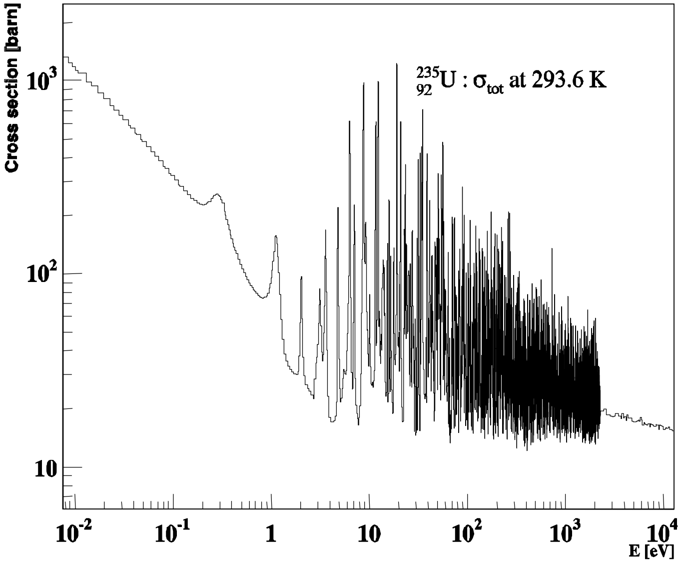
Nuclear Data for Reactor Physics: Cross Sections and Level Densities in the Actinide Region



J.N. Wilson

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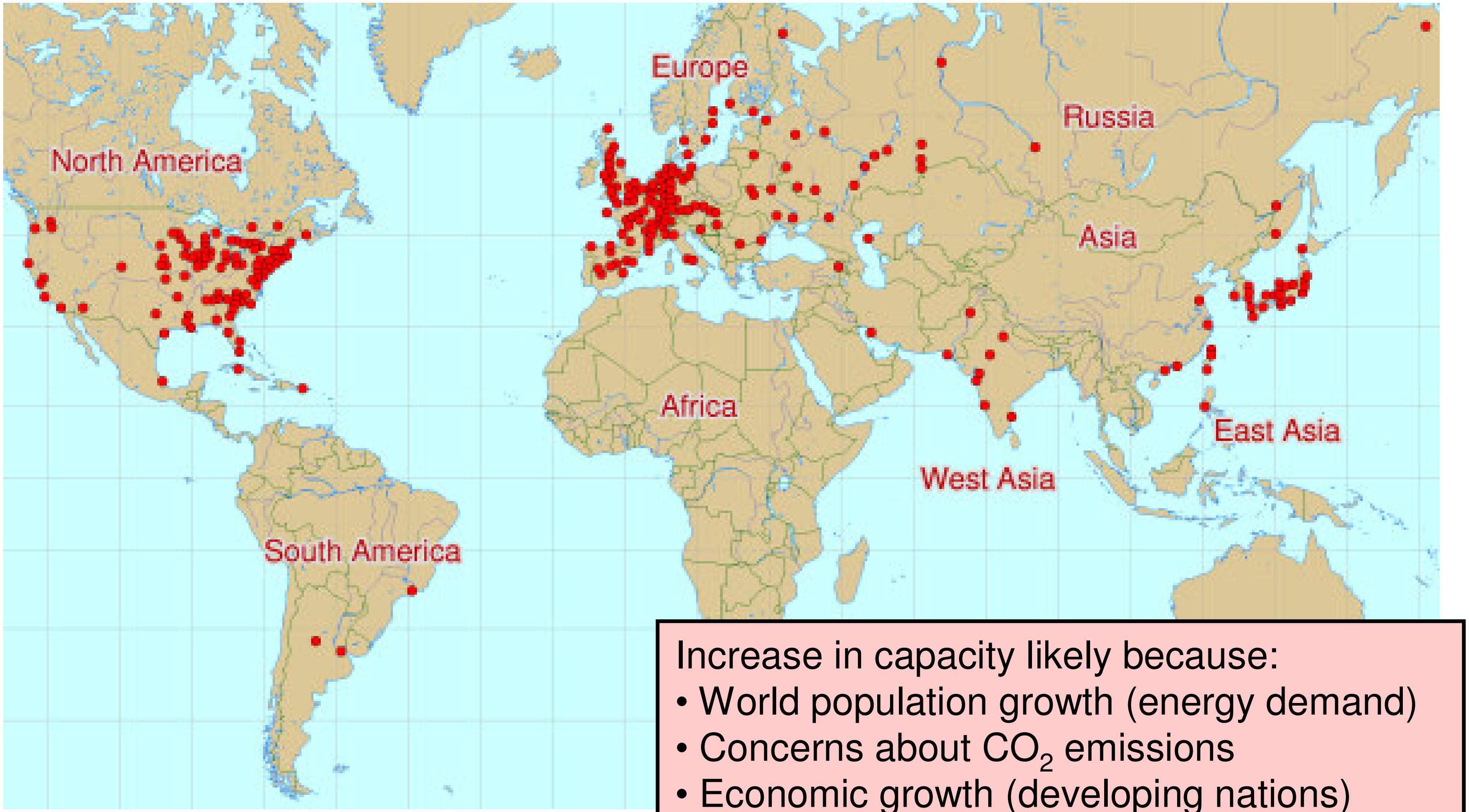
Talk Plan

- The importance of innovative nuclear reactors
- The need of cross section data for reactor simulations
- The difficulty of certain measurements and why there is a need to rely on theory/extrapolations
- How level density measurements can improve cross section calculations
- Norway and the Thorium fuel cycle

Current Nuclear Reactors



Increase in capacity likely because:
- World population growth (energy demand)
- Concerns about CO_2 emissions
- Economic growth (developing nations)
- Depletion of reserves of oil, gas (coal)
- No current economically viable alternative

Generations of Nuclear Energy

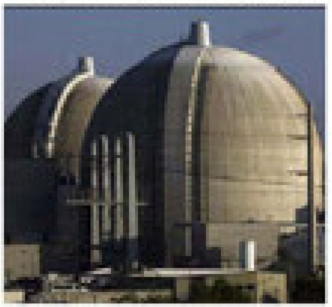
Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power



- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

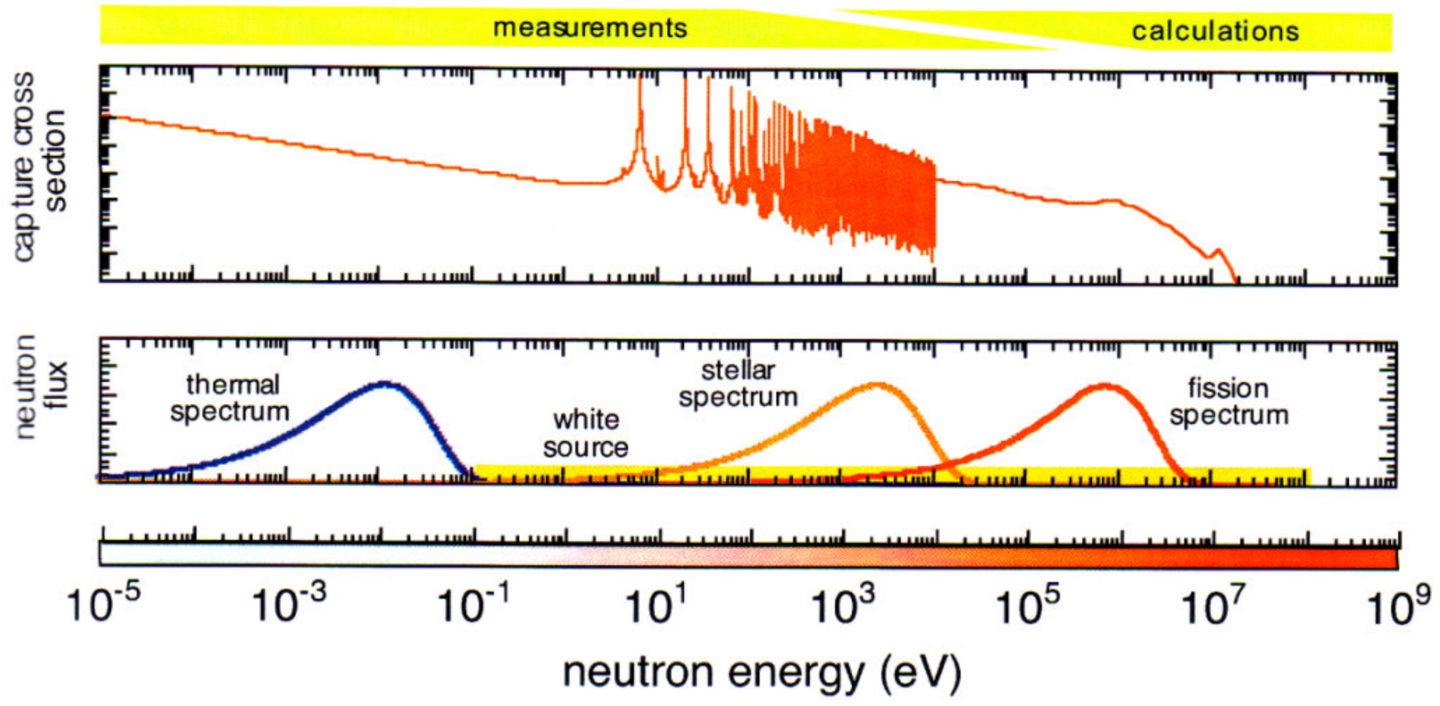
Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure

1950 1960 1970 1980 1990 2000 2010 2020 2030

Gen I | **Gen II** | **Gen III** | **Gen III+** | **Gen IV**

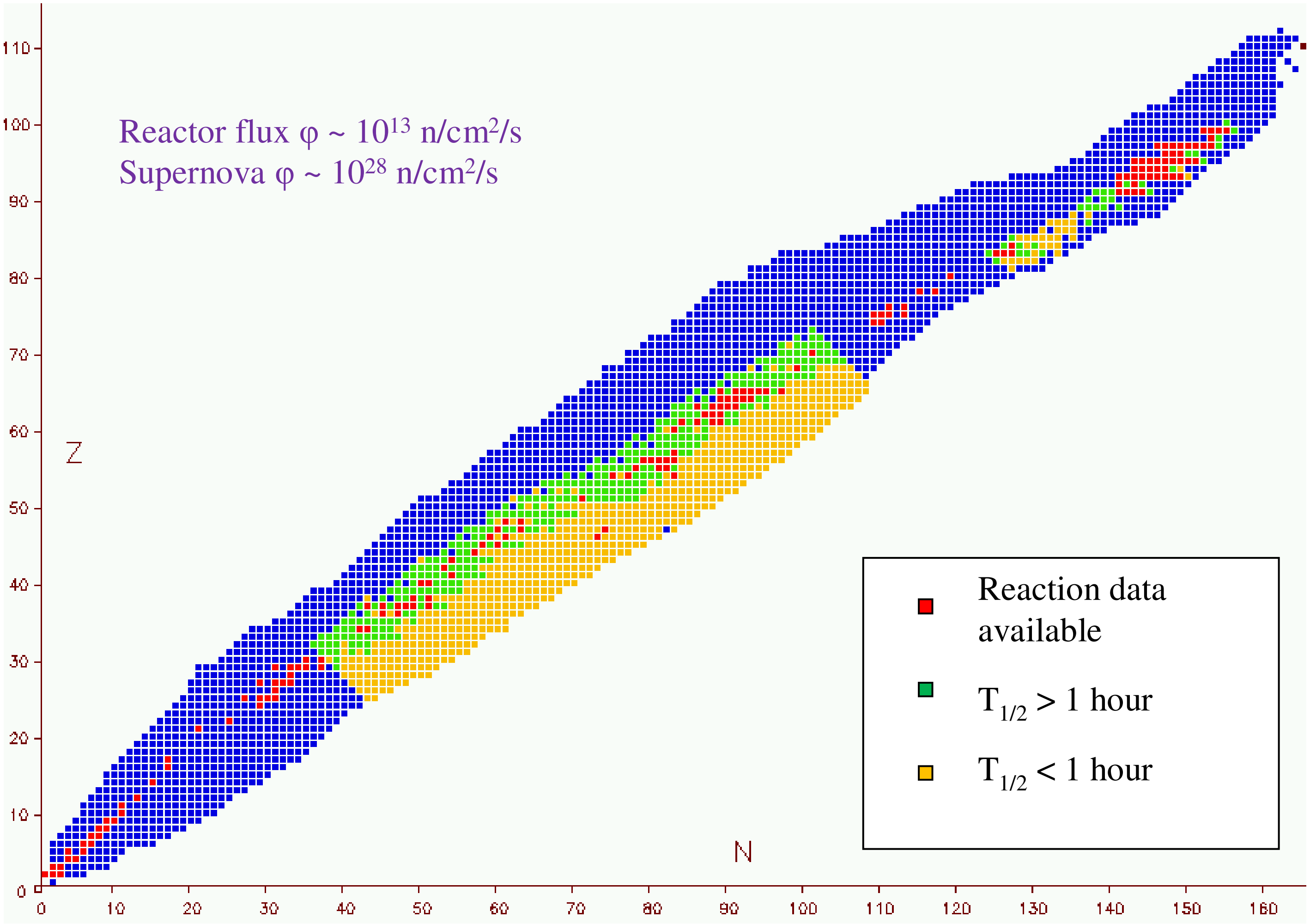
Cross section data



- **Reactor simulations require X-section data over large range of nuclei and a huge range in energy**
- **Measurements are often partial and/or have large uncertainties**

Creation of evaluated data libraries, e.g. ENDF, JENDL, JEFF

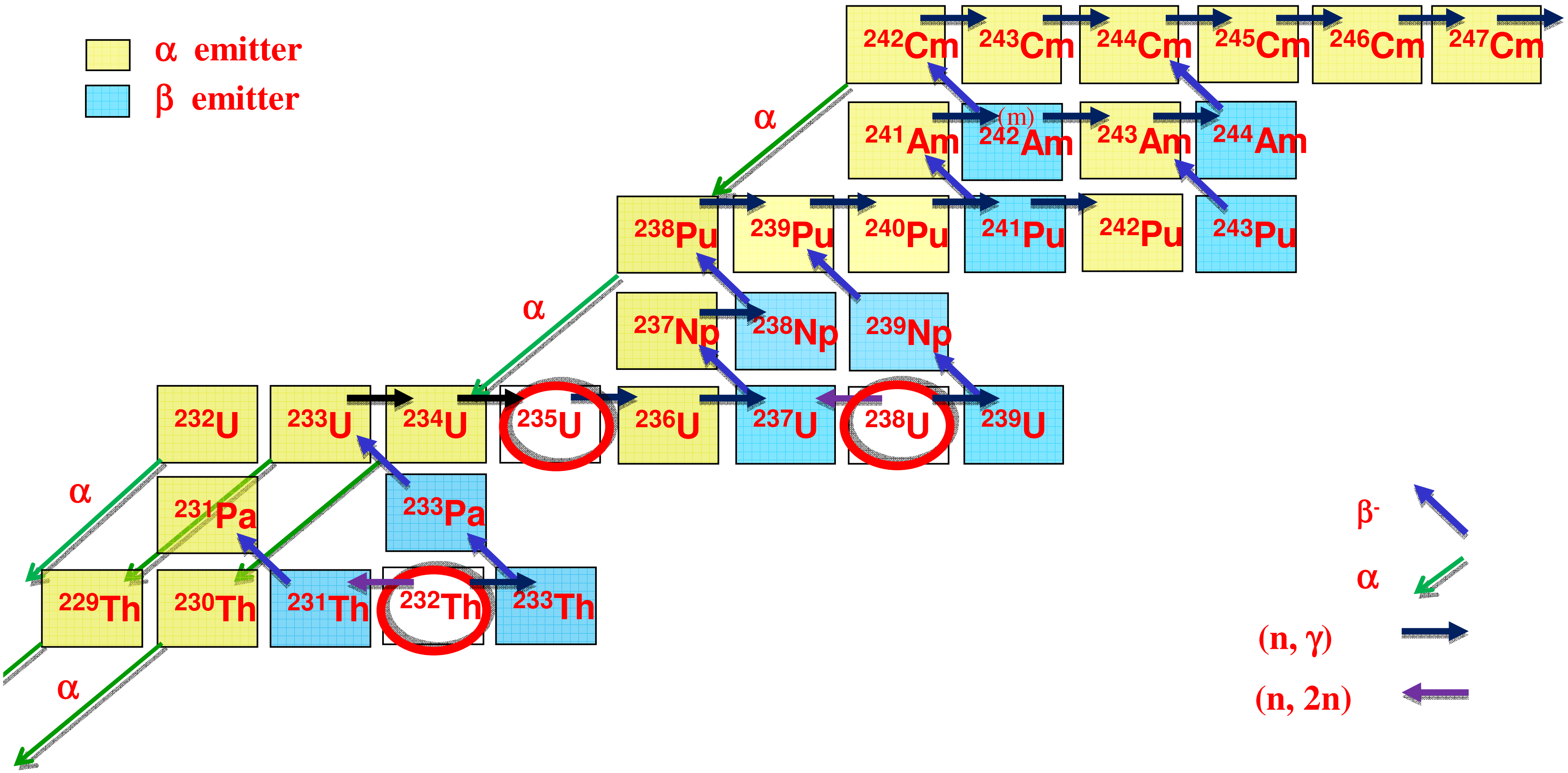
Nucleosynthesis in a Reactor Core



Reactor flux $\varphi \sim 10^{13}$ n/cm^2/s

Supernova $\varphi \sim 10^{28}$ n/cm^2/s

Nucleosynthesis in reactors



Reactor Criticality

Multiplication factor, k_{eff}

$$k = \frac{\sum \nu_i N_i \sigma_f \phi}{\sum N_i \sigma_c \phi + \sum N_i (\sigma_f + \sigma_c) \phi}$$

We need the sensitivity of multiplication factor, k, to nuclear data

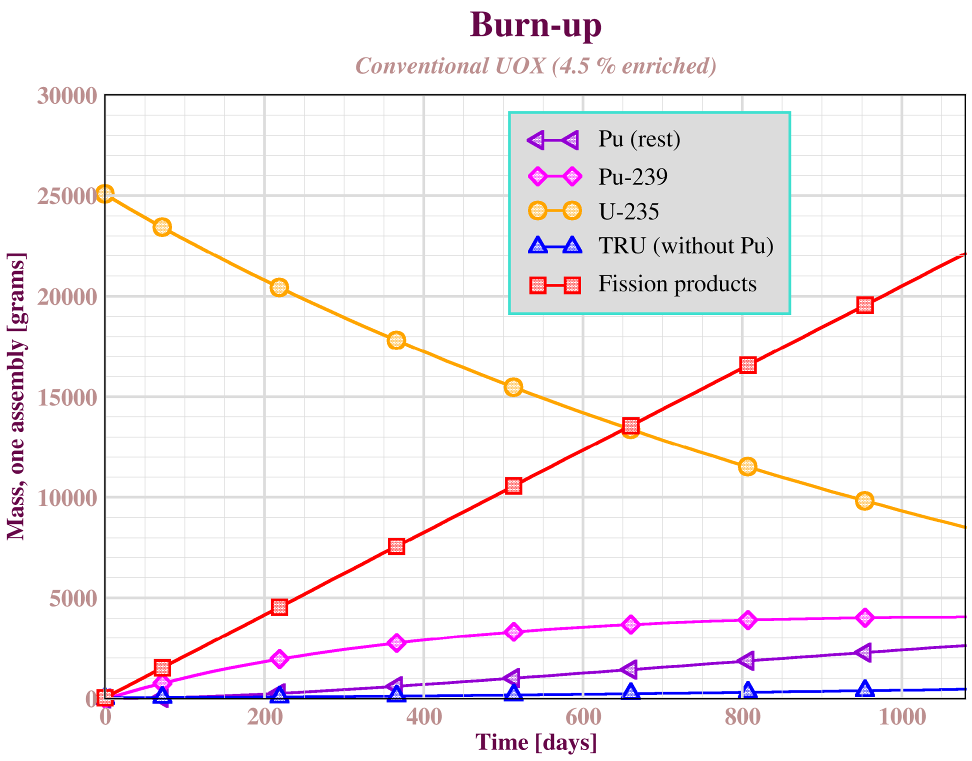
➡ **Improved accuracy of nuclear data can help reduce safety margins of innovative generation IV designs**

Cost of data measurements << Cost of generation IV reactor prototype construction

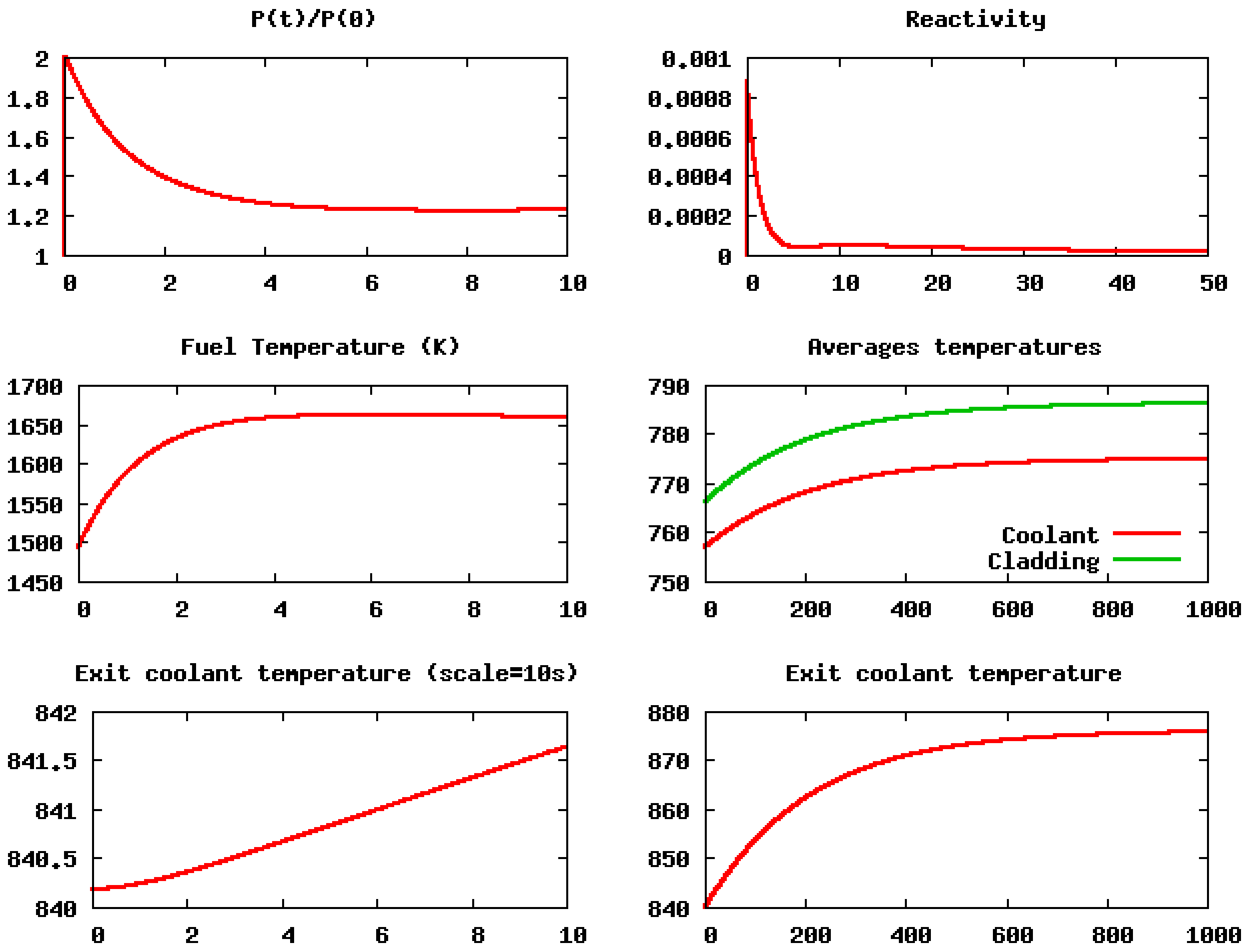
Reaction rates in the Core: Long Time Scales

- What is the composition of the spent nuclear fuel?
- How much fissile material can be recovered in fuel reprocessing?
- How will this limited amount of fuel constrain scenarios of the growth of nuclear power?
- How big will the geological repository need to be to dissipate the decay heat of the spent fuel?

$$\frac{\partial N_i}{\partial t} = \underbrace{-\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j}_{\text{Decay}} + \underbrace{-N_i \sum_{\forall r} \sigma_i^{(r)} <\phi> + \sum_j N_j \sigma_j^{j\to i} <\phi>}_{\text{Reaction}}$$

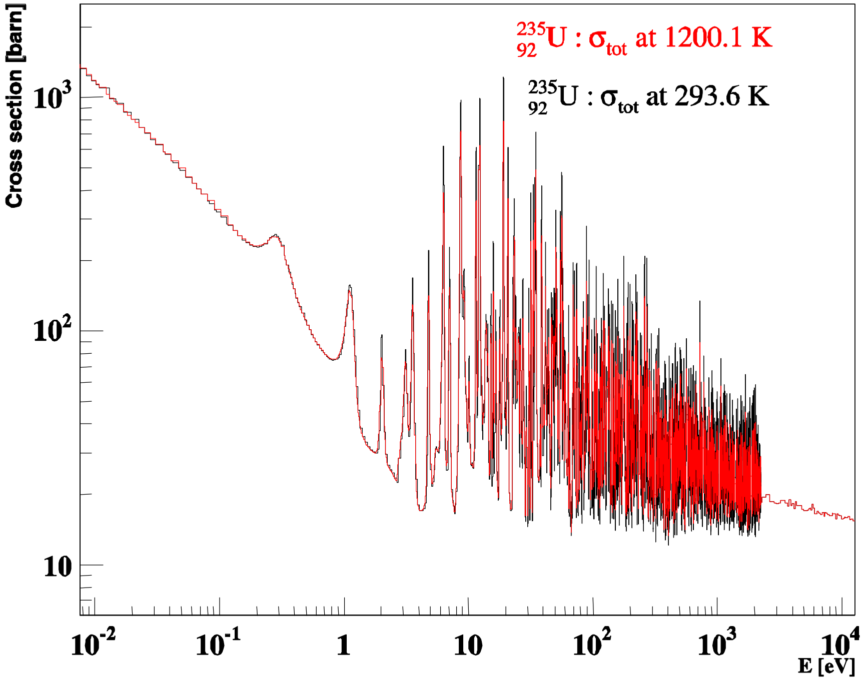


Reaction rates in the Core: Short time scales



PhD Thesis: N. Capellan

Dependence of Cross sections on Temperature

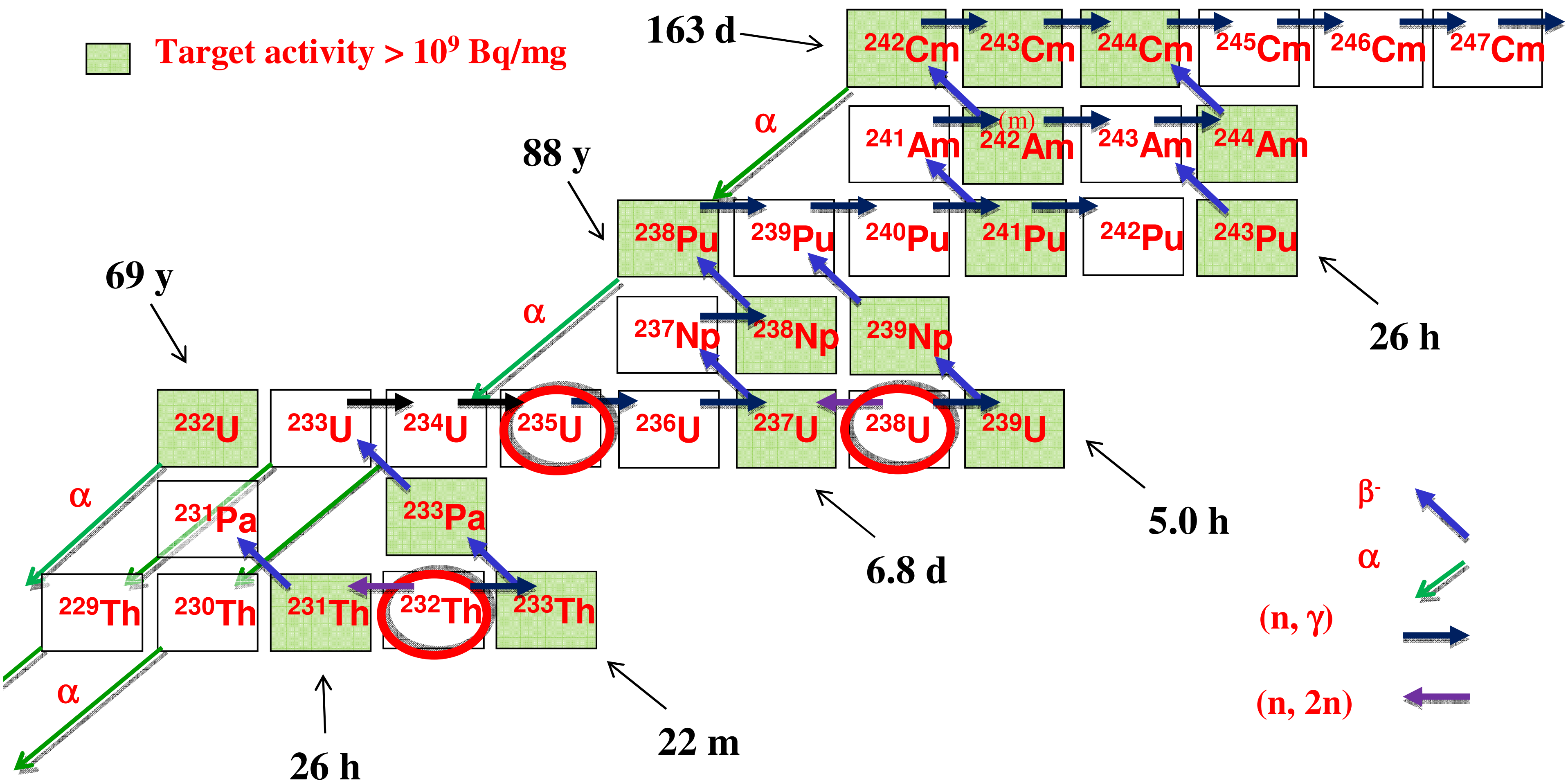


Doppler Broadening of the resonances can be calculated

Neutronics $\rightleftarrows$ ***Thermalhydraulics***

Nuclei where measurements are difficult

🟩 Target activity > 10^9 Bq/mg



Target activities

Nuclide	Target Activity (bq/mg)
^{232}Th	5.88
^{243}Am	1.01e+07
^{241}Am	1.83e+08
^{233}Pa	1.11e+12

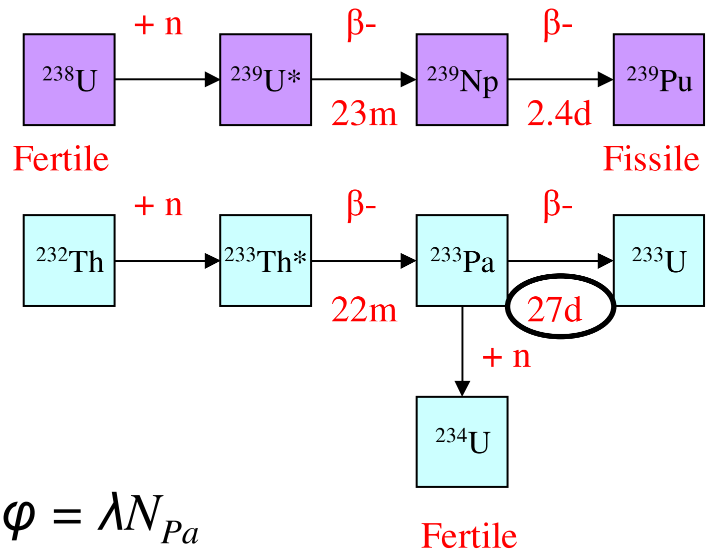
(nTOF facility limited to 800 bq activity maximum for ~100 mg of target material !)

Nuclei at equilibrium

$T_{1/2}$ << Fuel Irradiation Time ~ 3-5 years

Uranium/ Plutonium Cycle

Thorium/ Uranium Cycle



At equilibrium: $N_{Th}\sigma_{Th}\varphi = \lambda N_{Pa}$

Rate of production of ^{234}U: $dN_{U4}/dt = N_{Pa}\sigma_{Pa}\varphi$

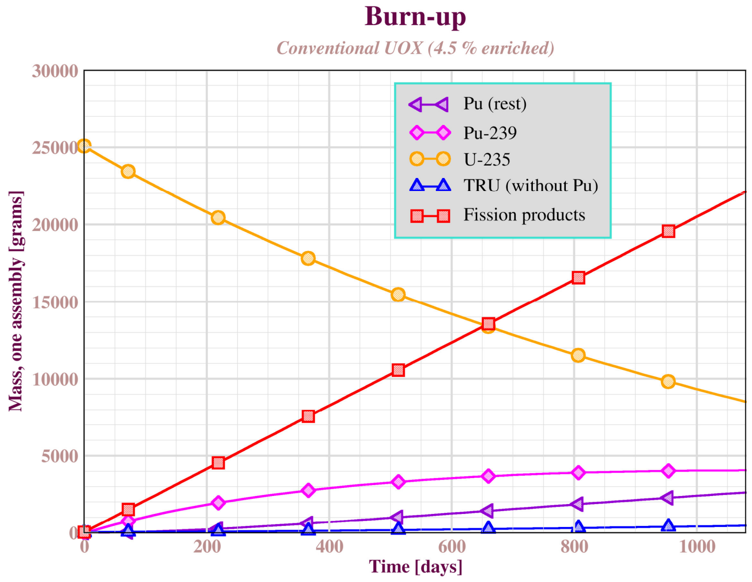
$$\boxed{dN_{U4}/dt = \frac{N_{Th}\sigma_{Pa}\,\sigma_{Th}\,\varphi^2}{\lambda}}$$

It is tempting to conclude:

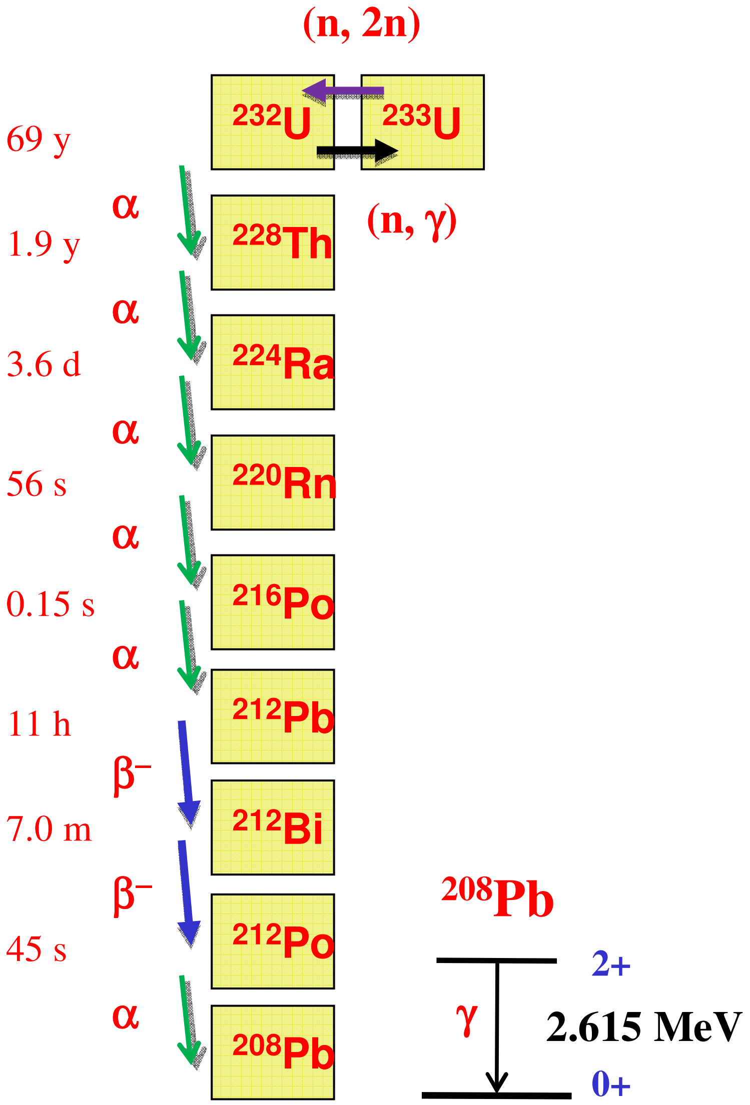
The importance of a given nucleus ~ Mass present in the core
Which for nuclei at equilibrium: ~ $1/\lambda$ ~ $T_{1/2}$

PWR Reactor core inventory at BOC and EOC

	t=0	t=3 y
^{238}U	26328	25655
^{235}U	954	280
^{236}U	0	111
Pu	0	266
Np, Am, Cm	0	20
FP	0	946



Important short-lived nuclei



(n, 2n)

^{232}U ← ^{233}U

^{232}U → ^{233}U (n, γ)

69 y — ^{232}U

α

1.9 y — ^{228}Th

α

3.6 d — ^{224}Ra

α

56 s — ^{220}Rn

α

0.15 s — ^{216}Po

α

11 h — ^{212}Pb

β−

7.0 m — ^{212}Bi

β−

45 s — ^{212}Po

α

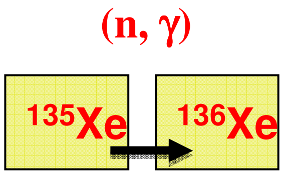
^{208}Pb

^{208}Pb

2+

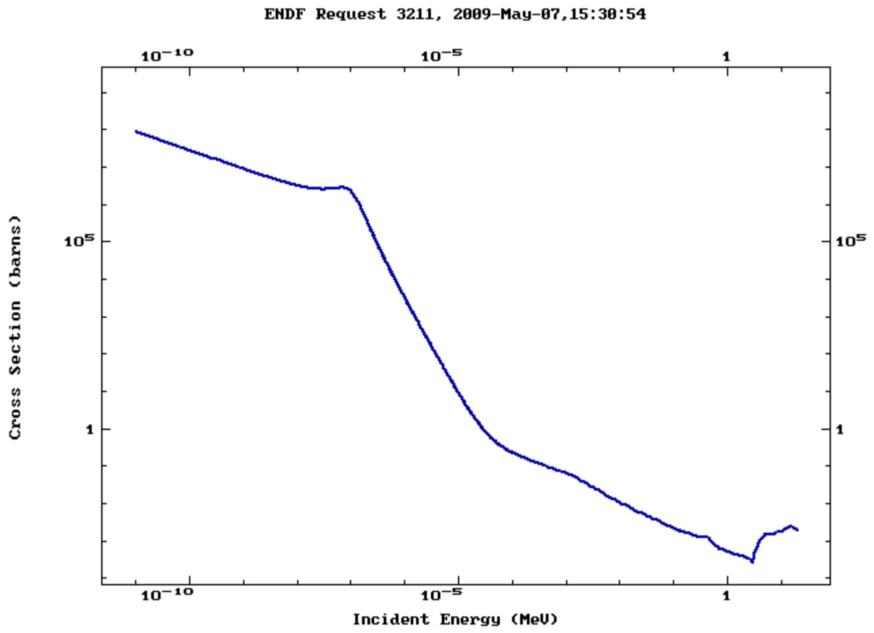
γ 2.615 MeV

0+



(n, γ)

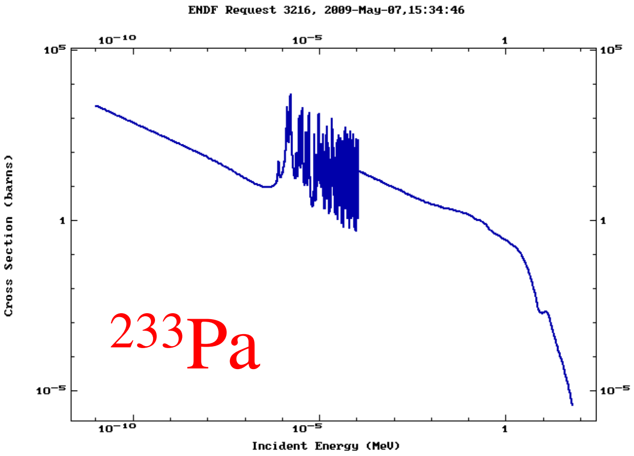
^{135}Xe → ^{136}Xe



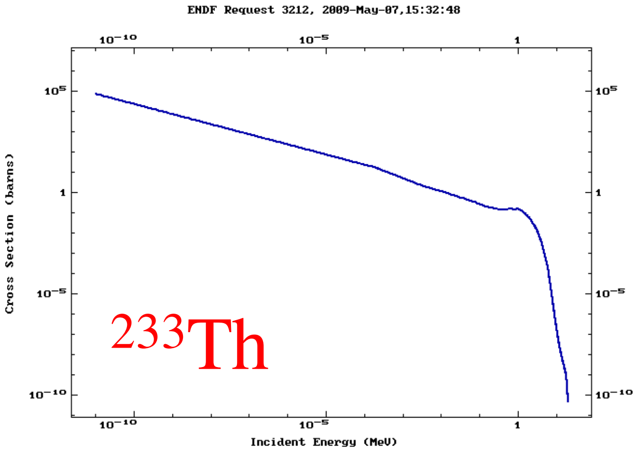
Limitations of Nuclear Data

For certain nuclei, x-section data are:

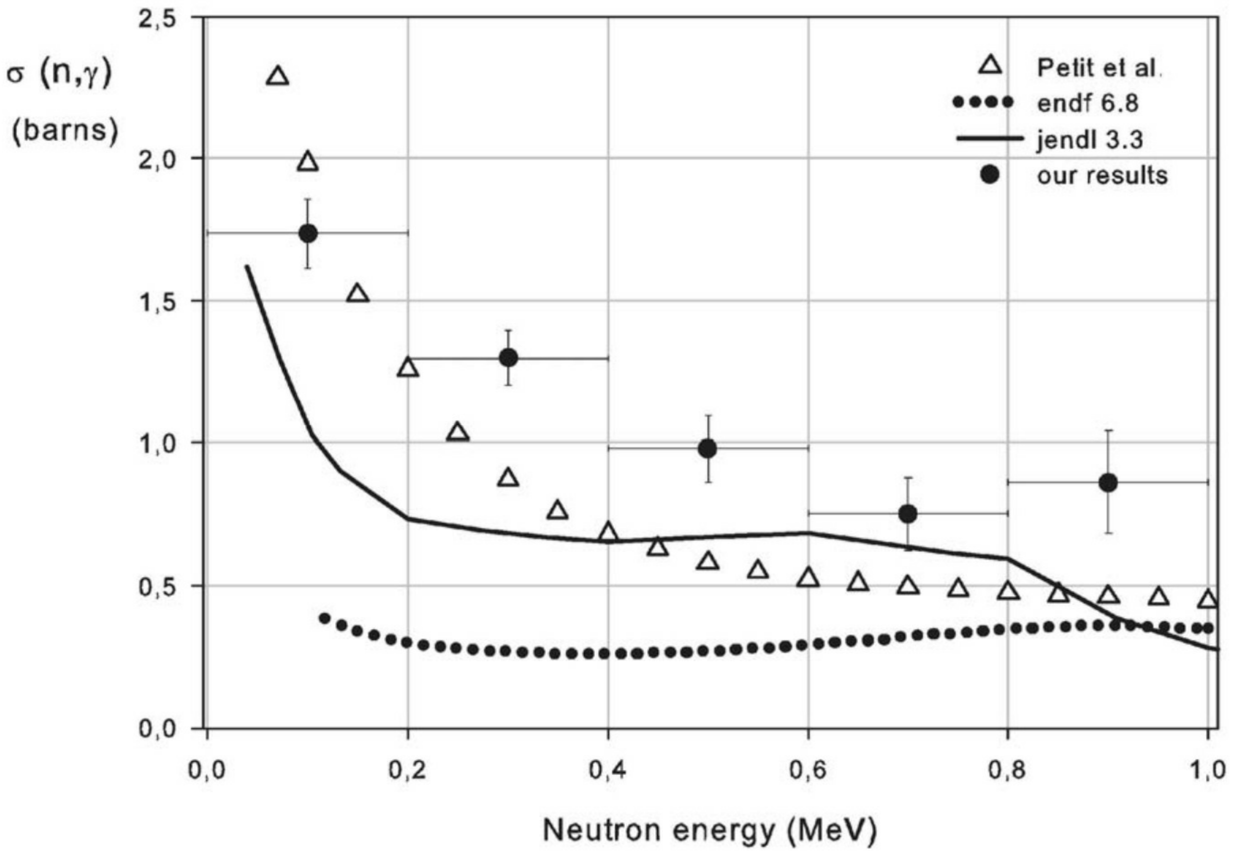
- Sparse (limited energy range)
- Large uncertainties (> 20%)
- Evaluated data bases rely heavily on theory and extrapolations



For some nuclei there is no experimental data available: Evaluated data bases rely entirely on theory



^{233}Pa Capture Experiment Results



S. Boyer et al. Nucl.Phys. A775, 175 (2006)

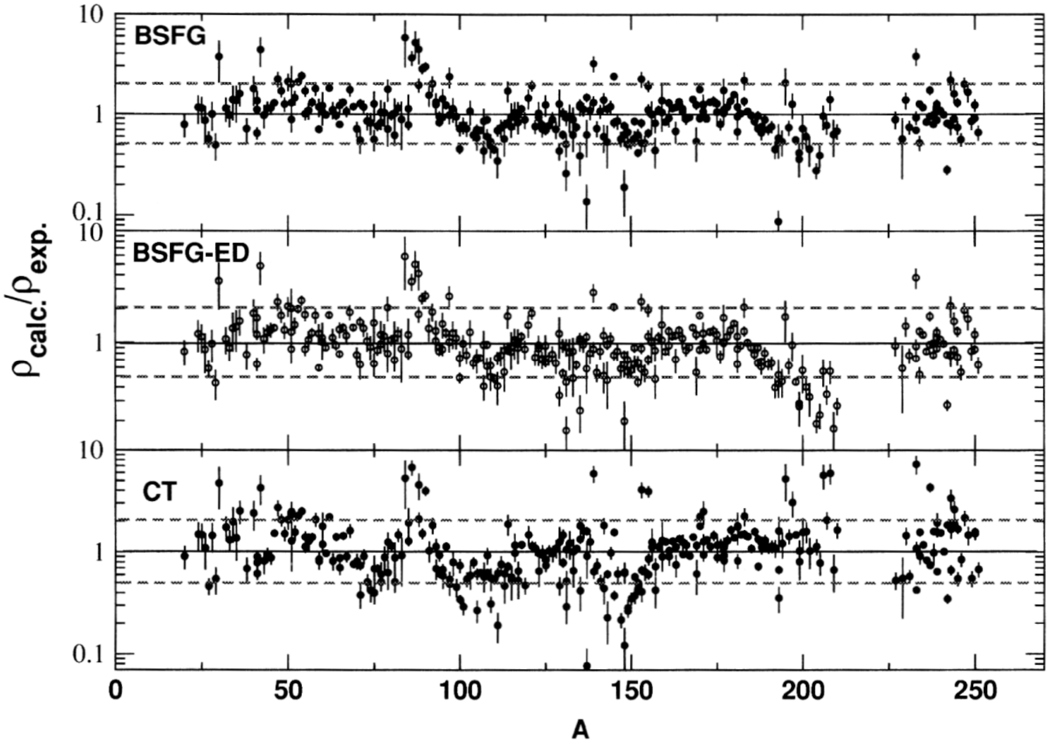
Hauser-Fessbach Formalism

a ⟶ **b**

$$\frac{d\sigma}{d\varepsilon_b}(\varepsilon_a,\varepsilon_b) = \sum_{J\pi} \sigma^{\mathrm{CN}}(\varepsilon_a)\,\frac{\sum_{I\pi} \Gamma_b(U,J,\pi,E,I,\pi)\,\rho_b(E,I,\pi)}{\Gamma(U,J,\pi)}$$

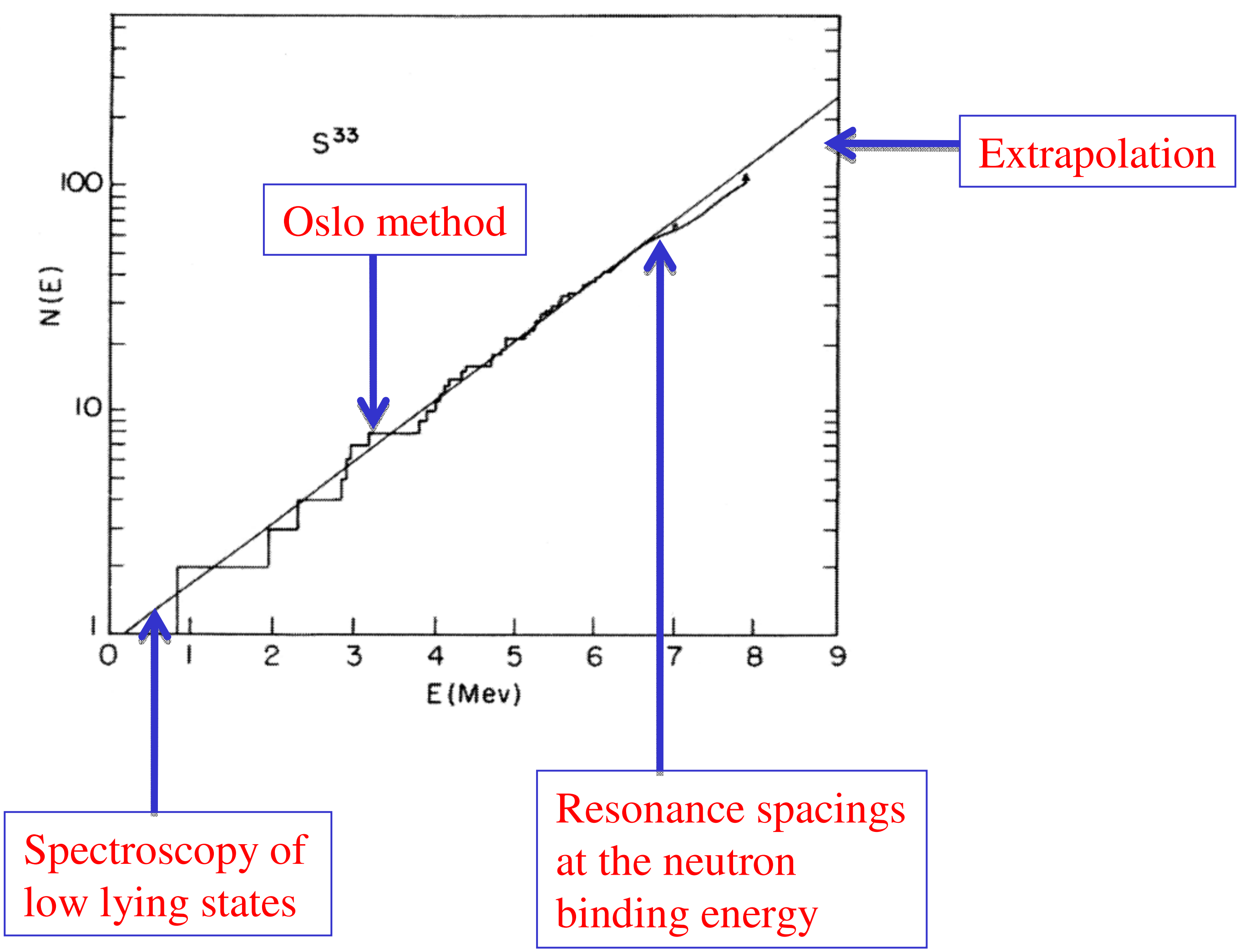
Differential cross section depends on transmission coefficients, **Γ** and level densities of the residual nuclei, ***ρ***

Level Densities Theory and Experiment



- Level density changes due to collectivity, deformation etc.
- Large effects can occur over a small number of nucleons

Level Density Measurements



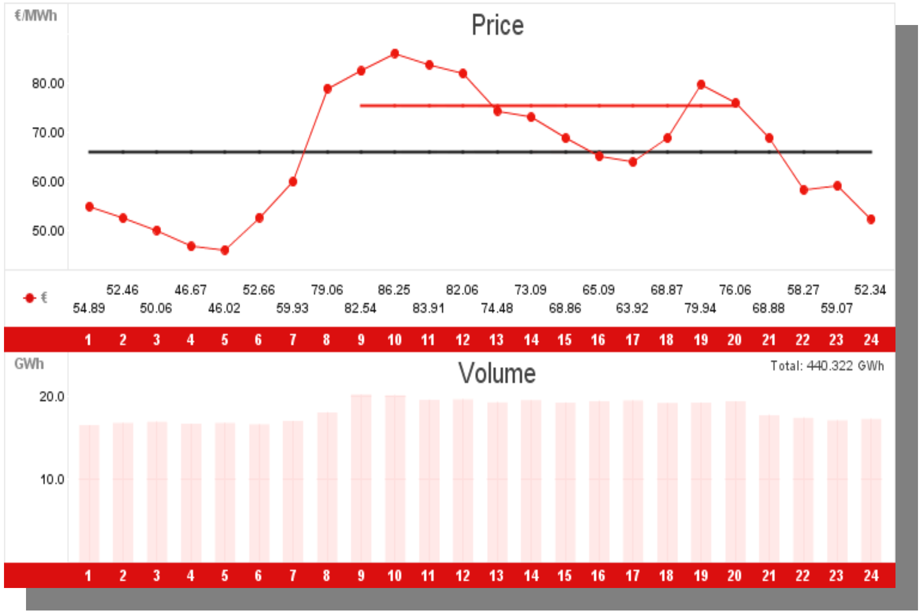
Oslo method

Extrapolation

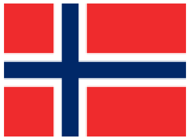
Spectroscopy of low lying states

Resonance spacings at the neutron binding energy

Norway, Nuclear Power and Thorium

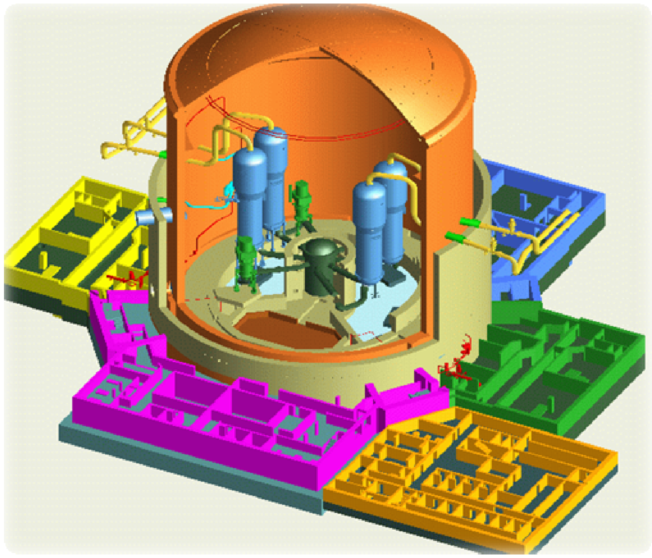


European Energy Exchange Spot Electricity prices – 13-02-08



- Baseload from hydro power (110 TWh in 2004 out of 120 TWh total)
- Occasional electricity imports from Europe (coal)

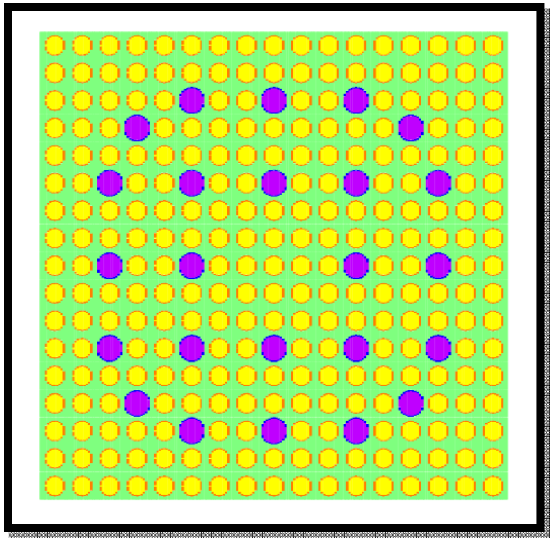
I: Introduction; The EPR



EPR

(European Pressurized water Reactor)

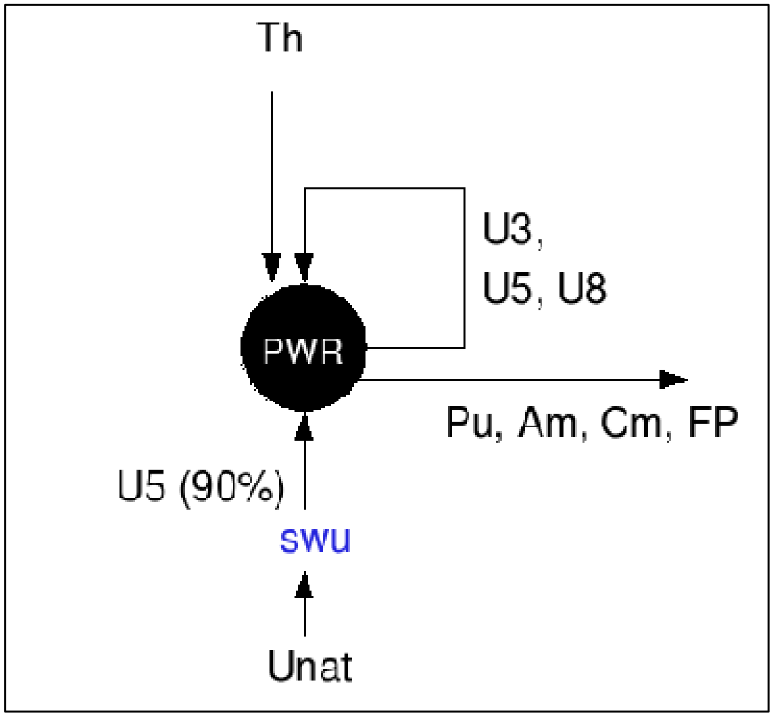
- 3rd generation PWR
- 1600 MWe, 241 assemblies
- Cycle length 18-24 months
- Burnable Gd_2O_3 poison for longer burn-up
- MOX compatible
- Flexible fuel loading
- Availability of 92 % of service life
- Technical service life of 60 years
- Olkiluoto, Finland (2010?)



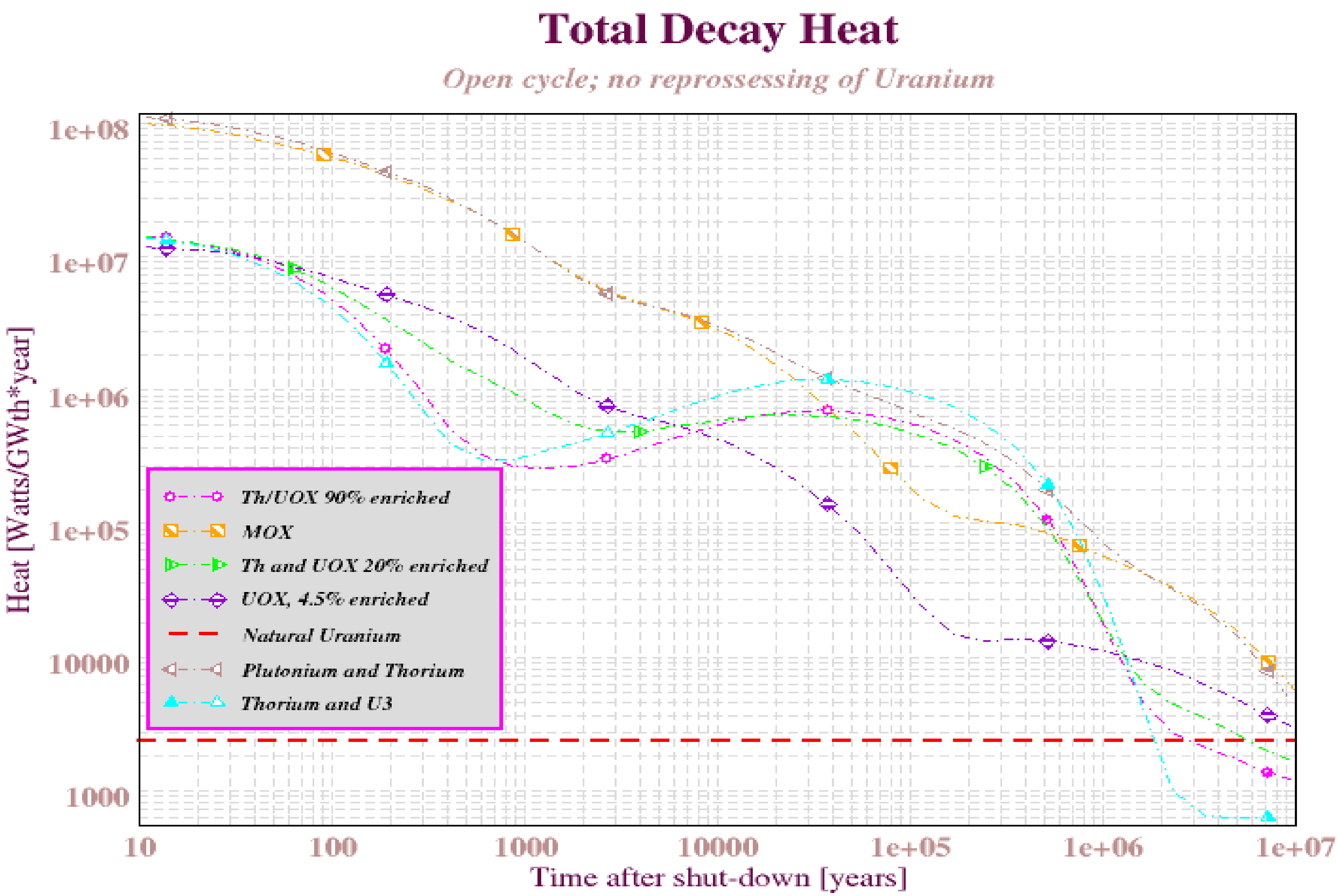
Dependent Thorium Cycle – Possibilities

Norway has the world's 3rd largest reserves of Thorium

If Norway built a commerical power reactor could Thorium be used?
What is the simplest way to incoporate Thorium into the fuel cycle?

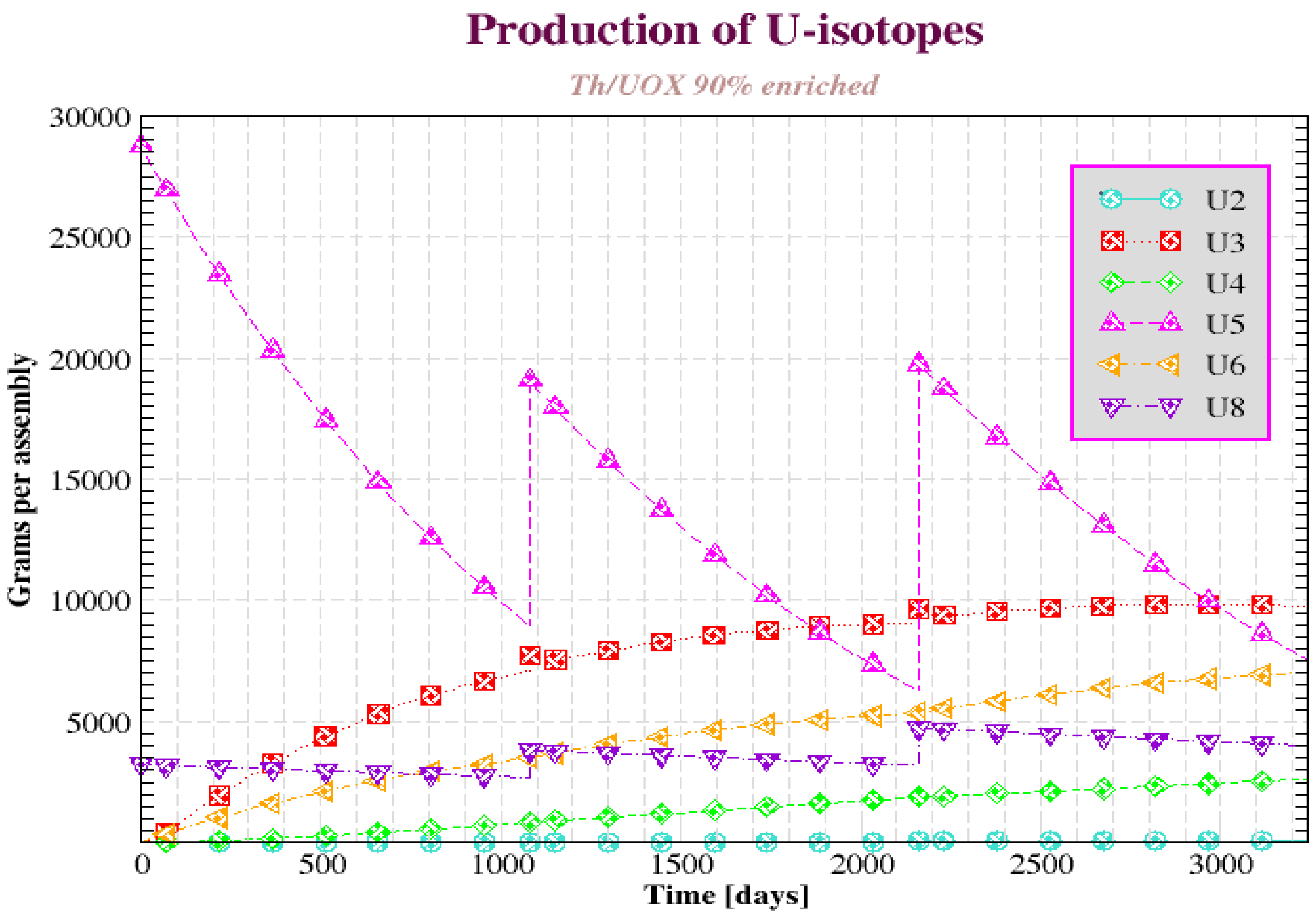


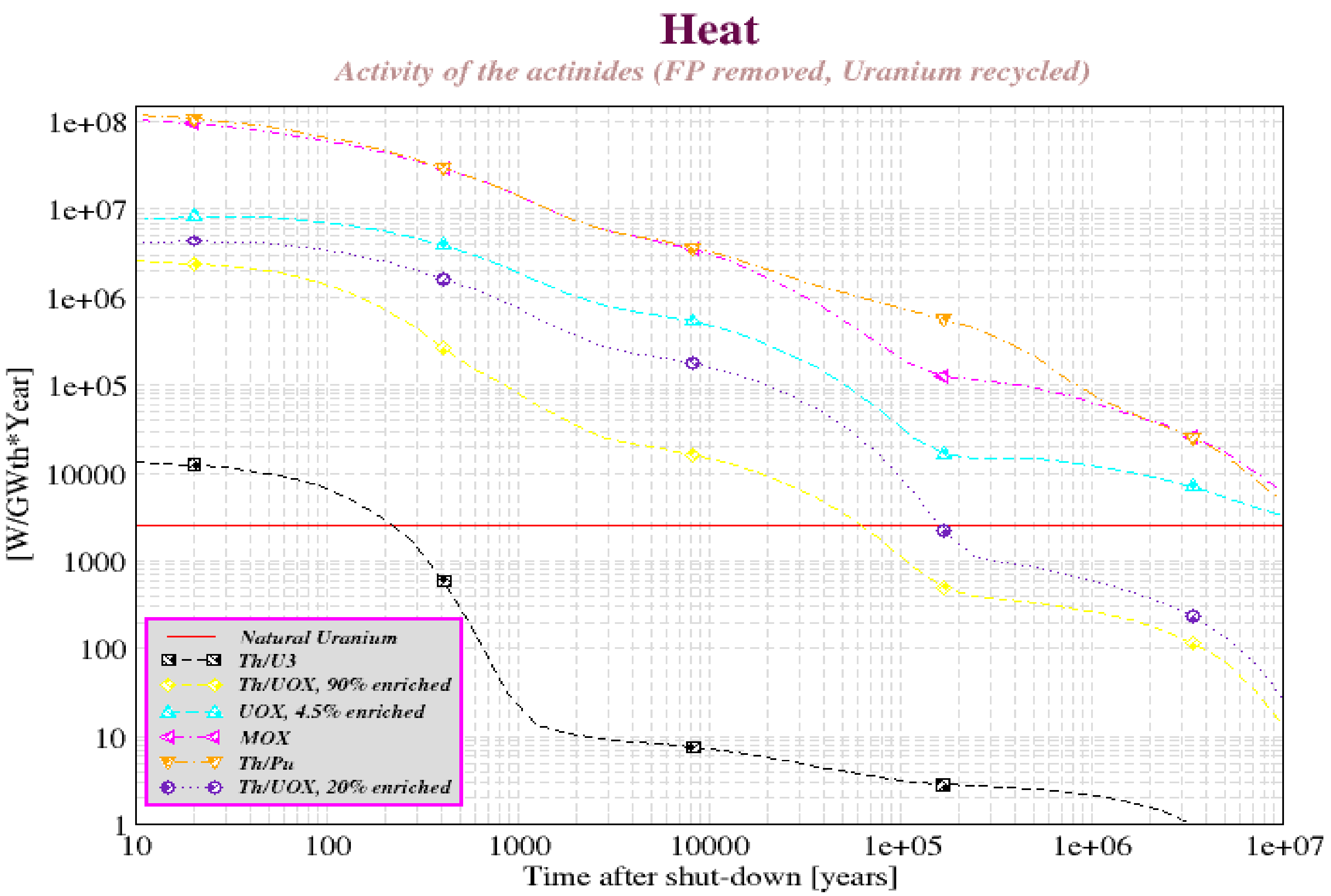
- **Remove ^{238}U waste precursor and replace with Th**
- **Multi-recycle the Uranium vector (Masters Thesis: Sunniva Rose)**



Total Decay Heat

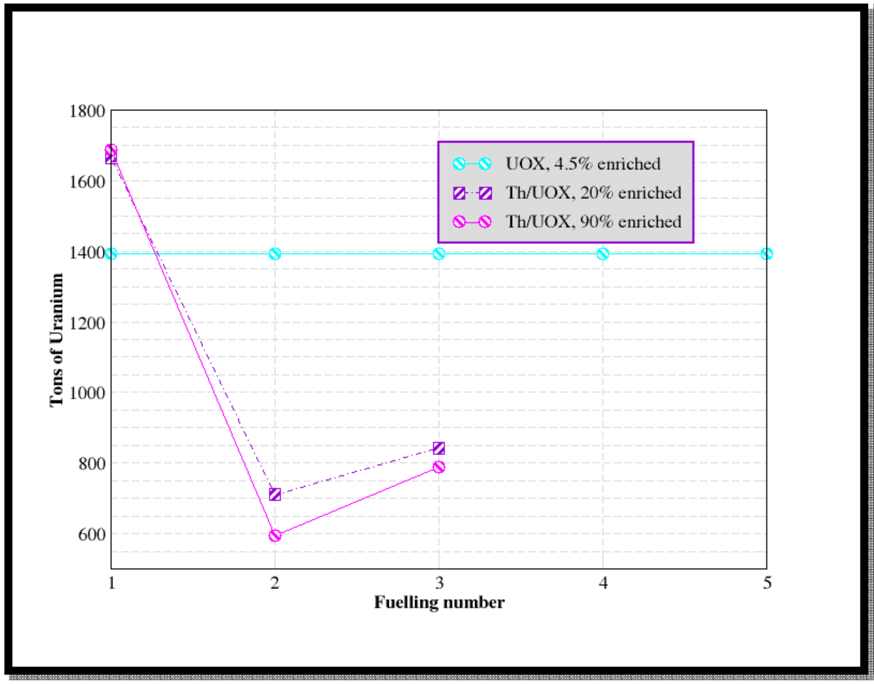
Open cycle; no reprossessing of Uranium


Production of U-isotopes
Th/UOX 90% enriched
Grams per assembly
30000
25000
20000
15000
10000
5000
0
500
1000
1500
2000
2500
3000
Time [days]
U2
U3
U4
U5
U6
U8

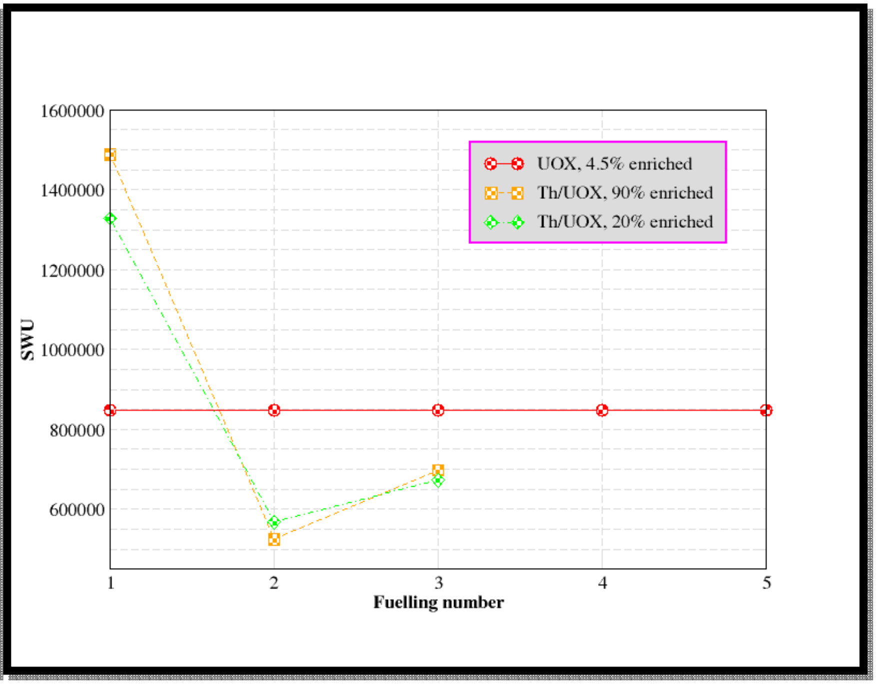

Heat
Activity of the actinides (FP removed, Uranium recycled)
[W/GWth*Year]
1e+08
1e+07
1e+06
1e+05
10000
1000
100
10
1
10
100
1000
10000
1e+05
1e+06
1e+07
Time after shut-down [years]
Natural Uranium
Th/U3
Th/UOX, 90% enriched
UOX, 4.5% enriched
MOX
Th/Pu
Th/UOX, 20% enriched

Inventories and Economics

Tons Unat



SWU



Over a 60 year life-time the reactor will need:

- UOX: ~**28 000** tons of Uranium, ~**17 M** SWU
- Th/UOX 90% enriched: ~**15 000** tons of Uranium, ~**13.8 M** SWU
- Th/UOX 20% enriched: ~**17 000** tons of Uranium, ~**13.0 M** SWU

Advantages

- Reduction in MA waste
  - Less decay heat
- Use of local natural resource (Norway)
- High U-233 fissile content in the spent fuel
  - Multircycling desirable
- Spent fuel U2/3/4/5/6/8 is proliferation resistant

Disadvantages

- Higher (initial) fuel cost
  - Spent Uranium must be handled remotedly
- Possible proliferation concerns (HEU)
- Pa-233 reactivity effects on safety
- Breeding not possible

The Thorium fuel-cycle

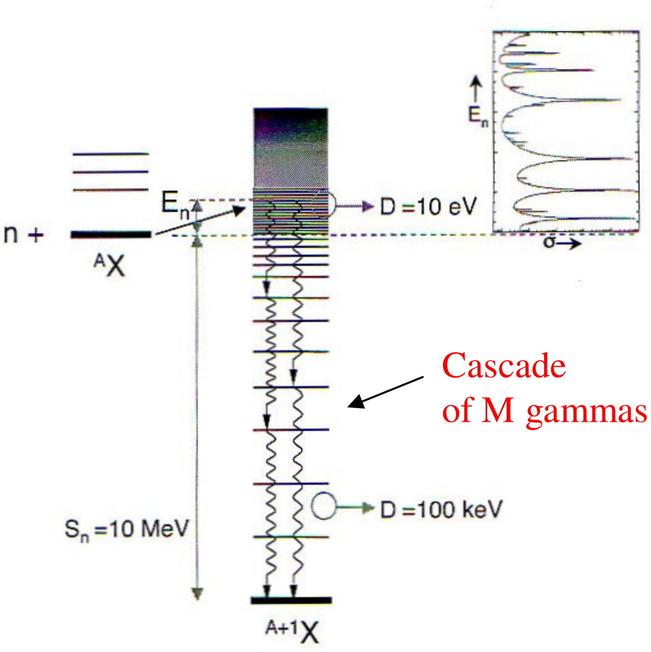
Dependent Th-cycle

- Extra fissile (U5/Pu) needed
  - Dependent of the U-cycle
- Mining of Uranium still necessary
  - U5+Th2 → Pa3 → U3
- U-233 fissions and contributes to total energy production
- CR always less than 1

Independent Th-cycle

- Regenerates its own fissile (U-233) from the Thorium
- CR bigger than 1
- No extra fissile needed
- No mining of Uranium necessary

Neutron capture measurements



Cascade
of M gammas

The neutron capture process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Nuclear Instruments and Methods in Physics Research A 511 (2003) 388–399

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Measurements of (n, γ) neutron capture cross-sections with liquid scintillator detectors

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If the detector had THIS property…

$$\boxed{\varepsilon = kE_\gamma}$$

$$\varepsilon_c = 1 - \prod_{j=1,\dots,m} (1 - \varepsilon_j)$$

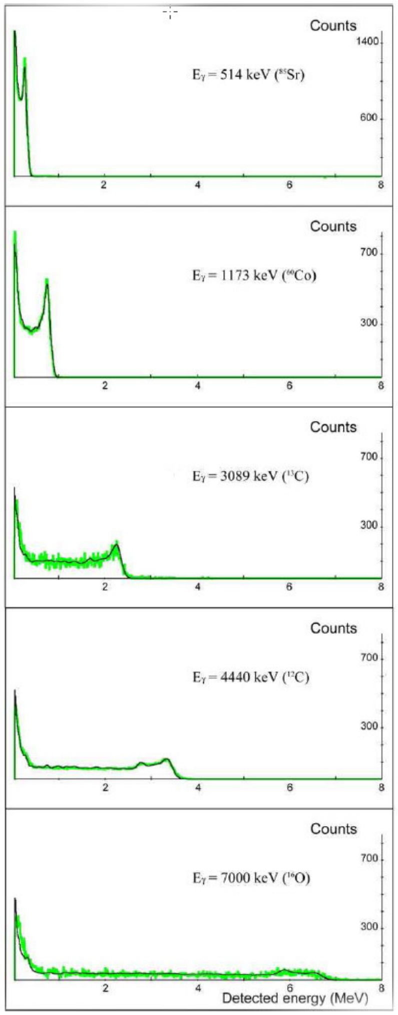
Efficiency of detecting a
Cascade of M gammas

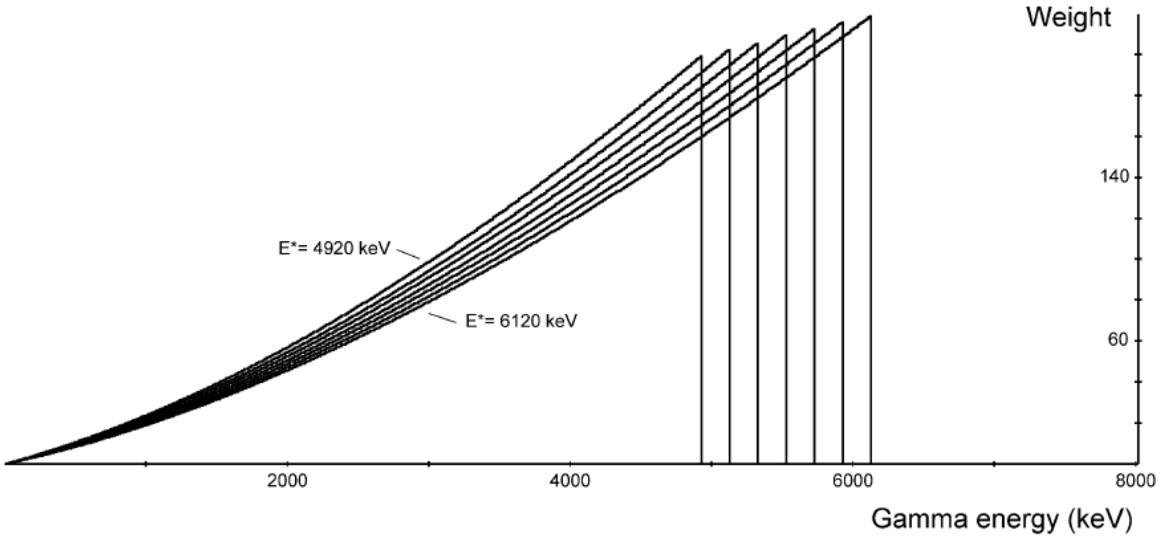
$$\varepsilon_c = k \sum_{j=1,\dots,m} \varepsilon_j = kE_c.$$

$$\varepsilon_c \approx \sum_{j=1,\dots,m} \varepsilon_j$$

(if efficiency is low)

…then efficiency of detecting the cascade
is proportional to cascade total cascade energy,
which is constant





$$\sum_i R(E_i, E_j) = \varepsilon(E_j)$$

Actual detector response

$$\sum_i W(E_i) R(E_i, E_j) = kE_j$$

It is possible to find weighting functions, $W(E_i)$ which give the detector the desired response