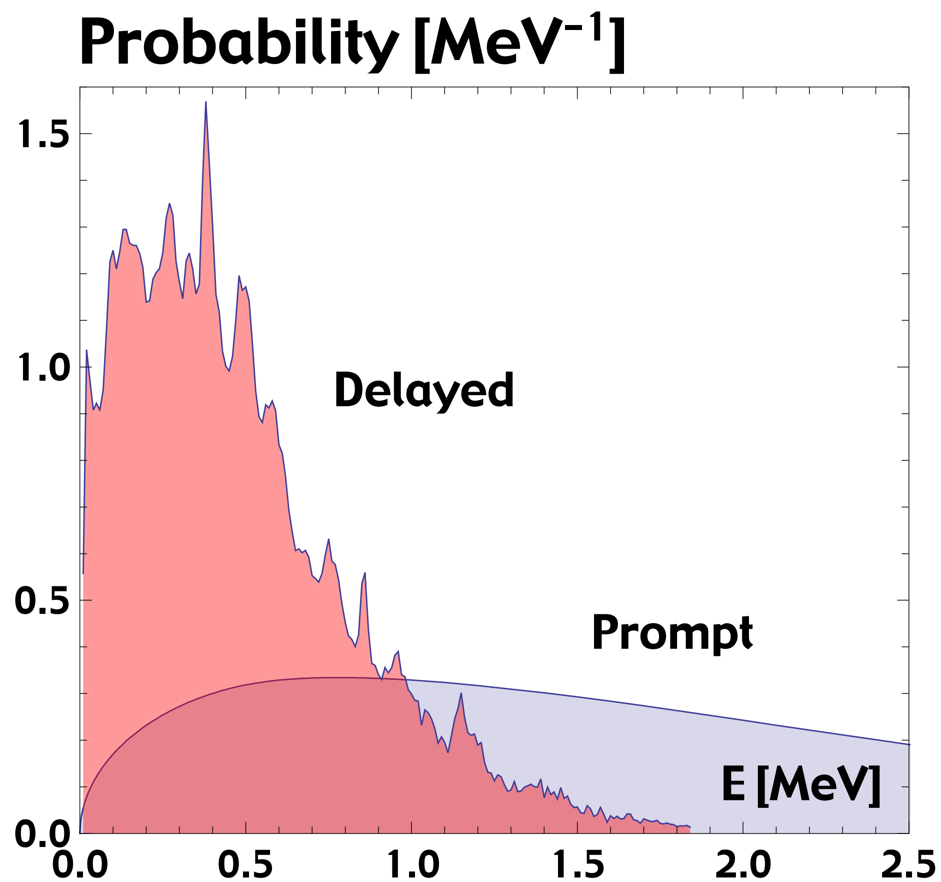
Fast reactor kinetics and reactivity feedbacks



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Intended learning outcomes

Fast spectrum Generation IV-reactors offer sustainable energy production by conversion of ^{238}U to fissile nuclides. The down-sides include

Reduced delayed neutron production and efficiency

Reduced neutron generation time

Positive coolant temperature coefficients

Reduced Doppler feedback

After this lecture you will be able to:

- **Assess the detrimental impact of U-Pu fuels on safety parameters**
- **Design a fast reactor to make use of leakage for improved safety**

Background

- In a well designed reactor, a transient mis-match between power and primary coolant flow is mitigated by negative reactivity feedbacks.
- A large fraction of fissions induced by delayed neutrons and a long neutron generation time ensure that such feedbacks have ample time to act.
- Any perturbation should result in a new stable state where temperatures either
  - Have not been out of operationally permitted boundaries, permitting restart of the reactor.
  - Have not been out of boundaries for integrity of fission product barriers, permitting to exclude emergency planning actions

Point-kinetics with reactivity feedback

- In the point-kinetic approximation, we may describe the power evolution of a reactor according to the following set of coupled differential equations:

$$\frac{d\dot{Q}}{dt} = \frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{eff}}{\Lambda_{eff}} n(t) + \sum_{i=1}^{k} \lambda_i C_i(t)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda_{eff}} n(t) - \lambda_i C_i(t) \qquad \beta_{eff} = \sum_{i=1}^{k} \beta_i$$

- The reactivity feedback $\delta\rho$ in a fast reactor may be approximated by

$$\delta\rho(t) = K_D \, ln\left(\frac{\bar{T}_{fuel}(t)}{\bar{T}_{fuel}(0)}\right) + \alpha_{axial}\, \delta\bar{T}_{fuel}(t) + \alpha_{coolant}\, \delta\bar{T}_{coolant}(t) + \alpha_{radial}\, \delta\bar{T}^{in}_{coolant}(t)$$

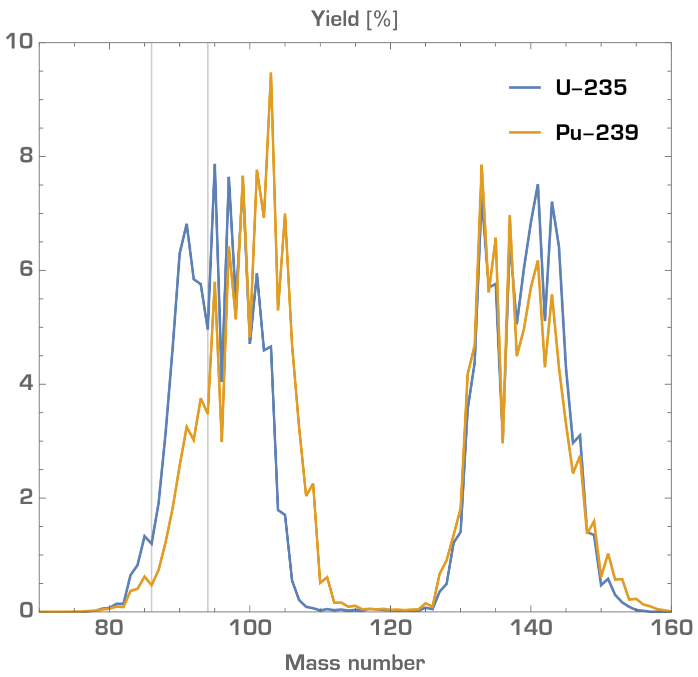
Fuel Doppler feedback

Fuel axial expansion

Coolant density change

Fuel SA diagrid radial expansion

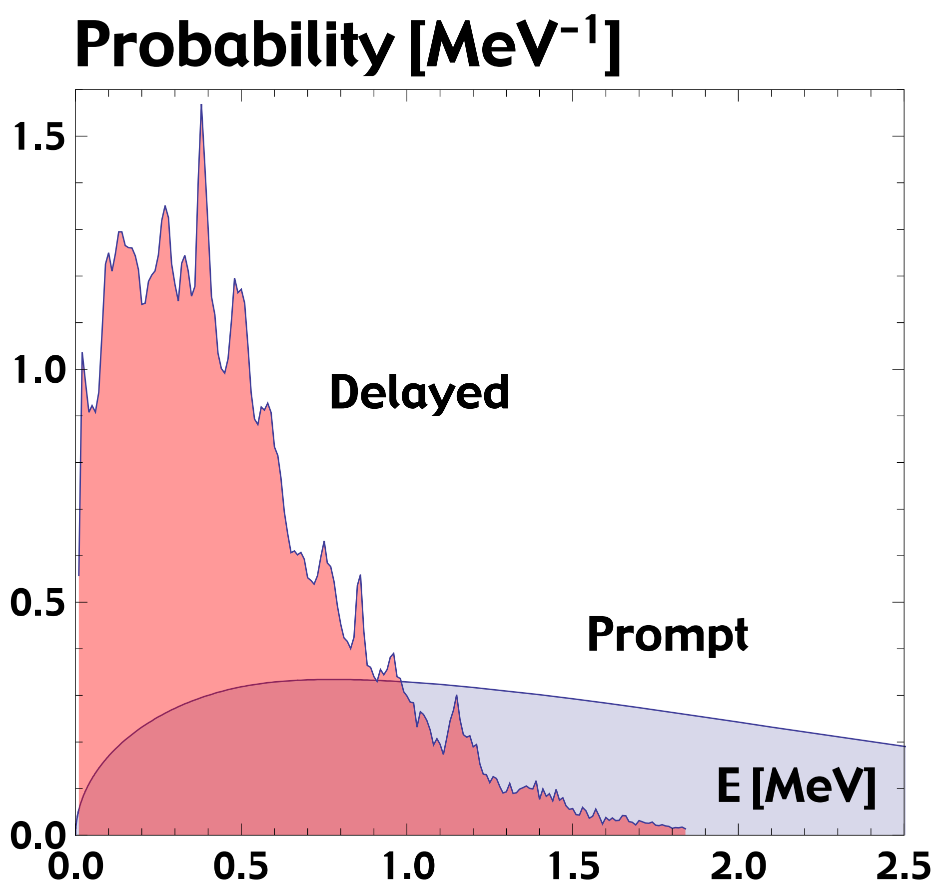
Delayed neutrons



Nuclide	ν_{tot}	$\beta = \nu_d / \nu_{tot}$
^{235}U	2.46	0.64%
^{238}U	2.79	1.89%
^{239}Pu	2.94	0.22%
^{240}Pu	3.02	0.30%

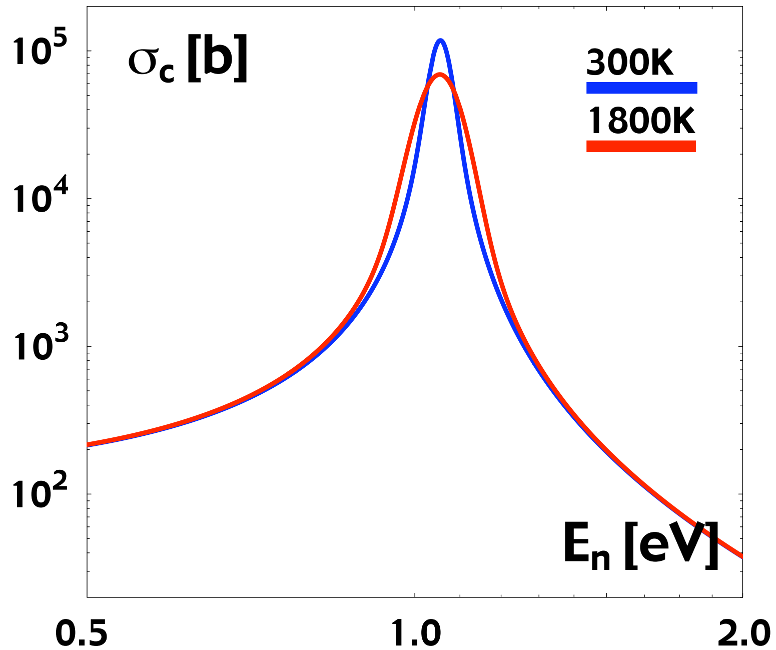
- Delayed neutrons are emitted by unstable fission products having a half-life of up to 55 s.
- Main contributors: Kr, Br, I, Rb, Cs
- Increasing mass of mother nuclide shifts mass of the lighter fission product (Why?)
- Yield of Kr and Br is reduced.
- Increasing neutron number of mother nuclide increases delayed neutron fraction.
- Pu fuel yields lower β than ^{235}U fuel.
- Fission in ^{238}U contributes to delayed neutron production in a fast reactor!

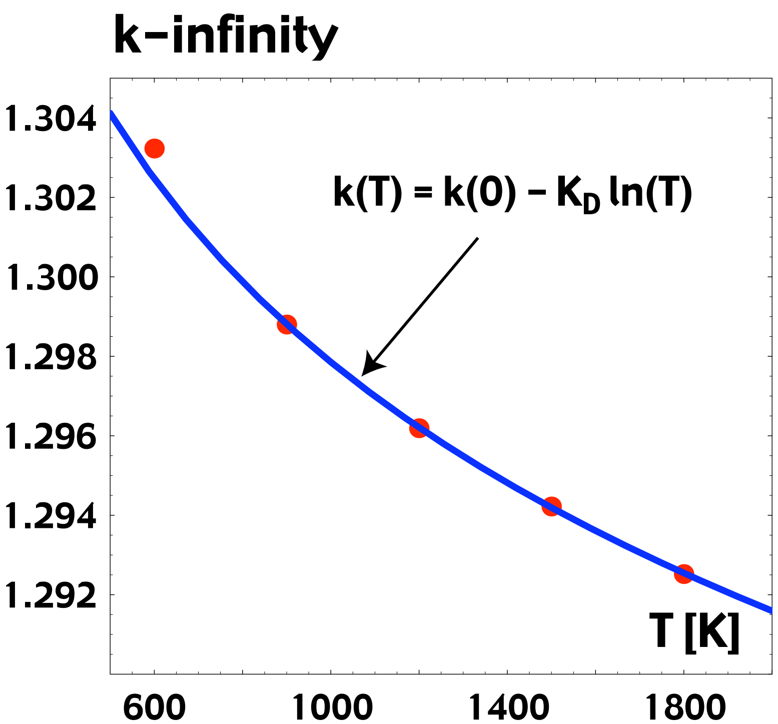
Effective delayed neutron fraction



- Effective delayed neutron fraction β_{eff} is the fraction of fissions induced by delayed neutrons.
- Delayed neutron spectrum is softer than prompt neutron spectrum
- β_{eff} must be calculated explicitly for a given spectrum.

Doppler feedback





- When the fuel temperature increases, all nuclides vibrate with larger amplitude around their average crystal lattice positions.
- In the lab system, the cross section for resonance absorption is reduced at the peak and increases at the tails. Area under resonance peak is conserved.
- Neutrons under moderation first experience an increase in absorption cross section when approaching the higher energy tail. Fewer neutrons reach the energy of the resonance peak.
- Net effect: increase in spectrum averaged cross section for capture and reduction in reactivity.
- In fast reactors, the reactivity decreases logarithmically with temperature.

Doppler feedback (2)

The Doppler coefficient α_D is the change of reactivity with temperature due to broadening of absorption cross section.

$$\alpha_D \equiv \frac{d\rho}{dT} = \frac{1}{k^2}\frac{dk}{dT}$$

In a fast spectrum, reactivity decreases logarithmically with temperature.

$$\rho(T) = \rho(0) + K_D \ln(T)$$

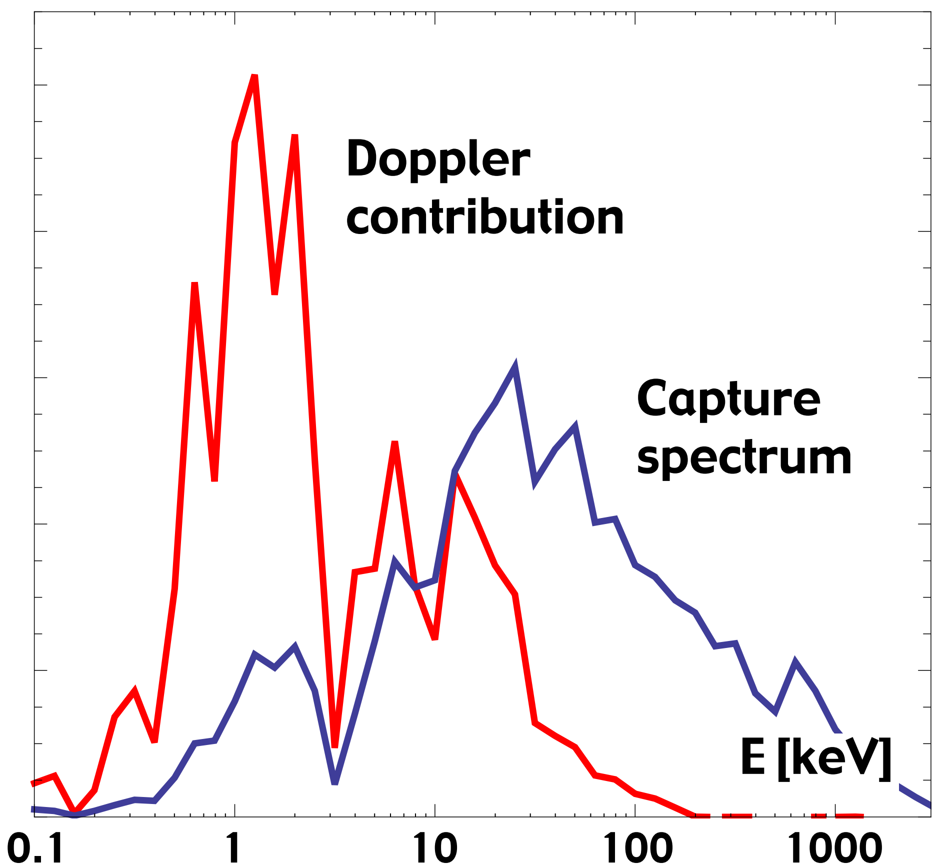
The constant of proportionality K_D is called ”The Doppler constant”

$$K_D = T\frac{d\rho}{dT}$$

The Doppler coefficient is obtained by dividing the Doppler constant with T

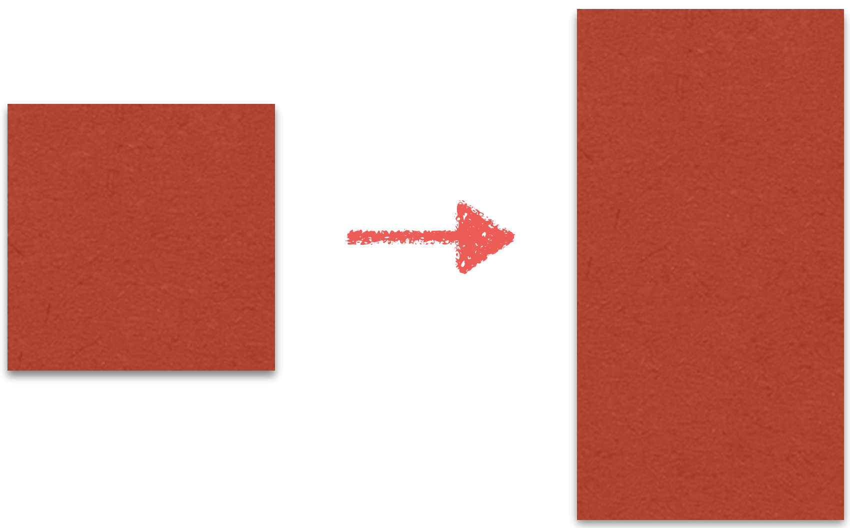
$$\alpha_D = \frac{K_D}{T}$$

Doppler feedback (3)



- Doppler feedback mainly derives from neutron captures occurring below 100 keV
- The lower the energy of the resonance where capture occurs, the more efficient is the Doppler feedback
- In an SFR with standard MOX fuel, 65% of the Doppler feedback derives from neutron captures below 3 keV, constituting only 15% of all captures!
- Typical order of magnitude: K_D = 500 pcm
- Spectrum dependence is significant!

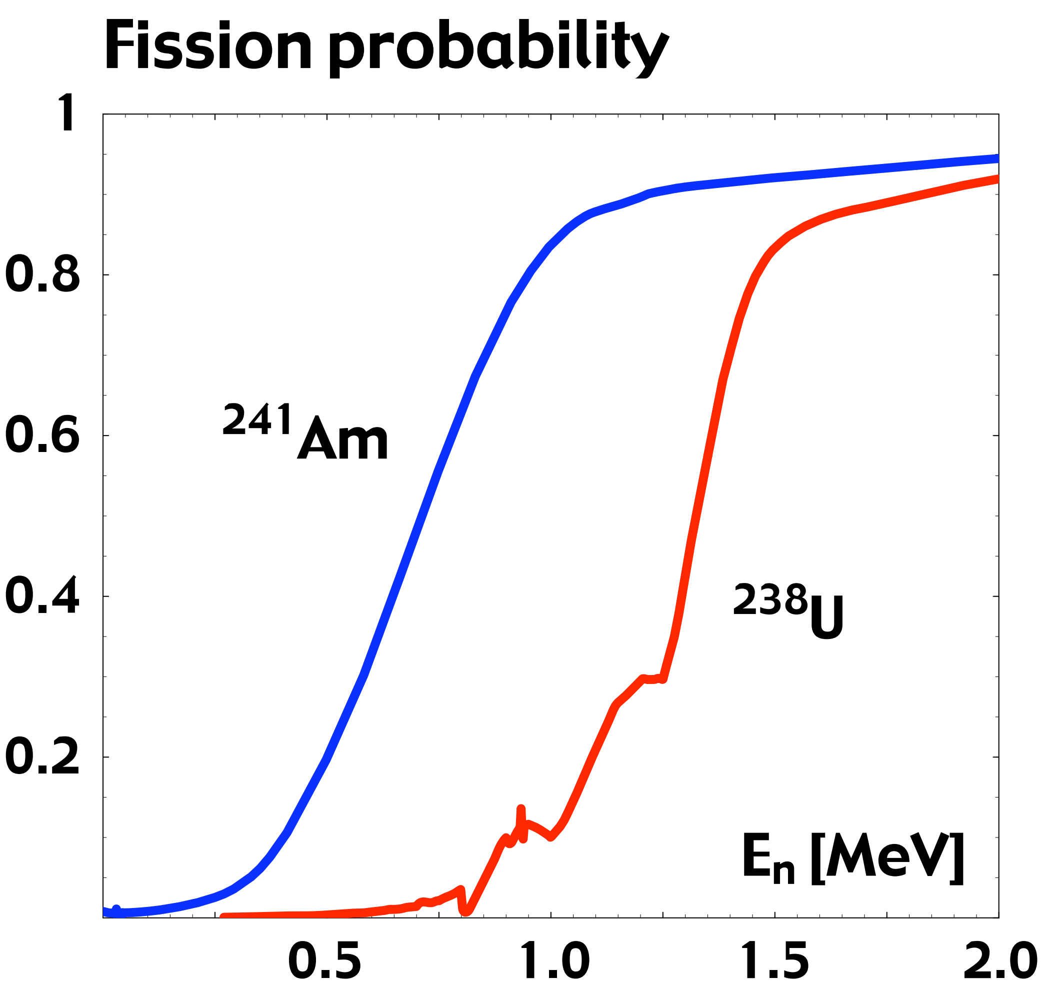
Fuel axial expansion



When the fuel heats up, fuel pellets will expand in volume.

- Axial expansion of pellets leads to an increase in core active height (By how much?)
- Radial expansion of pellets does not lead to an expansion in core radius (Why?)
- Axial expansion will increase the radial leakage of neutrons (Why?)
- Axial expansion feedback is more important for cores with large H/D ratio (Why?)
- Feedback is delivered with speed of sound (How fast is that?)

Coolant temperature feedback

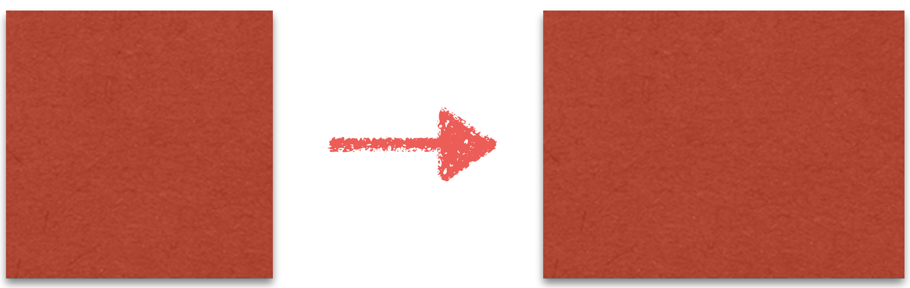


- When the coolant heats up, the coolant density decreases.
- Moderation of fast neutrons by in-elastic and elastic scattering is less efficient
- Fission probability increases
- Reactivity increases
- Leakage of neutrons increases
- Reacticity decreases
- Balance determines coolant temperature coefficient

Fuel radial expansion

When the grid plate heats up, the distance between fuel assemblies will increase.

By how much does the core radius increase?



Radial expansion will increase the axial leakage of neutrons (Why ?)

Radial expansion feedback is more important for cores with low H/D ratio (Why?)

Feedback is delivered once the hot coolant temperature has been translated to the inlet of the core (How fast is that?)

Safety parameters depend on core dimensions!

ELFR: 600 MWe

Parameter	Value
α_{Pb}	+ 0.23 pcm/K
K_D	- 960 pcm
α_{axial}	- 0.10 pcm/K
α_{radial}	- 0.32 pcm/K

SLFR:100 MWe

Parameter	Value
α_{Pb}	- 0.02 pcm/K
K_D	- 660 pcm
α_{axial}	- 0.13 pcm/K
α_{radial}	- 0.47 pcm/K

Explain why!