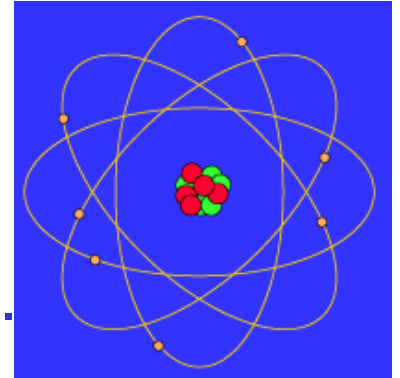
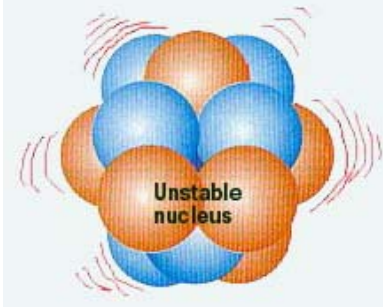


## 2.8. Isotope analysis and neutron activation techniques

The previously discussed techniques of material analysis are mainly based on the characteristic atomic structure of the elements and the associated unique signature of the characteristic x-ray energies.



Alternative and complementary techniques are based on the use of nuclear signatures which rely on the characteristic structure of the atomic nucleus and its associated energy and time-scale conditions. Since it is not only characteristic for elemental analysis but also for isotope analysis it has emerged as a powerful tool in material analysis and also in the dating of archaeological artifacts.



# Activation Analysis

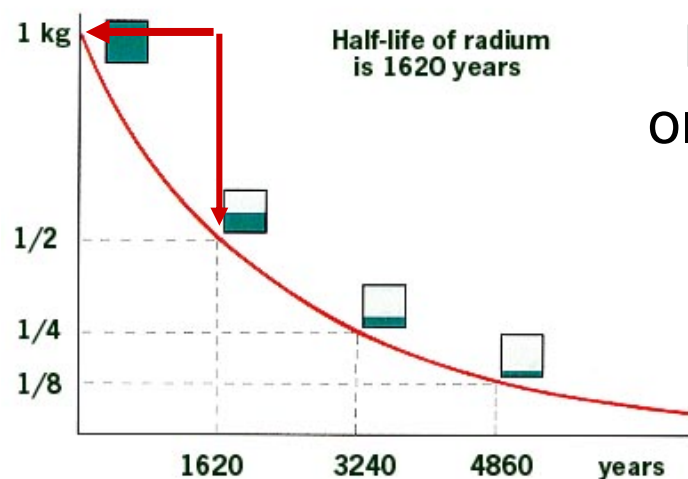
This section concentrates on the activation analysis as one of the main application of nuclear physics tools in the analysis of historical artifacts.

Activation analysis is based on the synthetic production of radioactivity in the sample to use decay characteristics (like decay radiation, decay energy, half life/decay constant, & activity) as unique analytical signature.

Characteristic decay mechanisms,  $\alpha$ ,  $\beta$ ,  $\gamma$

Activity  $A$  reveals the abundance  $N$ :

$$A = \lambda \cdot N$$



Half life  $T_{1/2}$  of decay or the decay constant  $\lambda$  are unique for each radioactive isotope:

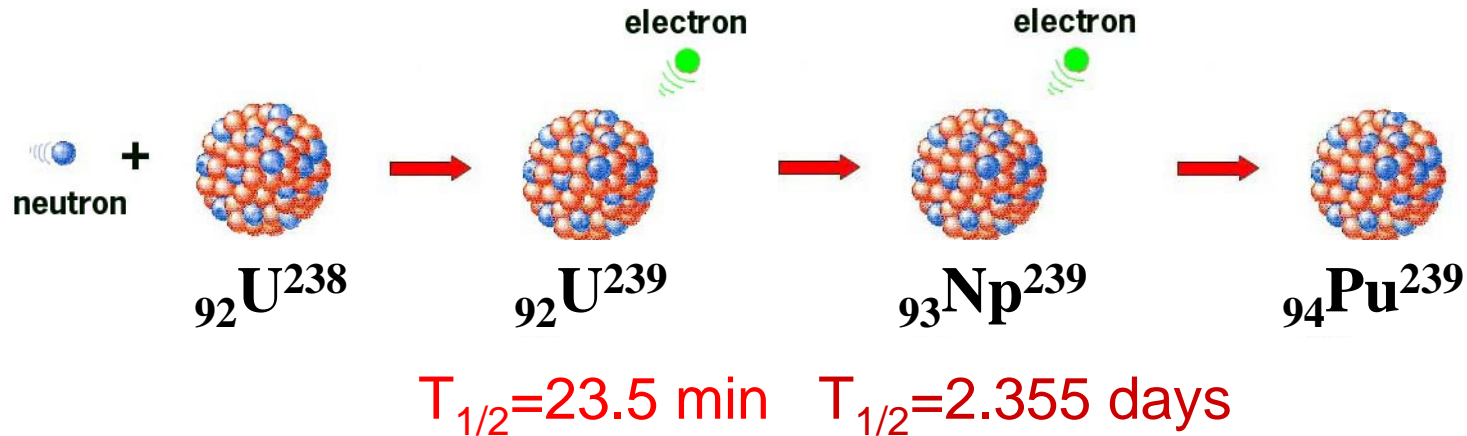
$$T_{1/2} = \ln 2 / \lambda$$

$A \Rightarrow$  number of decays/time

# Production of Radioactivity

Radioactivity is typically produced through nuclear reactions which trigger a change of neutron and proton number in the sample nuclei.

e.g. neutron induced radioactivity of stable  $^{238}\text{U}$



Each decay is associated with emission of characteristic  $\beta$  and  $\gamma$  radiation



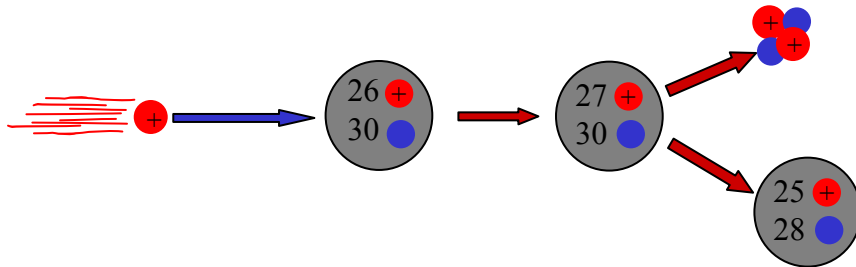
# Example: Iron

4 stable isotopes:  $^{54}\text{Fe}$  (5.8%),  $^{56}\text{Fe}$  (91.7%),  $^{57}\text{Fe}$  (2.2%),  $^{58}\text{Fe}$  (0.3%)

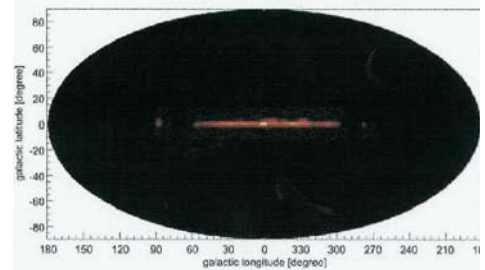
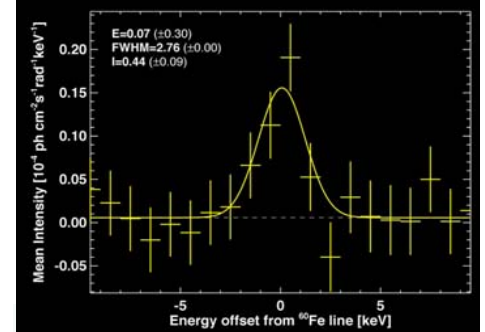
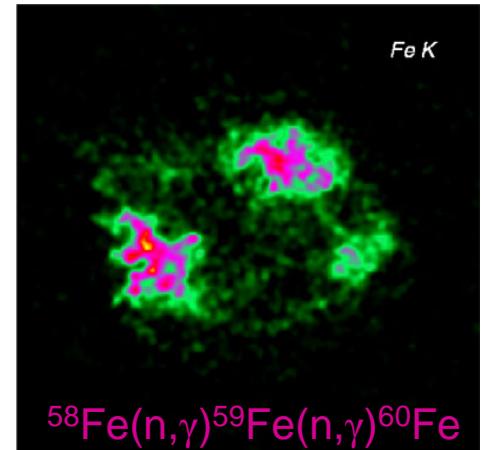
Neutron activation would create mostly  $^{57}\text{Fe}$  through  $^{56}\text{Fe}(n,\gamma)^{57}\text{Fe}$

But activation of  $^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$  ( $T_{1/2}=44.5\text{d}$ )

other possibility:  $^{56}\text{Fe}(p,\alpha)^{53}\text{Mn}$  ( $T_{1/2}=3.7\cdot 10^6\text{ y}$ )



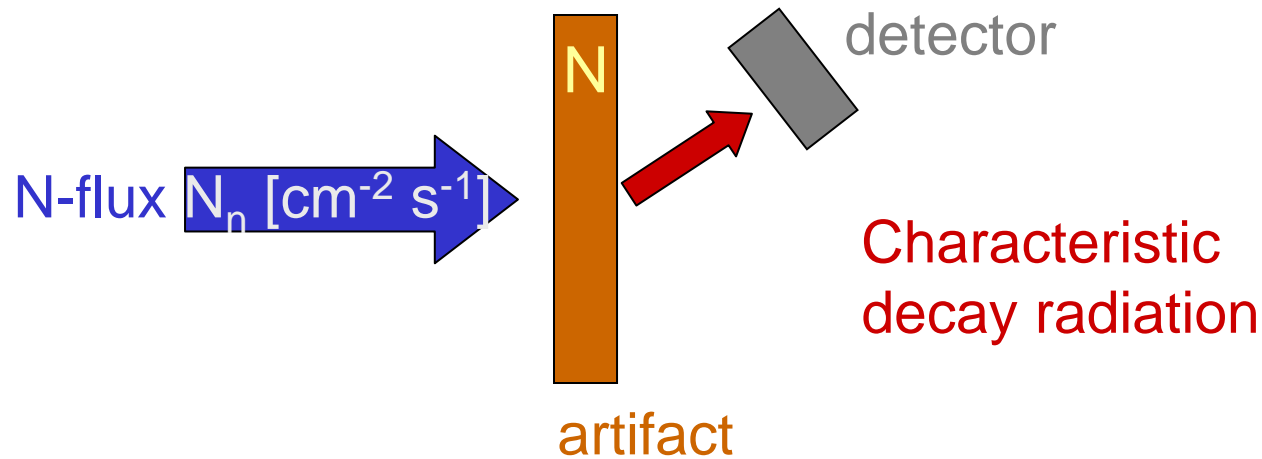
This method requires high energy proton beam for penetrating the iron and on-line detection of the energetic exiting a particle!



# Neutron Activation Analysis NAA

Advantages:

- neutrons can penetrate deeply into material
- neutrons can be produced by accelerators and reactors
- neutron induced reactions have large cross section  $\sigma$

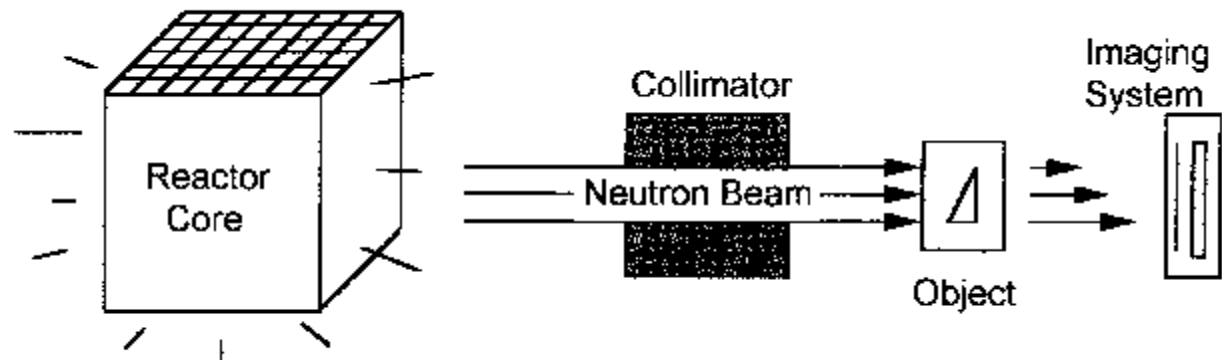
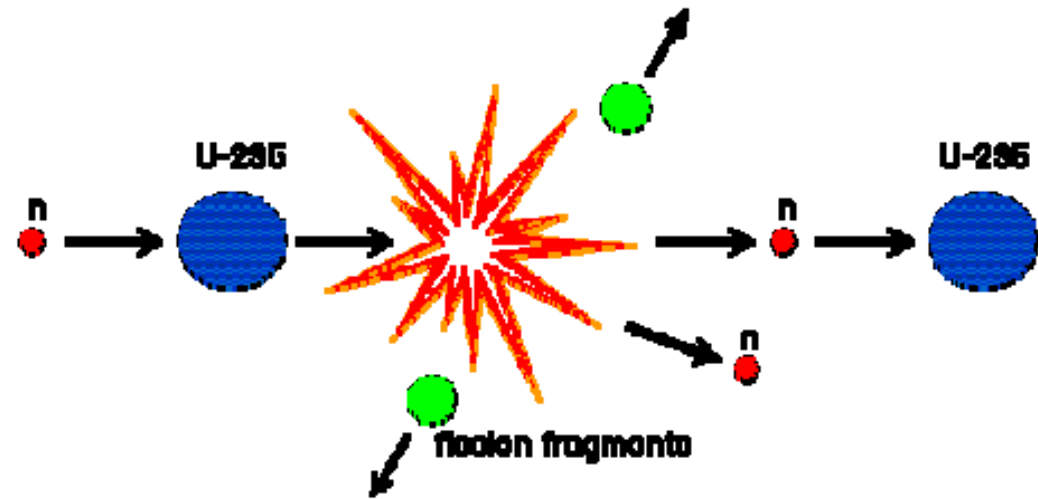


Disadvantage:

- no depth resolution

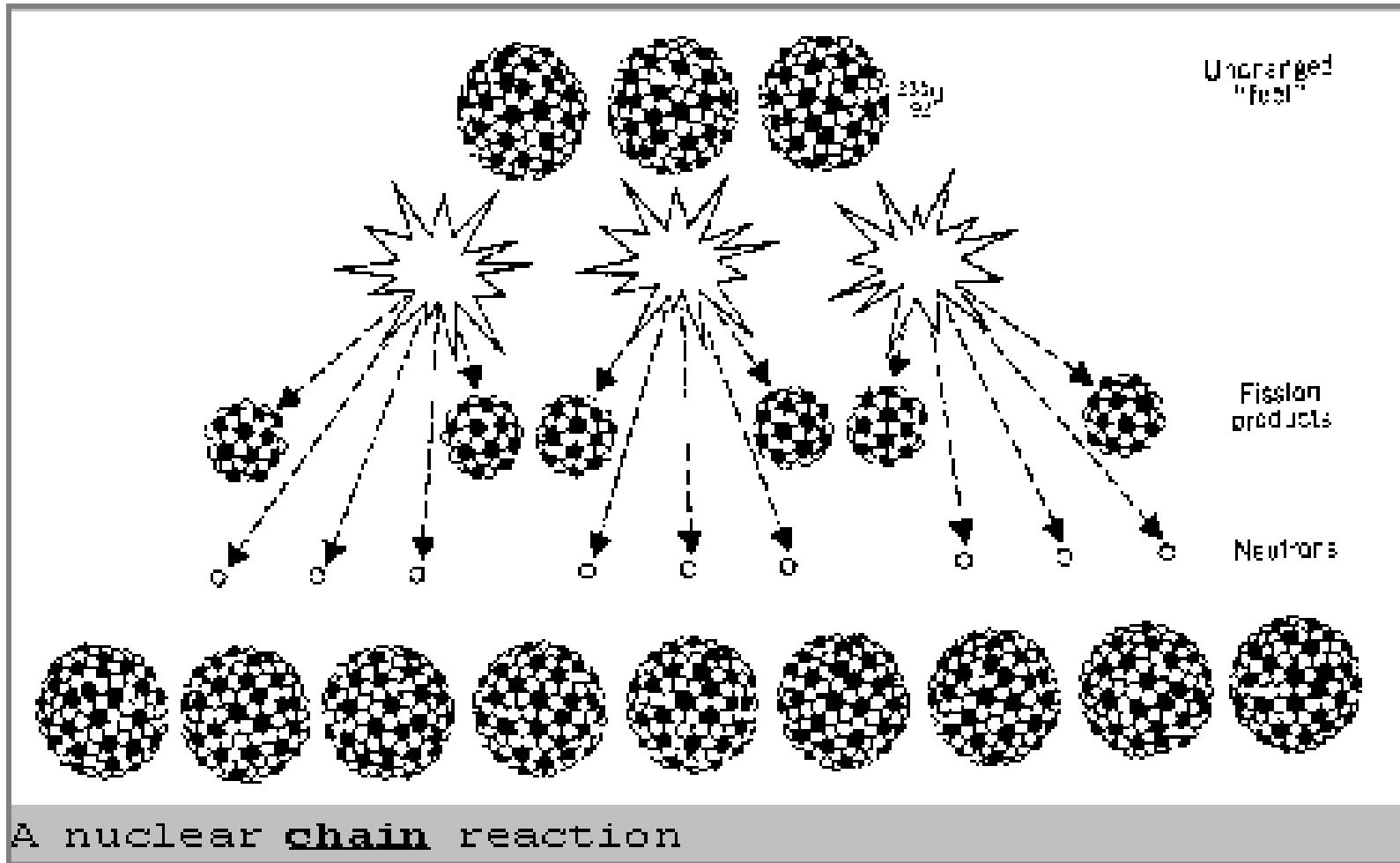
$$\text{Production rate } P = \sigma \cdot N_n \cdot N$$

# Reactors as neutron sources



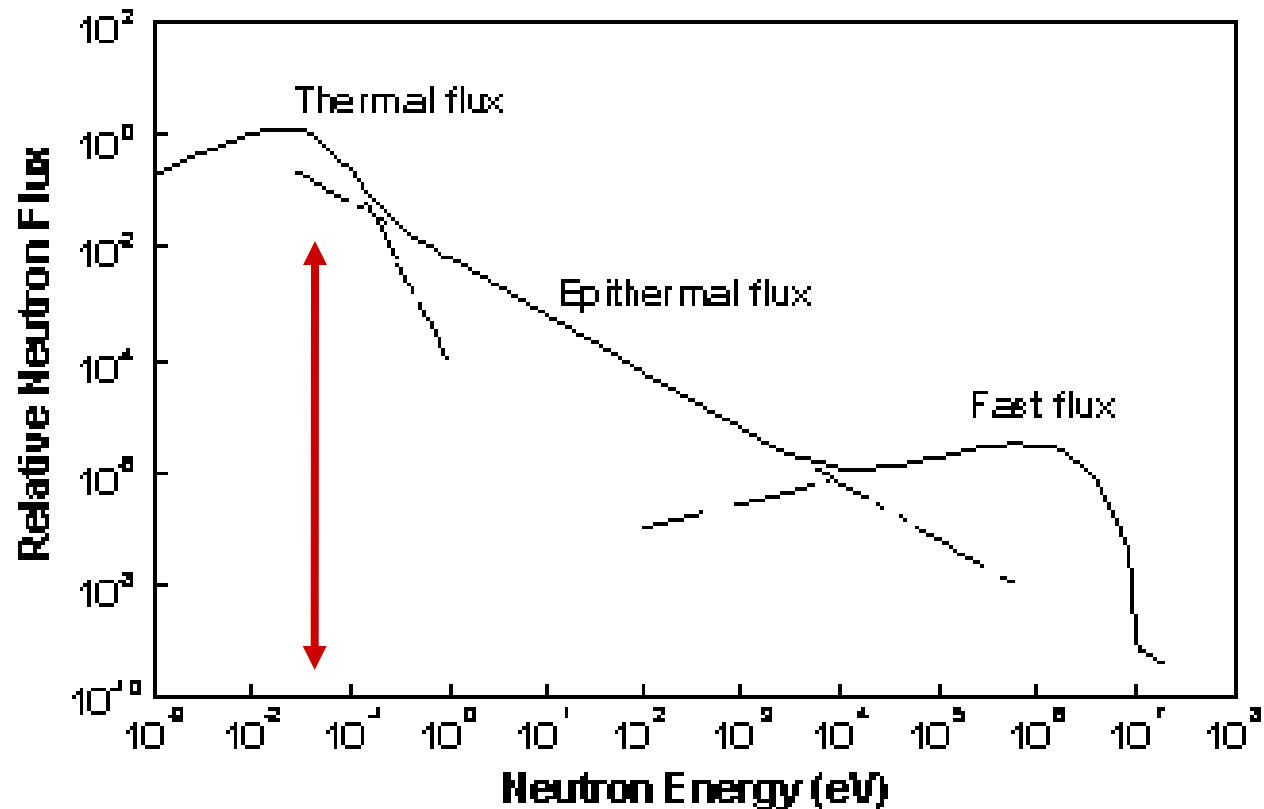
Neutrons are produced by fission of  $^{235}\text{U}$  isotopes in reactor core and subsequently scattered as neutron beam towards to object.

# Fission mechanism and neutron flux



Neutron flux multiplies in fission chain to up to  $10^9$  to  $10^{14}$  neutrons/cm<sup>2</sup>s  
Fission process is controlled by neutron absorption material between the uranium elements.

# Neutron flux and energy distribution



Reactor neutrons come with certain complex energy distribution due to scattering and “thermalization” processes which slow the initially fast fission neutrons down to mostly “thermal” energies;  
 $T=25^{\circ}\text{C}=273+25 \text{ K}=298 \text{ K}$ ,  $E=kT=8.617 \cdot 10^{-5} \text{ eV/K} \cdot 298 \text{ K}=26 \text{ meV}$

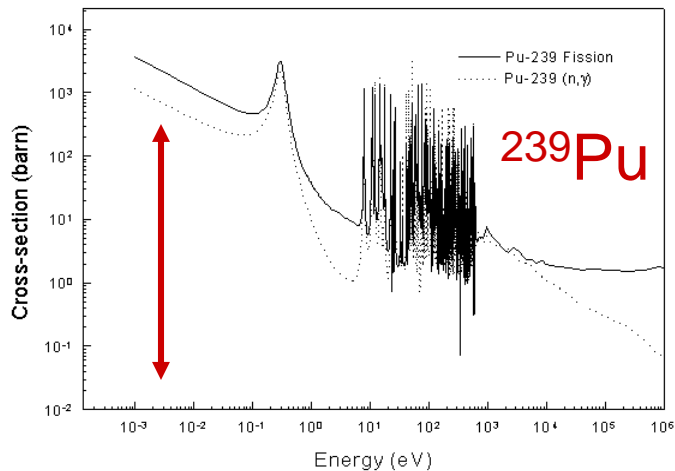
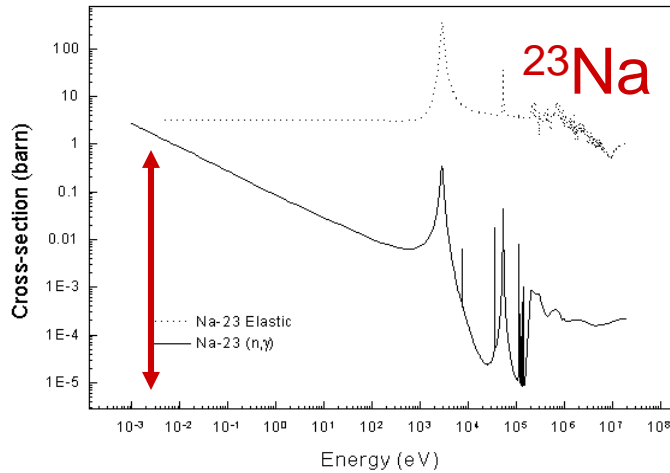
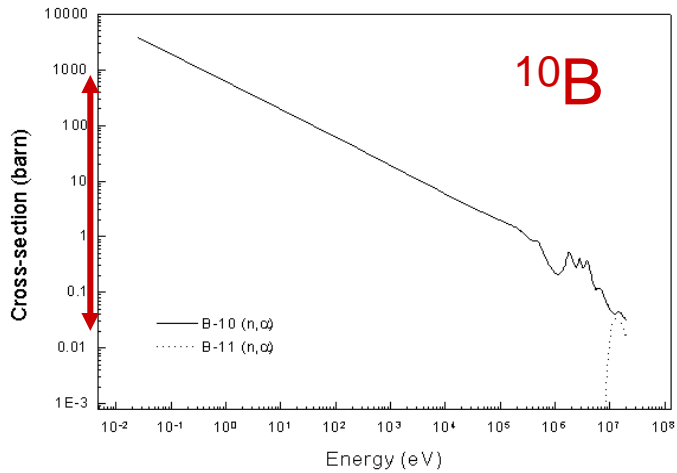
# Neutron Cross Section $\sigma$

Neutron capture cross section mostly follows the  $1/v$  law:

$$\sigma = S_n \cdot 1/v$$

with  $v$  equal to the velocity of the neutron and  $S_n$  being a reaction specific (single particle) parameter. Only at higher neutron energies more complex reaction mechanisms like resonance contributions contribute.

Thermalized neutrons have the highest cross section and detector count-rate!



# Prompt and delayed detection

Prompt technique is based on immediate decay radiation ( $\gamma, \alpha$ ) after neutron capture

Detector count rate for prompt ( $n, \gamma$ ) or ( $n, \alpha$ ) reaction:

$$I = \sigma \cdot N \cdot N_n \cdot \eta \quad [\text{cts/s}]$$

$\sigma$ : cross section;

$N = 6.023 \cdot 10^{23} \cdot m/A$ : number of particles in sample;

$N_n$ : neutron flux

$\eta$ : total efficiency of detector arrangement

Delayed technique is based on detection of characteristic decay radiation ( $\alpha, \beta, \gamma$ ) of the produced long-lived radioactive isotope.

# Production of radioactive Isotope $N_x$ for delayed activity measurements

$$\textit{production rate: } P = \sigma \cdot N_n \cdot N \text{ [1 / s]}$$

radioactive isotopes  $N_x$  decay while being produced depending on decay constant  $\lambda$ :

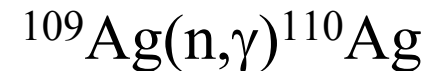
*characteristic activity:*

$$A(t) = \frac{dN_x}{dt} = -\lambda \cdot N_x(t) + P = P(1 - e^{-\lambda \cdot t})$$

# Example: neutron activation of a Ag coin

Neutron activation of a Ag coin of 1g mass with a neutron flux of  $10^{10}$  n/cm<sup>2</sup>s and a cross section of 1 barn (=10<sup>-24</sup> cm<sup>2</sup>);  $N_{\text{Ag}}=6.023 \cdot 10^{23}/109=5.5 \cdot 10^{21}$ :

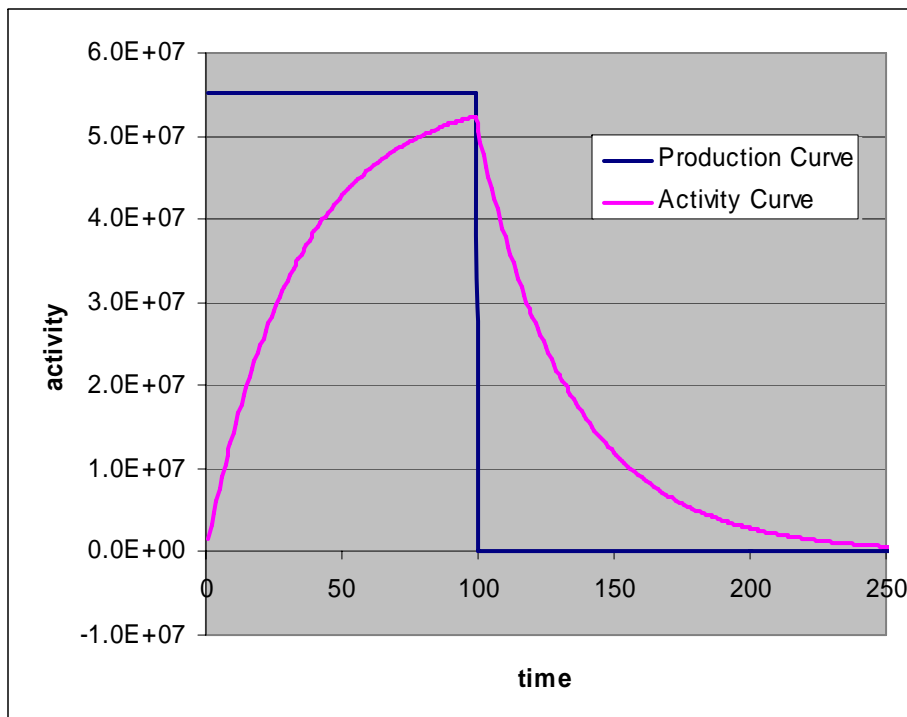
$$\Rightarrow P=5.5 \cdot 10^7 \text{ s}^{-1}. (\lambda=\ln 2/ T_{1/2})$$



$$T_{1/2}(^{110}\text{Ag})=24.6 \text{ s};$$

$$\lambda=2.82 \cdot 10^{-2} \text{ 1/s}$$

(short-lived component)

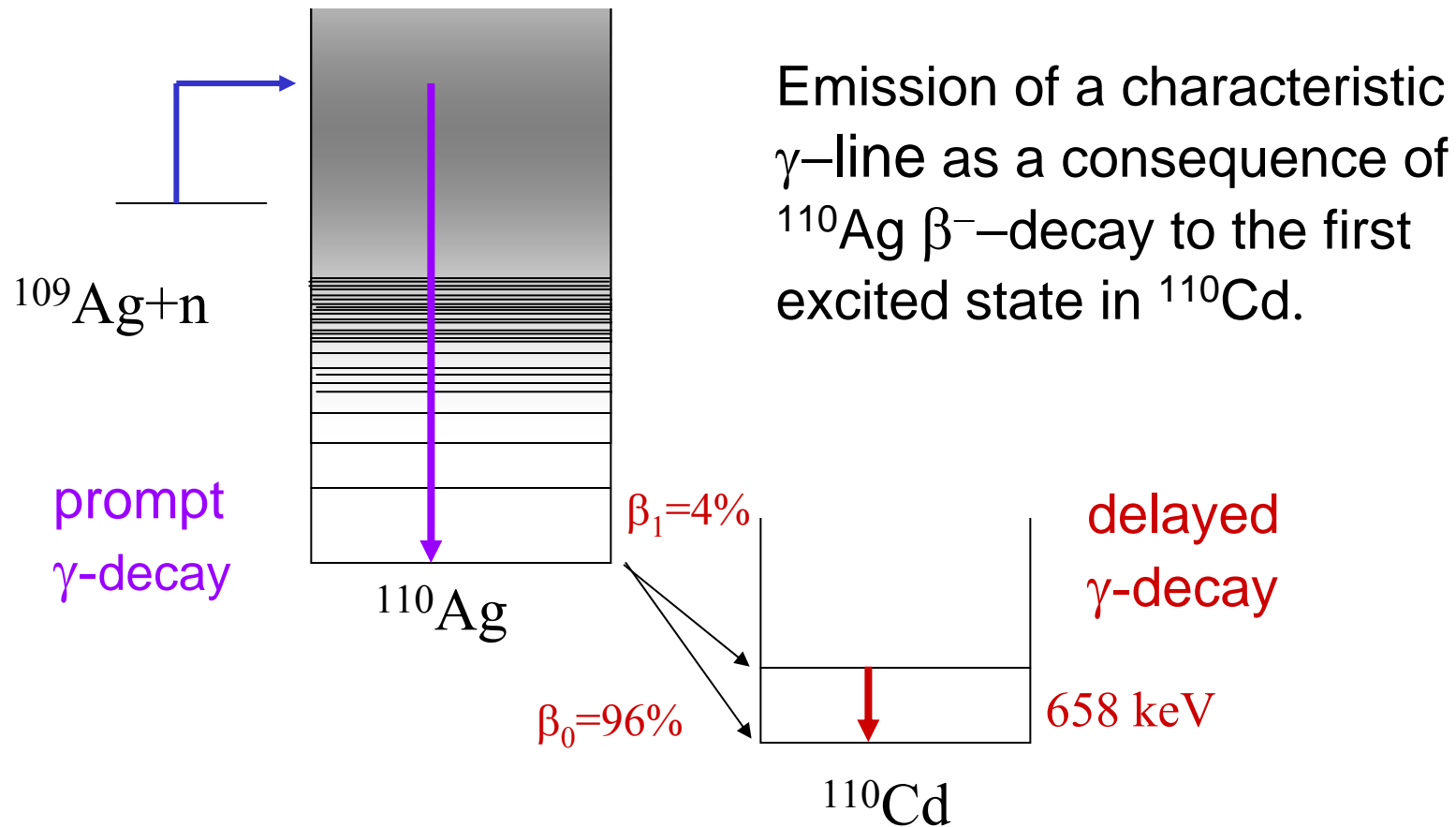


$$A(t) = P \cdot (1 - e^{-\lambda \cdot t}) \text{ during irradiation}$$

$$A(t) = \lambda \cdot N_0 \cdot e^{-\lambda \cdot (t-t_0)} = A_0 \cdot e^{-\lambda \cdot (t-t_0)}$$

after irradiation, with  $A_0$  being the activity at the end  $t_0$  of the irradiation period.

# Characteristic radiation signals



detector count rate:  $I_\gamma = A(t) \cdot \eta \cdot b_\gamma$

# Typical NAA-set-up

