutrons



The fate of neutrons in Uranium (II)

- ^{235}U will fission (n,f) at all energies of the absorbed neutron. It is a FISSILE material
- Note the $1/v$ behaviour of fission cross section at low velocities, typical of esothermal processes.
- ^{235}U fission cross section can grow very large, to 500 barns at thermal energies
- ^{238}U has a threshold for fission (n,f) at a neutron energy of 1MeV. This effectively prevents fission from occurring in ^{238}U
- There is very strong resonant capture of neutrons (n, γ) for energies in the range 10-100 eV - particularly in the case of ^{238}U where the cross-section reaches very high values.



0 1 2 4 6 8 10 M

