

Lab Course on Reactor Operation and Nuclear Chemistry

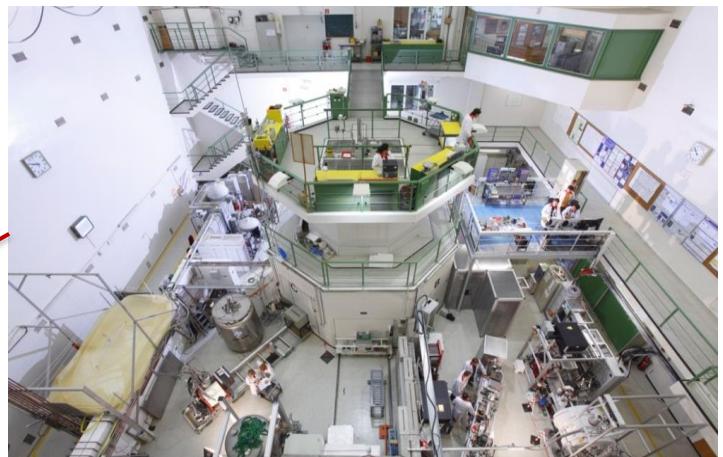
K. Eberhardt and C. Geppert



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

- Research Reactor TRIGA Mainz
- Education and Training at the TRIGA Mainz
- Lab Course on Reactor Operation and Nuclear Chemistry

Two Research Reactors in Germany



TRIGA Mainz (100 kW)



FRM II, Munich (20 MW)



- Founded in **1477**
- 1508: about 200 students
- 1792: most faculties closed
- **1818: last lectures took place**



- **May, 15th 1946:** Johannes Gutenberg-Universität (re)founded ⇒ 1947: more than 4200 students
- **2023:** 31000 students from 130 nations
2900 scientists
150 Institutes on Campus + University Hospital



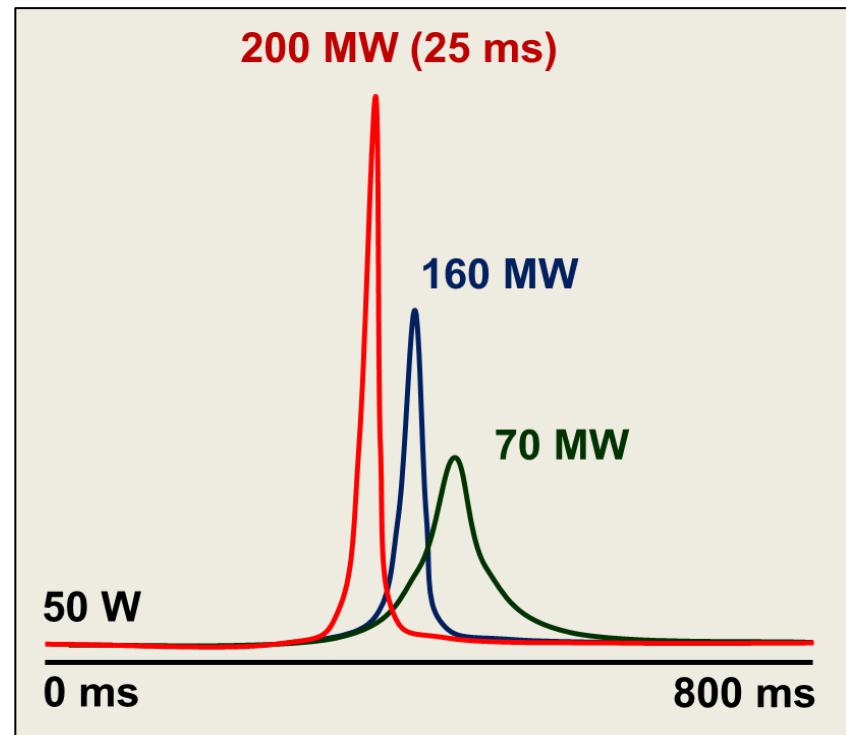
TRIGA Mainz

- Steady state power: $100 \text{ kW}_{\text{th}}$
- Pulse mode : $200 \text{ MW}_{\text{th}}$ (25 ms)
- **3rd of August 1965: First criticality**
- Normally one-shift operation
- 12 weeks per year two-shift operation (UCN-sources)

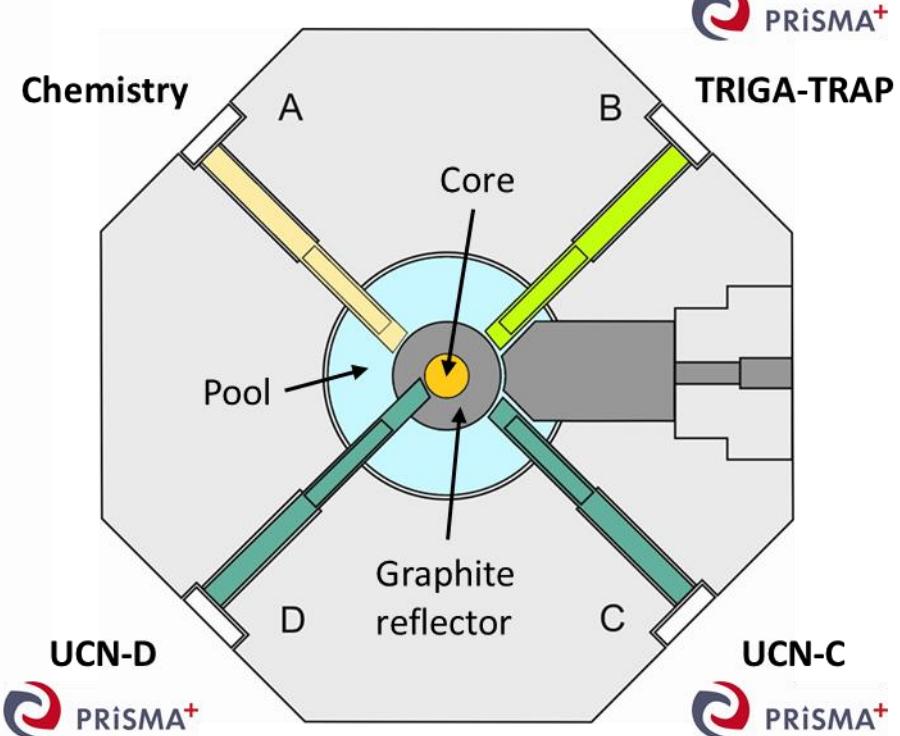
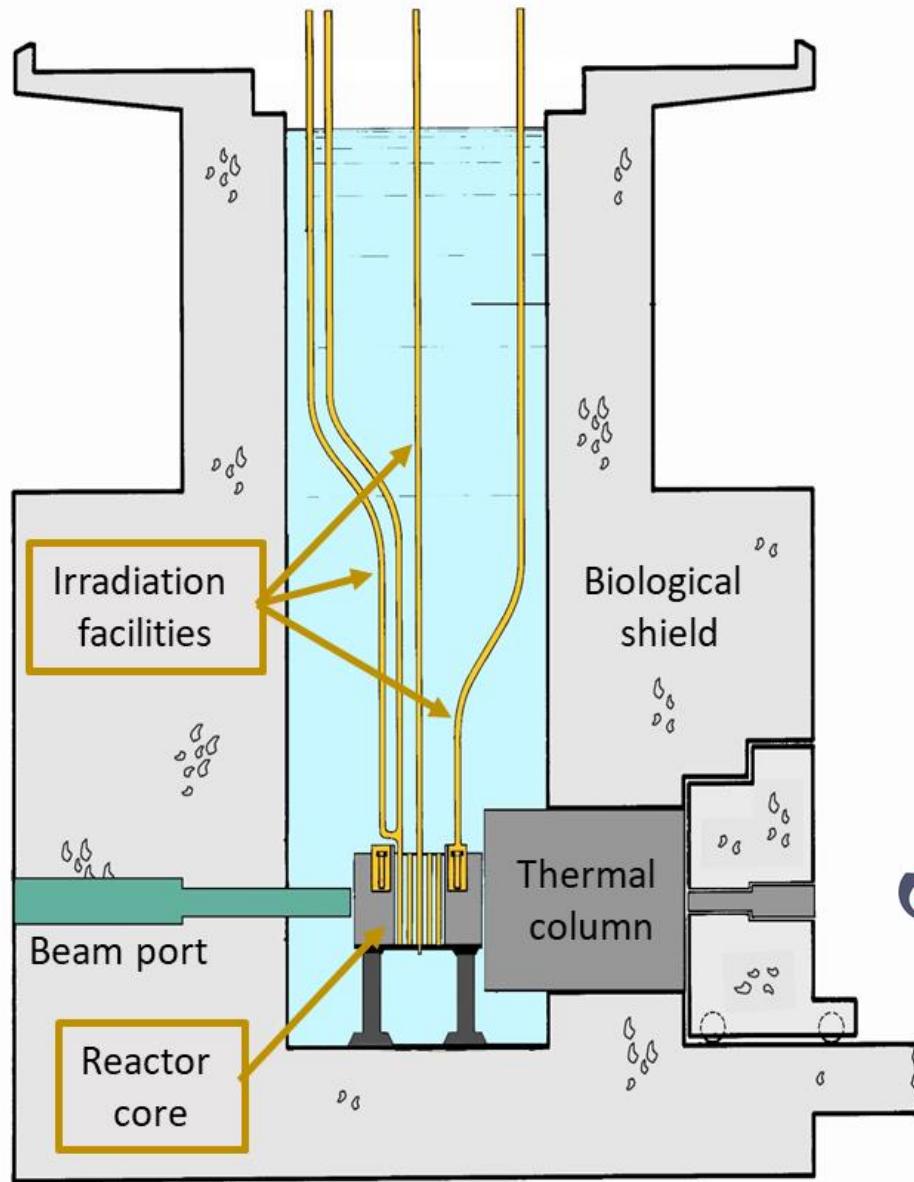


27454 Pulses since 1965

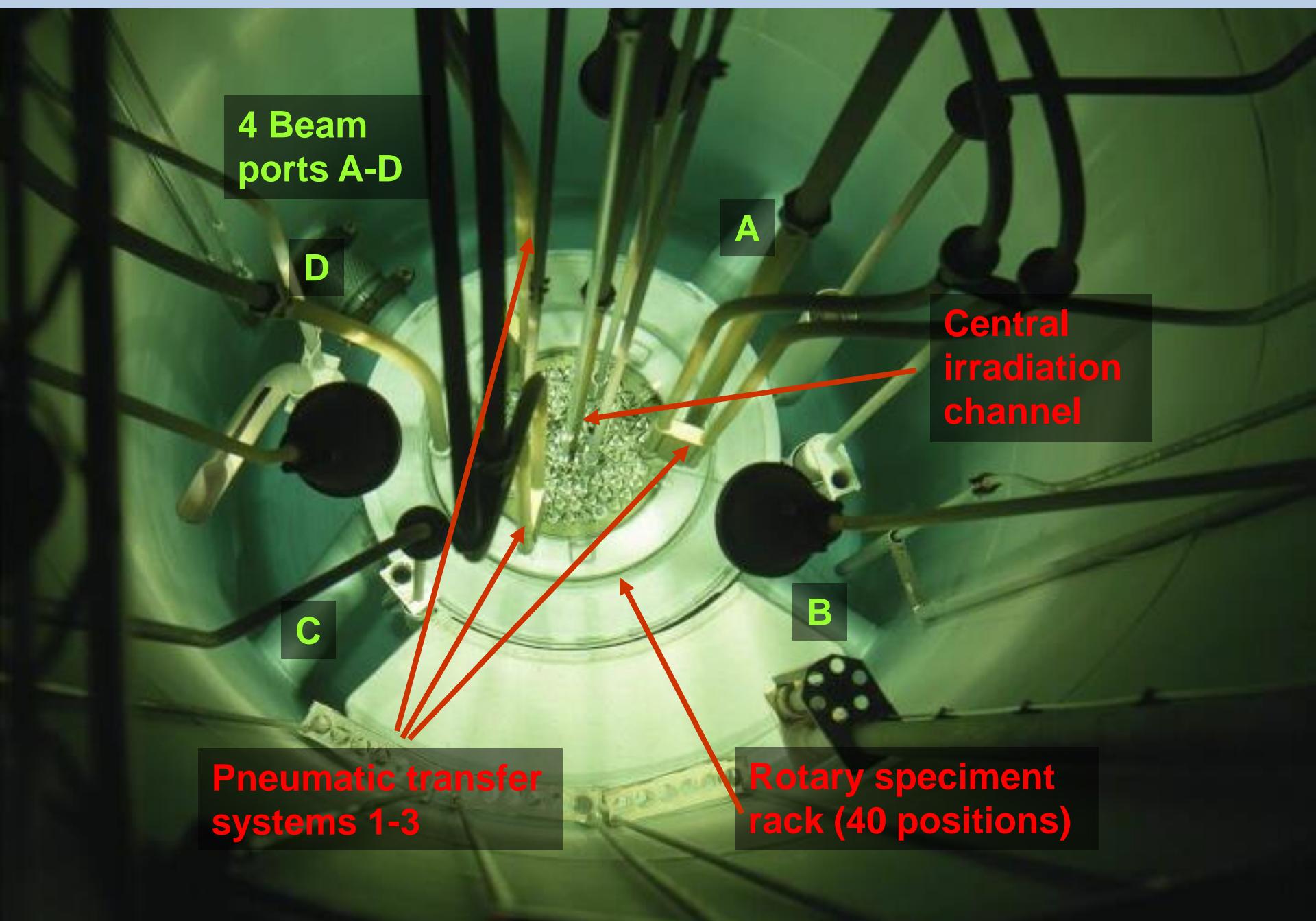
- Excess reactivity up to 2 \$
- $200 \text{ MW} / 25 \text{ ms} / 10^{15} \text{ cm}^{-2}$



TRIGA Mainz



TRIGA Mainz



Applications TRIGA Mainz

Fundamental research

- Chemistry of the heaviest elements (beam port A)
- Penning Trap Mass Spectrometry of exotic nuclei (beam port B)
- Experiment with ultra-cold neutrons - UCN (beam ports C+D)
- Neutron absorption cross section measurements (rabbit system, lazy susan)

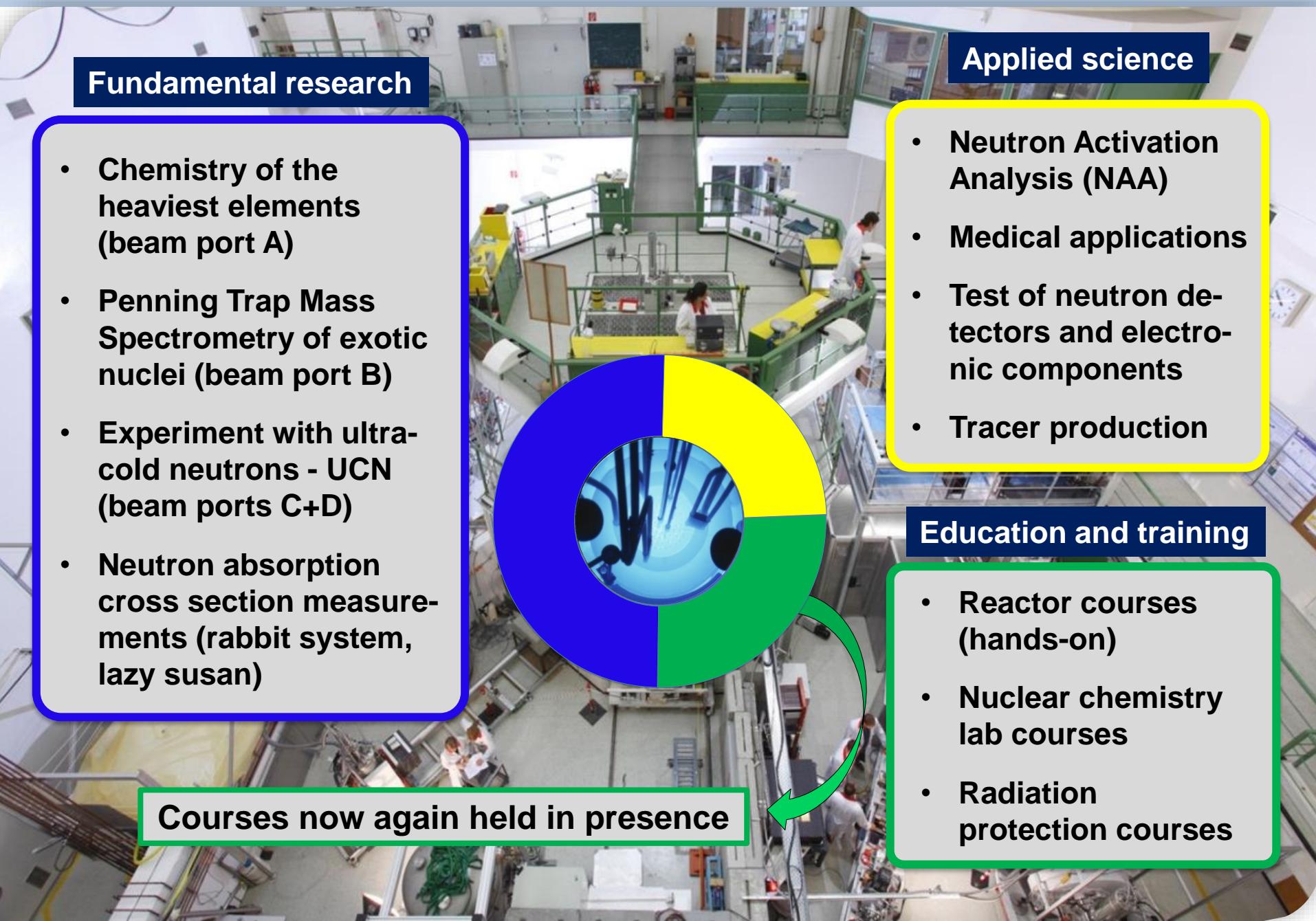
Applied science

- Neutron Activation Analysis (NAA)
- Medical applications
- Test of neutron detectors and electronic components
- Tracer production

Education and training

- Reactor courses (hands-on)
- Nuclear chemistry lab courses
- Radiation protection courses

Courses now again held in presence



Education and Training

PhD-, Bachelor- and Master-thesis

Chemistry

Physics

Lab courses for students

- Nuclear chemistry I
- Nuclear chemistry II
- Reactor operator course

Chemistry- and Physics magisterium

Radiation protection at schools

Other training courses

- Radiation protection (RP)
- Requisite qualification course on radiation protection at schools
- Operator training for future reactor operators
- RP training for fire fighters



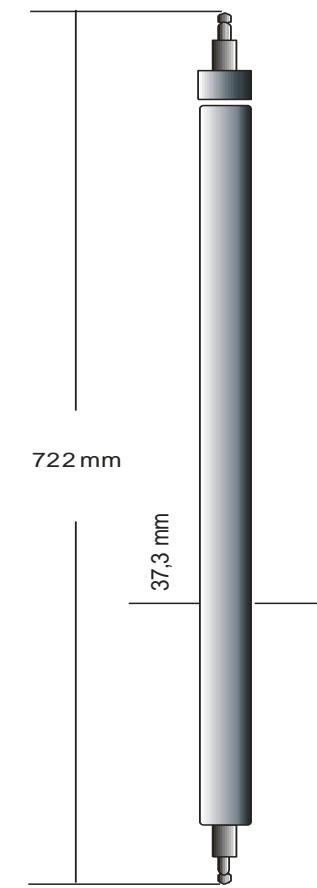
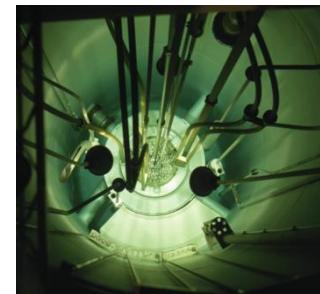
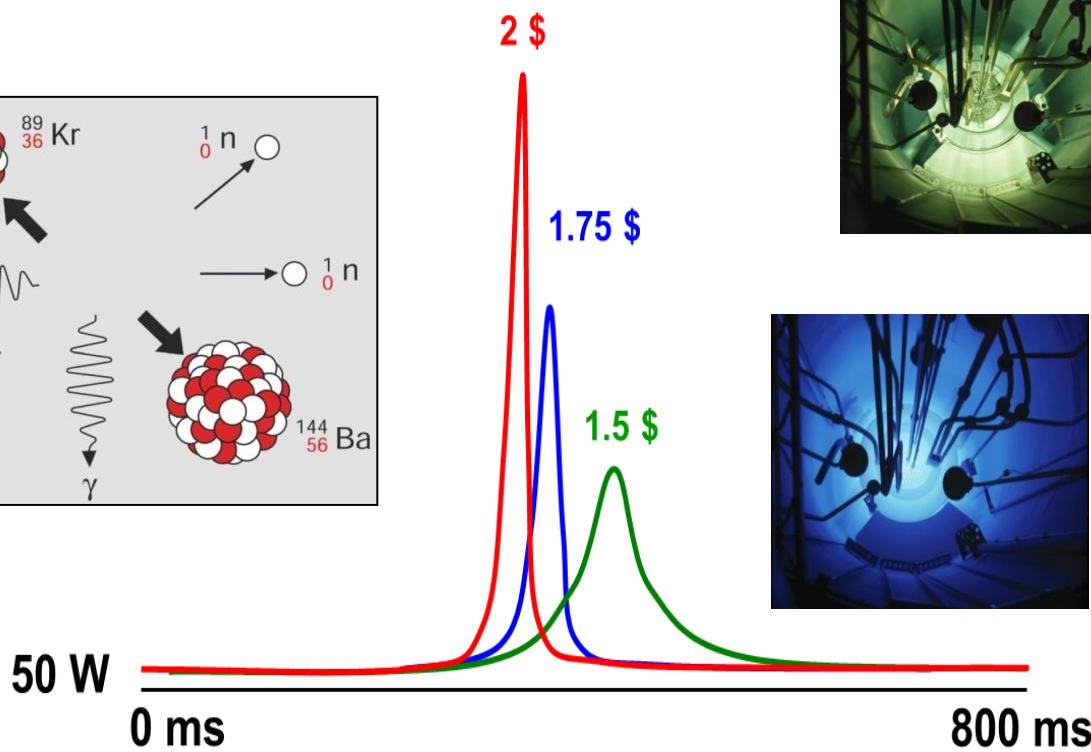
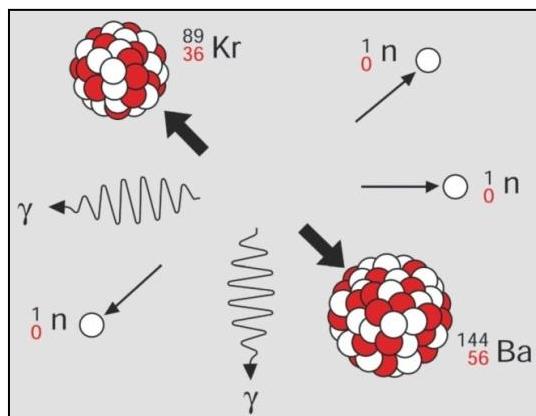
Students course within the
EU-project ARIEL

ARIEL

Hands-on course in Reactor operation and Nuclear Chemistry (1 week)

Hands-on course in reactor operation and -physics

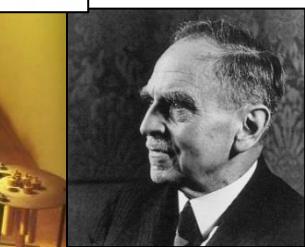
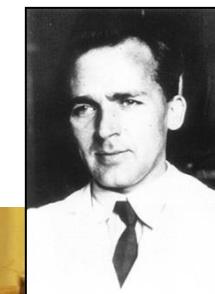
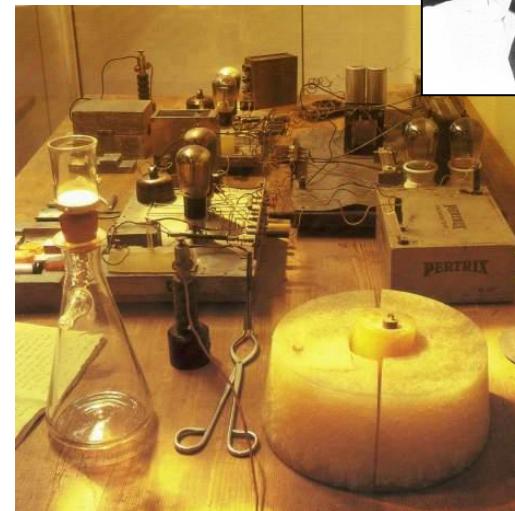
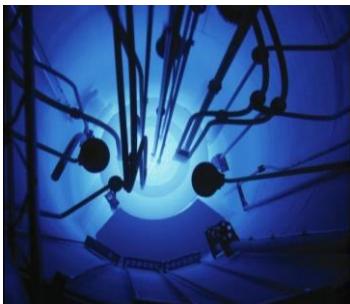
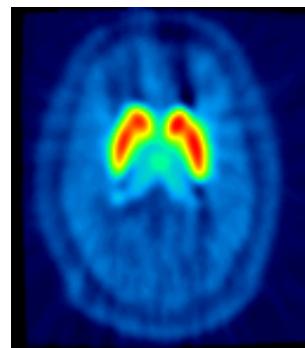
- Reactor operation in steady state and pulse mode,
- Calibration of a control rod
- Neutron flux measurements
- Optical inspection of the reactor pool and of fuel elements
- Reactivity effect of Cd-samples



Practical course in nuclear chemistry and -physics

Based on the course “**Praktische Radiochemie**” by Otto Hahn at the KWI

- Radioactive decay including mother-daughter equilibria,
- α -, β -, γ -spectroscopy , neutron detection
- Application of radioactivity in life sciences and medicine (PET)
- Neutron Activation Analysis (INAA, RNAA, DNAA)
- Fission: Radiochemical separation of Ba
- Application of radiotracers
- Chemistry of neptunium



For ARIEL: Fusion of the two courses. Selected experiments combined to a one week training course for 10 students

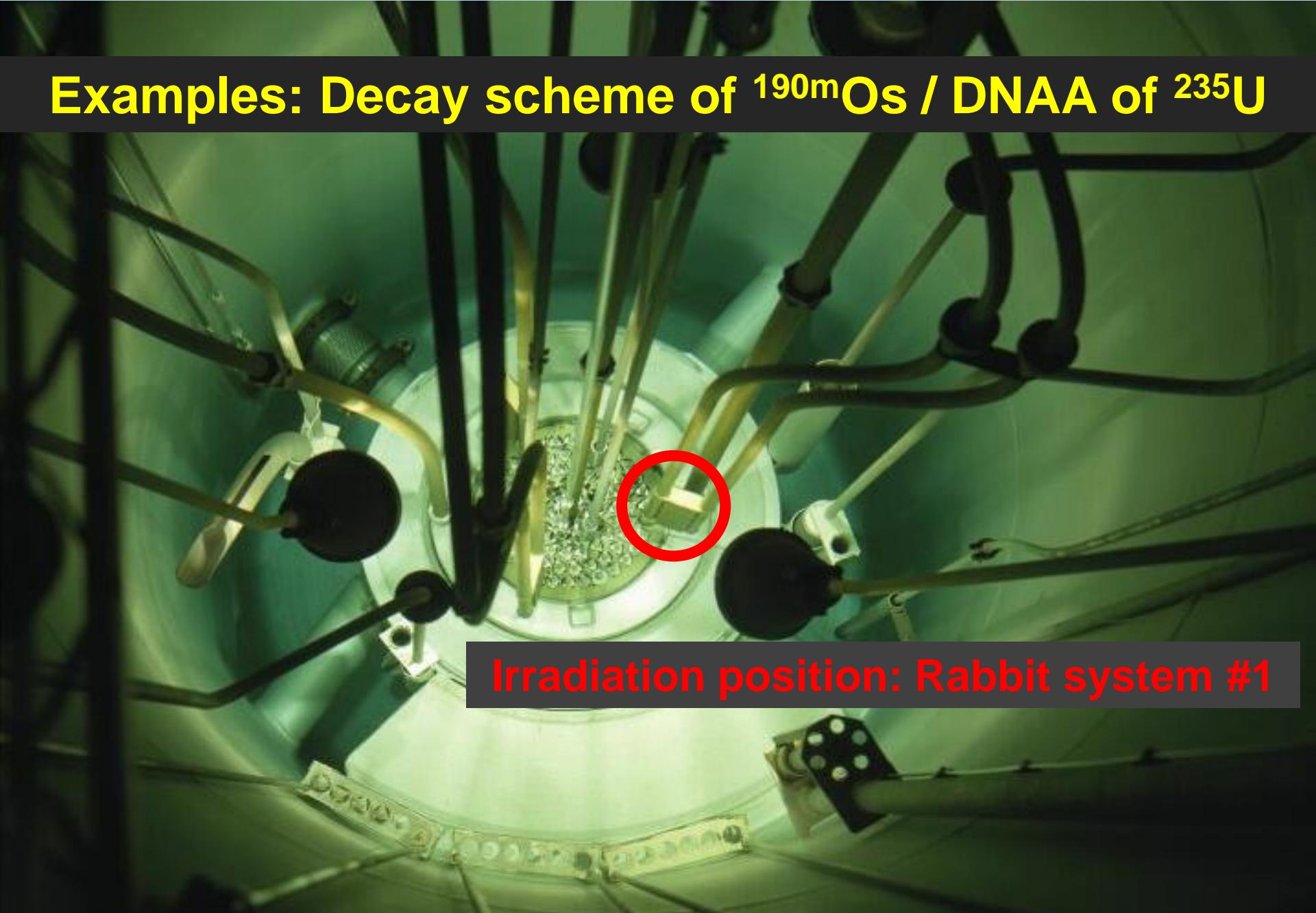
- Lecture: The discovery of nuclear fission (T. Reich, JGU)
- Lecture: Application of research reactors (N. Pesseo-Barradas, IAEA)
- Lecture: Neutron activation for nuclear astrophysics studies (T. Heftrich, Univ. Frankfurt)
- Lecture: The Oklo reactor (N.N.)

- Reactor operation in steady state and pulse mode
- Calibration of a control rod
- Optical inspection of the reactor pool and of fuel elements
- Reactivity effect of Cd-samples

- Chemical confirmation of nuclear fission: Radiochemical separation of Ba (as performed by Hahn and Strassmann)
- Measurement of β -delayed neutrons
- γ -Spectroscopy of Os-190m: Are nuclei rigid rotators?

Reactor operation schedule 2023

Examples: Decay scheme of ^{190m}Os / DNAA of ^{235}U



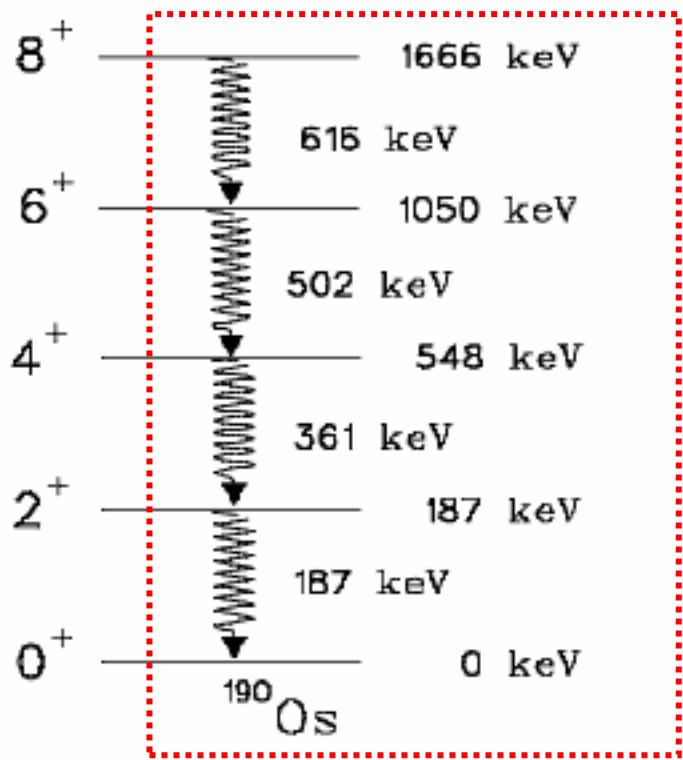
Example: Decay scheme of ^{190m}Os

- (n,γ)-reaction produces ^{190m}Os . $^{190m}\text{Os} \rightarrow ^{190g}\text{Os} + \gamma$
- Low-level excited states correspond to rotational and vibrational excitation of the nucleus
- Rotational energy as a function of total nuclear spin I :

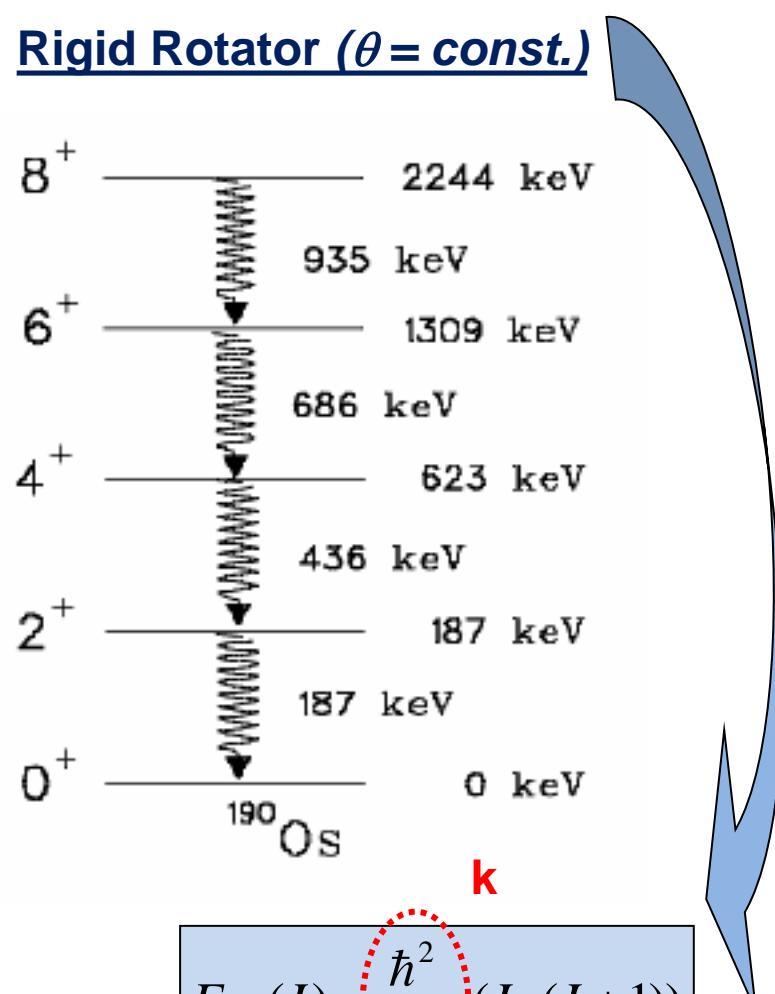
$$E_{rot}(I) = \frac{\hbar^2}{2\theta} \cdot (I \cdot (I + 1))$$

with $I = 0, 2, 4, \dots$ (rigid rotator)

- Irradiation of ^{nat}Os -sample (powder) for 3 min in rabbit system:
Via (n,γ)-reactions production of ^{190m}Os with $T^{1/2} = 9.9$ min.
 - γ -spektroscopy of irradiated sample after 2, 4, 620 min.
 - Peak analysis of the spectra. Identification of ^{190m}Os -levels as determined by half-life-analysis
- ⇒ Determination of $T^{1/2}$ for ^{190m}Os and moment of inertia θ of the ^{190}Os -nucleus for different I

Measured

$^{190\text{m}}\text{Os}$ -nucleus is no rigid rotator

Rigid Rotator ($\theta = \text{const.}$)

$$E_{\text{rot}}(I) = \frac{\hbar^2}{2\theta} \cdot (I \cdot (I+1))$$

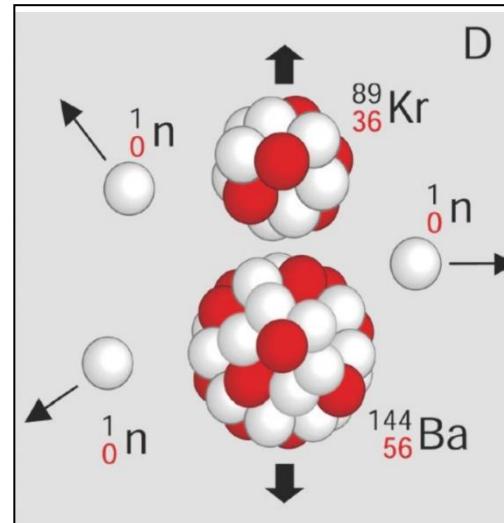
$$\Delta E(I_{n+2} \rightarrow I_n) = k [I_{n+2}(I_{n+2}+1)] - k [I_n(I_n+1)]$$

Example: β -delayed neutrons

Fission of ^{235}U :

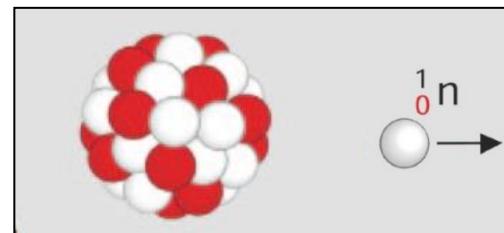
Emission of 2.4 prompt Neutrons per fission event. Time scale: ca. 10^{-15} s

⇒ Prompt neutrons cannot be detected off-line



Fission products:

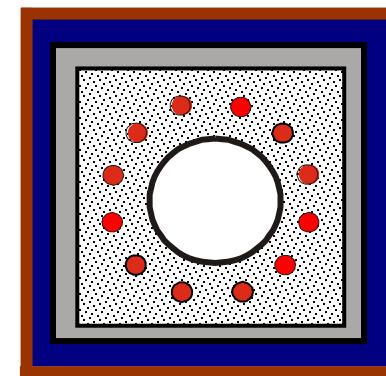
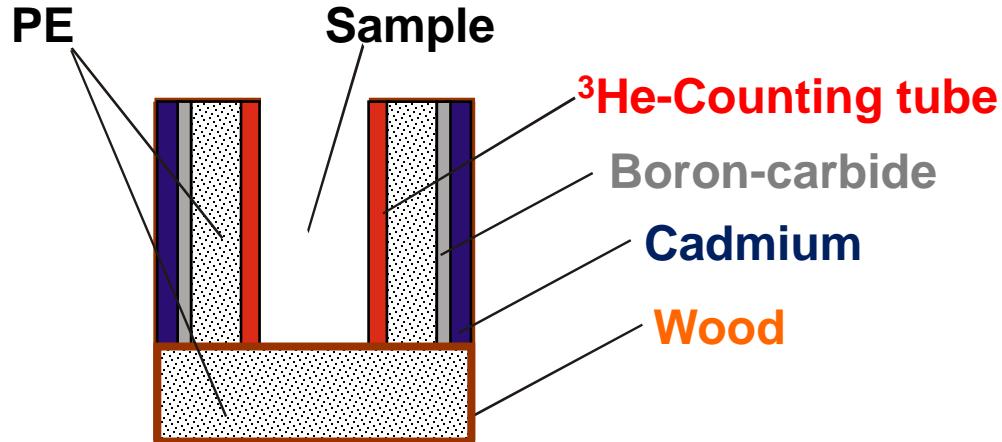
Emission of a neutron if excitation energy of a daughter nucleus resulting from preceding β -decay is sufficiently high.



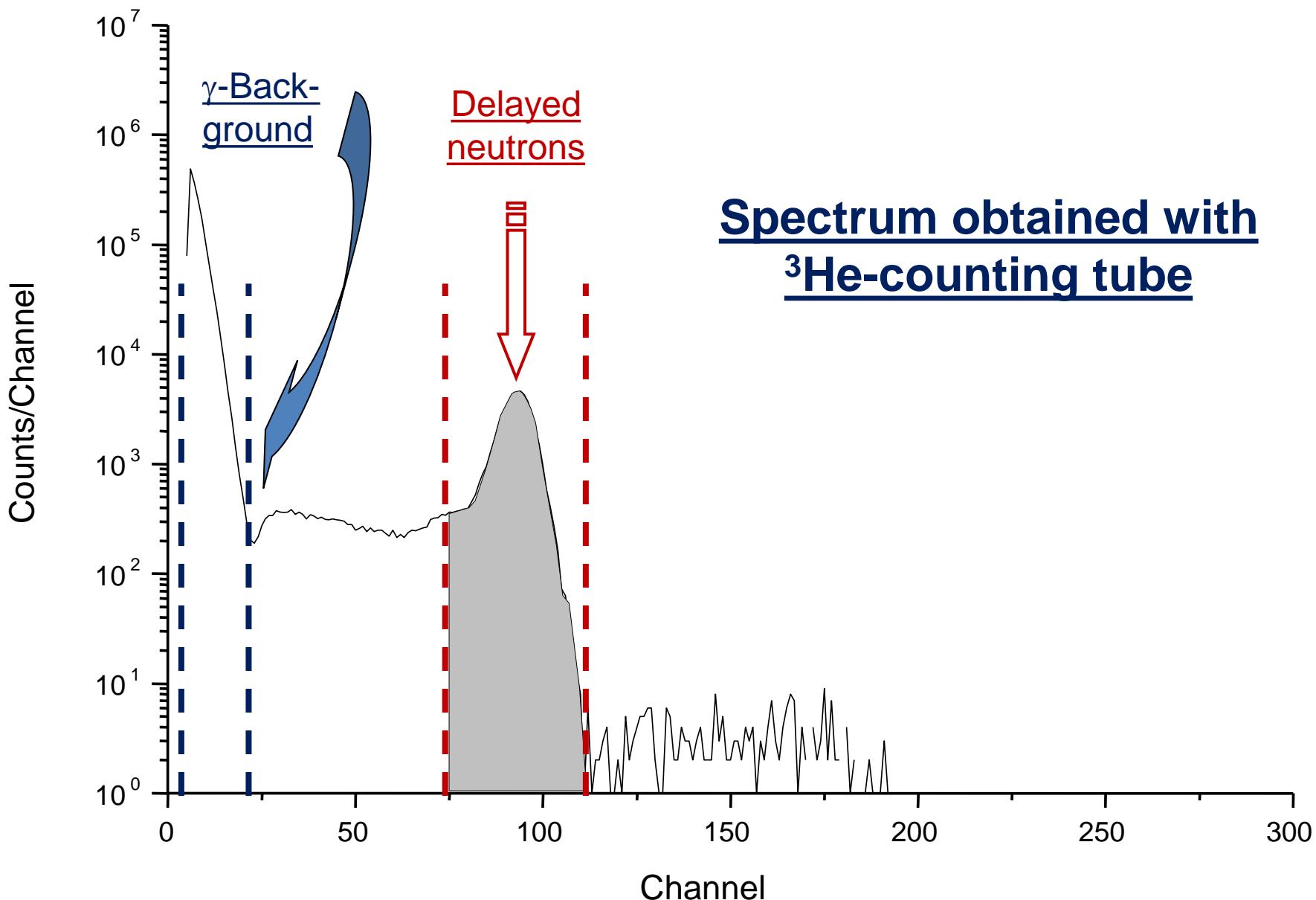
Time scale: β -decay half-life of precursor
⇒ $^{87/89}\text{Br}$, ^{94}Rb , ^{135}Sb , ^{137}I ($T_{1/2} = 2 - 56$ s)

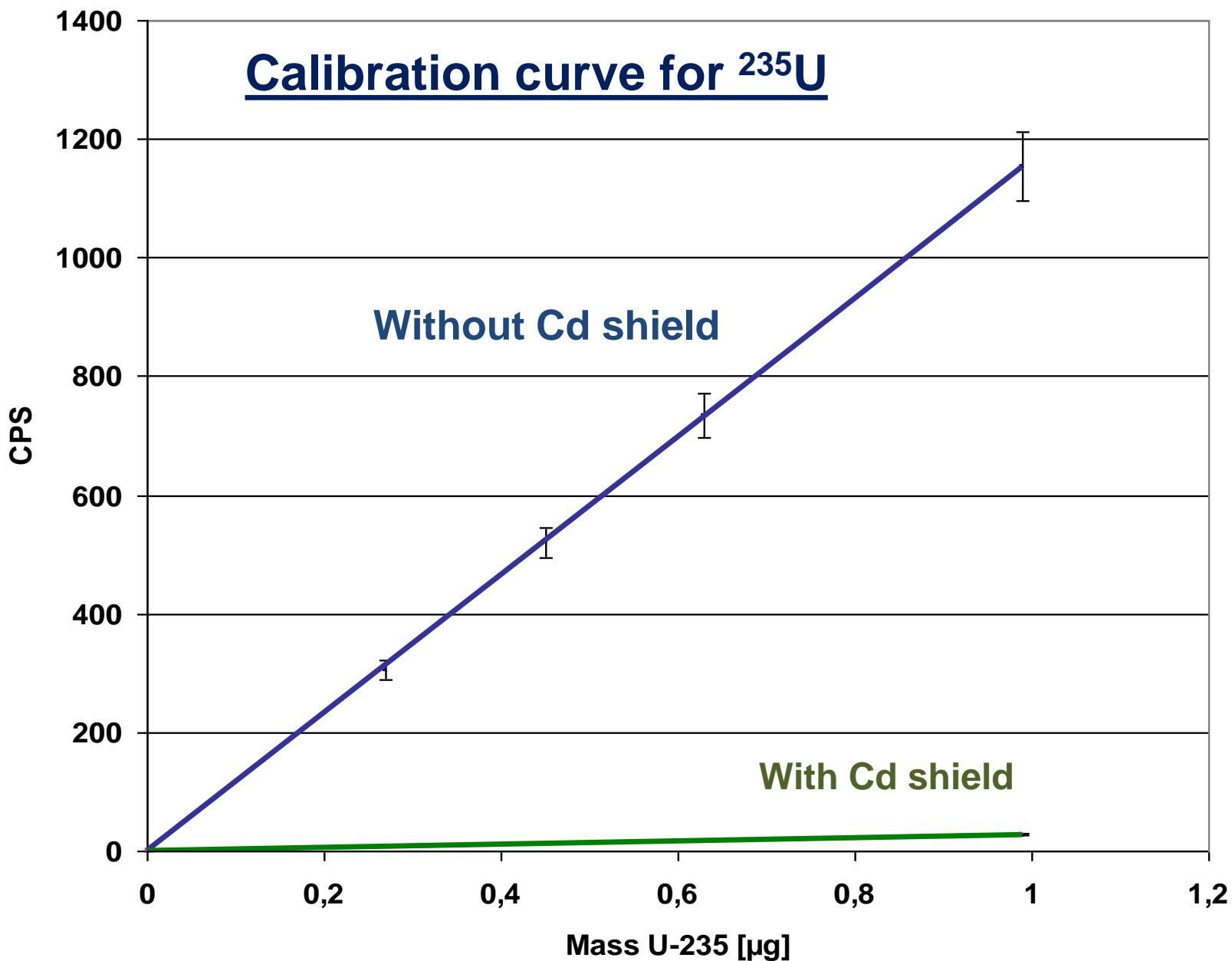
DNAA: Delayed Neutron Activation Analysis

- Cycle: 2 min. (100 kW) – 20 s cooling time – 1 min. Measuring time
- Detection of β -delayed neutrons with ${}^3\text{He}$ counting tubes via the reaction ${}^3\text{He}(\text{n},\text{p}){}^3\text{H}$
- Irradiation and measurement of several U- and Th-samples with and without Cd-shield. Determination of the ${}^{235}\text{U}$ -content in U-samples



12 ${}^3\text{He}$ -Counting tubes:
Efficiency.....18 %
Background.....4 cpm





Thank you for your attention



β -Delayed Neutrons

Group	$T_{1/2}$ [s]	Energy [keV]	Yield for thermal fission [%]		
			^{233}U	^{235}U	^{239}Pu
1	55	250	0,022	0,021	0,007
2	23	560	0,077	0,140	0,063
3	6,2	430	0,065	0,126	0,044
4	2,3	620	0,072	0,253	0,068
5	0,61	420	0,013	0,074	0,018
6	0,23	-----	0,009	0,027	0,009

Decay scheme of ^{190m}Os

$$(1.055 \times 10^{-34} \text{ J})^2$$

$$E_{rot}(I) = \frac{\hbar^2}{2\theta} \cdot (I \cdot (I + 1))$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

$$1 \text{ amu} = 1.6606 \times 10^{-27} \text{ kg}$$

$$1 \text{ fm} = 10^{-15} \text{ m}$$

⇒ Determination of $T_{1/2}$ for ^{190m}Os and moment of inertia θ of the ^{190}Os -nucleus for different I ($[8 \rightarrow 6]$ and $[2 \rightarrow 0]$)

⇒ Compare with moment of inertia θ of solid sphere with:

$$\theta_{(\text{Sphere})} = 2/5 \times M \times R^2 \text{ with } M=190 \text{ amu and } R=1.2 \text{ fm} \times A^{1/3}$$

