Utilization of the TRIGA Mainz

Gabriele Hampel, Institut für Kernchemie

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Overview

- ❖ **Introduction in the TRIGA Mainz**
- ❖ **Education and Training**
- ❖ **In-core applications: NAA and Isotope production**
  - **Solar grade silicon**
  - **Forensic investigations**
  - **Archaeological materials**
  - **Wine**
- ❖ **Thermal column: Medical and biological applications**
  - **Enhanced liver tumour therapy**
  - **Neutron irradiation of cell cultures**
  - **Dosimetry in mixed neutron and gamma fields**
- ❖ **Applications at the beam ports A, B, C and D**
  - **Transactinide research**
  - **TRIGA-SPEC**
  - **Production of Ultra Cold Neutrons**

The research reactor TRIGA Mainz

3rd August 1965:
The TRIGA Mainz became critical for the first time.

3rd April 1967
Official opening with the first pulse set by Otto Hahn.

Since 22nd February 2002
(the 100th birthday of Fritz Strassmann)

Historical Place of Science

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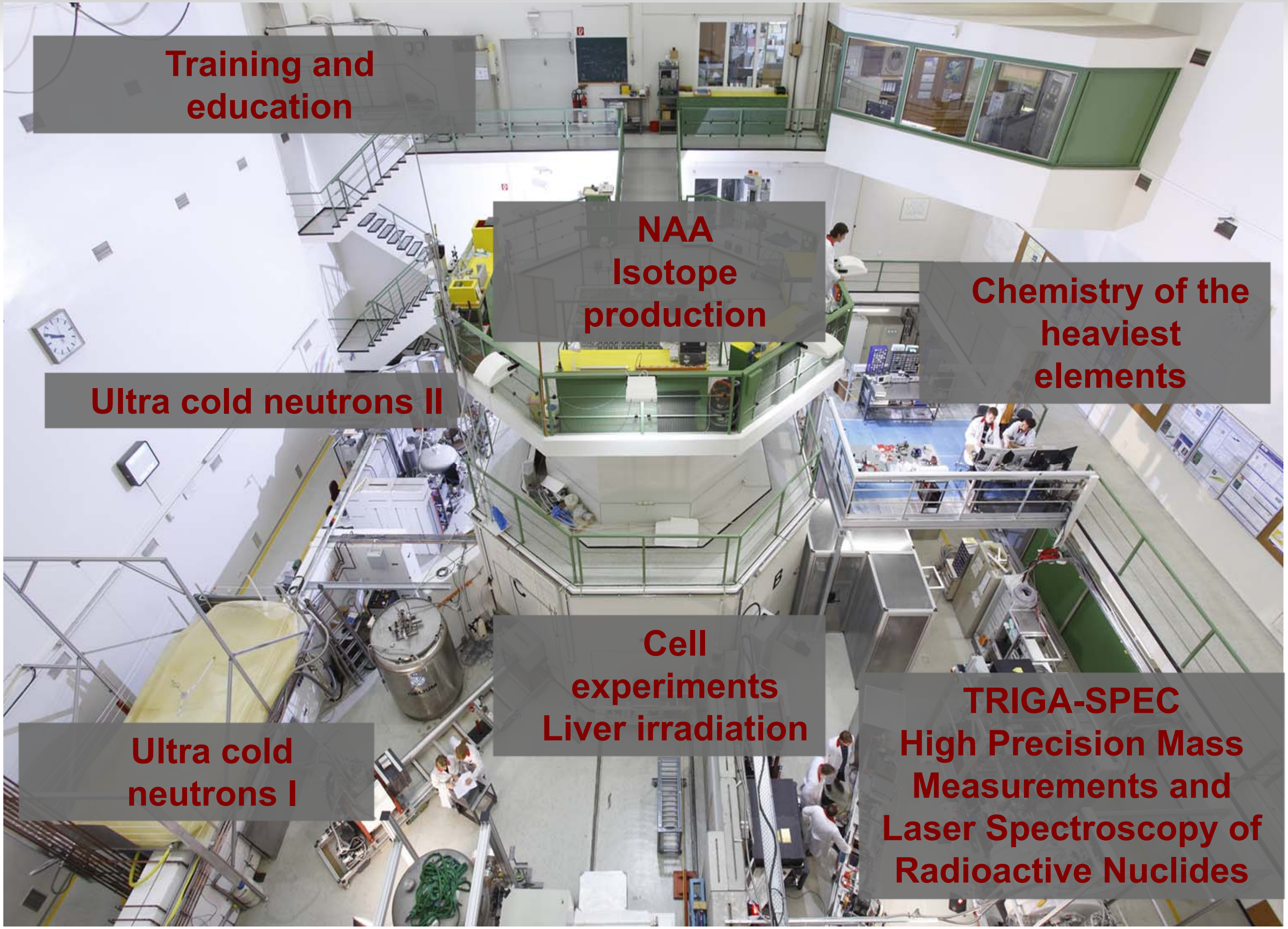
The research reactor TRIGA Mainz

- TRIGA Mark II
- Life time core with 75 fuel elements in the core
- 7 fresh fuel on stock
- Steady state mode: 100 kW
- Pulse mode: 2 $ 250.000 kW
- Operation time: about 200 day per year, 80% steady state mode and 20 % pulse mode
- More than 17000 pulses
- Burn-up: about 4 g U-235 per year
- 4 beam ports used for experiments in fundamental physics and chemistry
- Thermal column for biological and medical applications
- Staff: members of reactor management, 4 operators, radiation protection, electronical and mecanical workshop

View in the reactor hall of the TRIGA Mainz



Education and Training

Various training courses in

- **Reactor operation and -physics**
- **Nuclear and radiochemistry**
- **Radiation protection**

for

- **Engineers and technicians**
- **Teachers**
- **Researchers**
- **University students studying nuclear engineering and/or physics nuclear chemistry**

About 12 weeks a year with growing demand

Education and Training

Reactor operation and reactor physics

- **Inspections at the reactor**
- **Operation of the reactor in the steady state and pulse mode**
- **Neutron flux measurements at different irradiation positions**
- **Influence of test samples to the reactor operation**
- **Calibration of the control rods**
- **Fuel inspections**
- **Function and sensitivity of the compensated ion chamber**
- **Reactivity measurements and**
- **Error diagnostics**

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Neutron Activation Analysis

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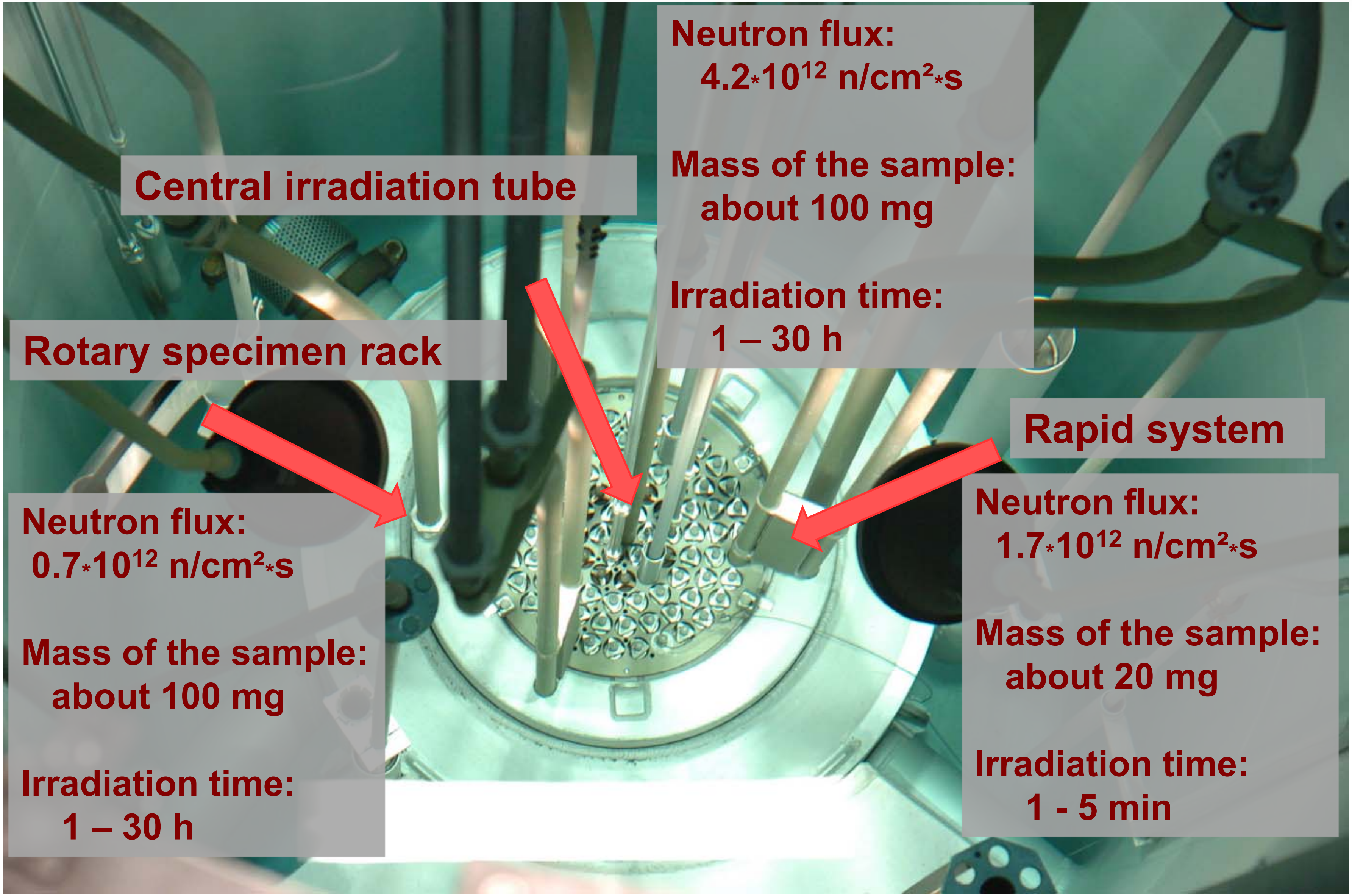
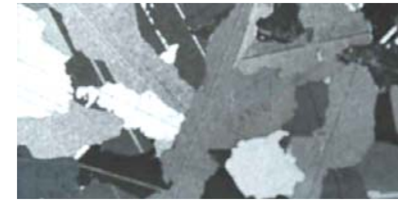
Irradiation positions for NAA



Alternative Energies

- Solar grade silicon for photovoltaics (N. Wiehl, J. Hampel)



Criminology (N. Scheid)

- Analysis of glass
- Brick stones
- Hair

Grapes and vine analysis (M. Feige)

Archaeometry

- Reverse paintings (I. Conjeos Sánchez, J. Riederer)
- Limestones
- Analysis of Hämatit (D. Rieth)
- Roman brick stone (J. Dolata)

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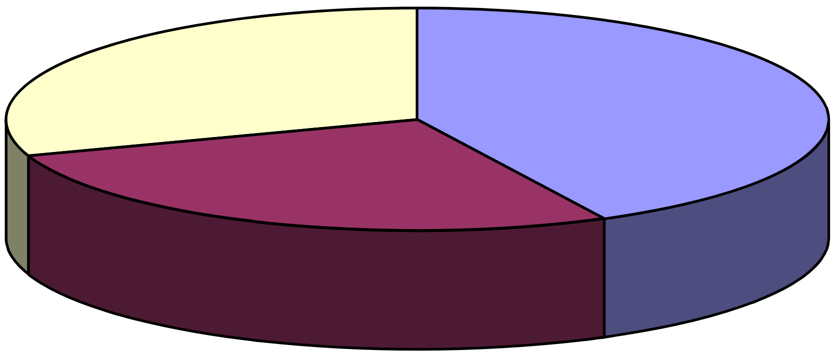
“Solar Grade” Silicon - motivation

Boom in the solar industry

⇒ Limited availability of high purity silicon (also applied in the production of semiconductors)

⇒ Increasing costs



Alternative

“solar grade silicon” (SG-Si)

SG-Si : silicon with acceptable purity grades (> 99.9999%)

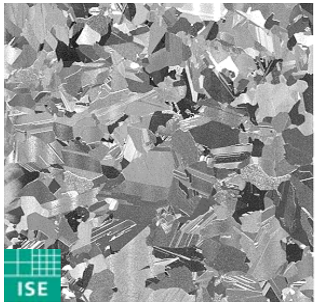
“Solar Grade” Silicon - motivation

The energetic efficiency of solar cells is affected by impurities of the 3 d transition metals, such as **Ti, V, Cr, Mn, Fe, Co, Ni, Cu**

Determination of the impurities in the feedstock

Development of methods to reduce the impurities

<u>HCl gas getter</u>



Treatment of the wafer by HCl gas at T > 900°C
Formation of volatile metal chlorides at the surface and diffusion of interstitial metals to the surface
Removal from the compounds by a stream of gas

Determination of the trace elements´ concentration after the purification

Motivation

Based on a real murder case:

- Dead body of a murder victim was weighted down with brick stones and submerged in a lake
- Suspect has brick stones at home

Questions:

- Do these two stone samples originate from the same producer?
- Do any similarities exist between these stones?

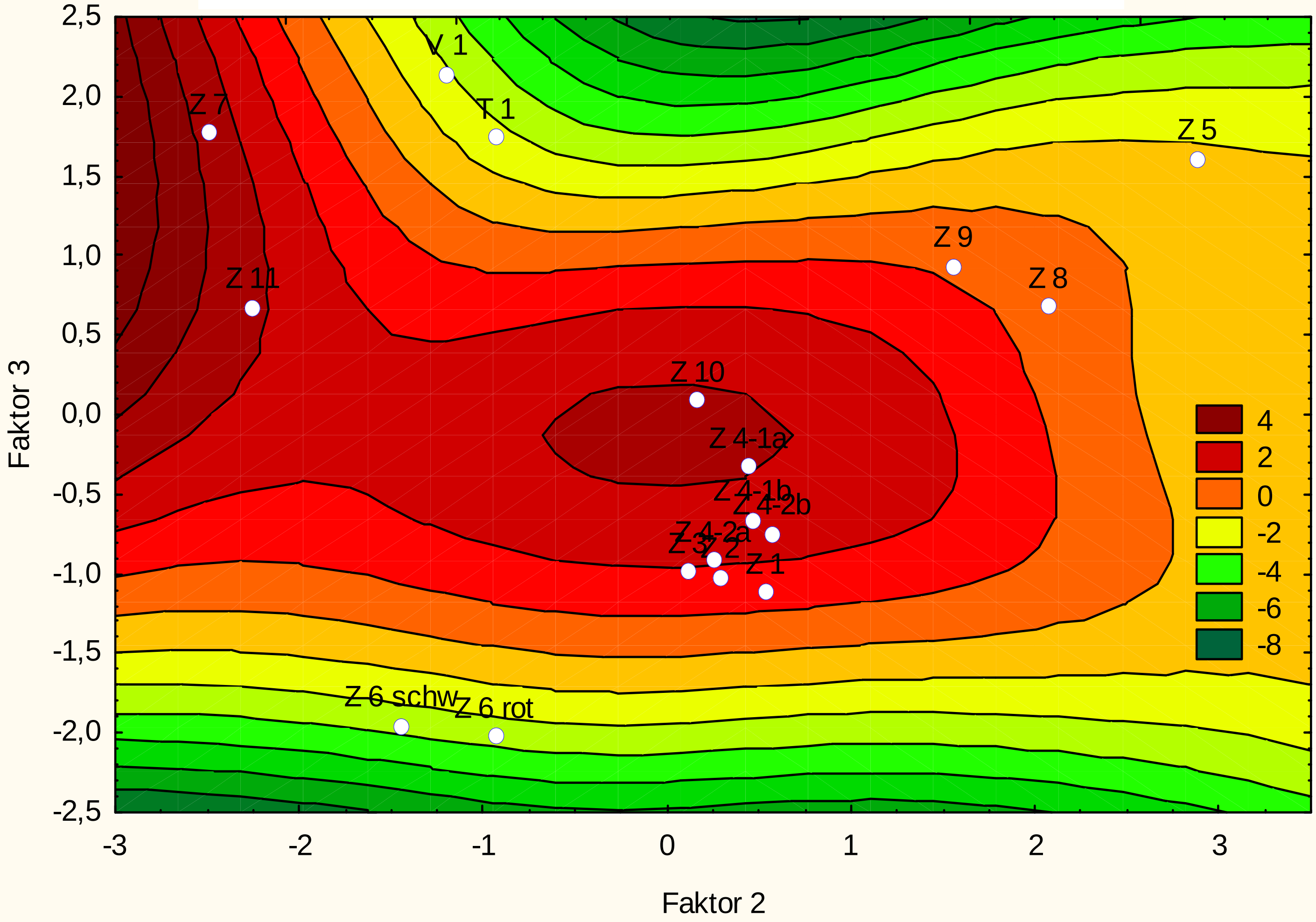
Strategy

- A single brick was divided into four parts → variation of the elemental composition in one brick (homogeneity)
- 4 stones of one production batch → variation in a batch/charge

- 4 stones from different production facilities → variation between different producers

Forensic investigation of brick stones using *NAA*

Analysis of the main components (3D plot)
For the elements V, Na, K, Sm, U, Sc, Fe, Co, Rb and Cs)



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Conclusion

Variation of the elemental concentrations between bricks originating from different producers are higher than the variation between stones from the same production facility

→ Elemental analysis using NAA is a valuable tool for forensic examinations of brick stones
but only similarities or differences can be shown, which cannot be used as the only incriminating evidence

Aim
Inference about geographic origin and attribute of the materials

Method
Compositional characterization of archaeological materials in conjunction with stylistic and petro-graphic criteria

Compositional data answers questions about
- group of materials belonging together,
- a common origin relating materials of unknown origin to a region or a quarry
- information about trade relations in the archaeological time period

⇒ Interest for museums and art historians

Limestone

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Rheinland-Pfalz
Generaldirektion Kulturelles Erbe

Landes museum Mainz

Johannes Gutenberg Universität Mainz – Institut für Vor- und Frühgeschichte

Universität Leipzig
Fakultät für Physik und Geowissenschaften
Institut für Geophysik und Geologie

JGU
Johannes Gutenberg Universität Mainz

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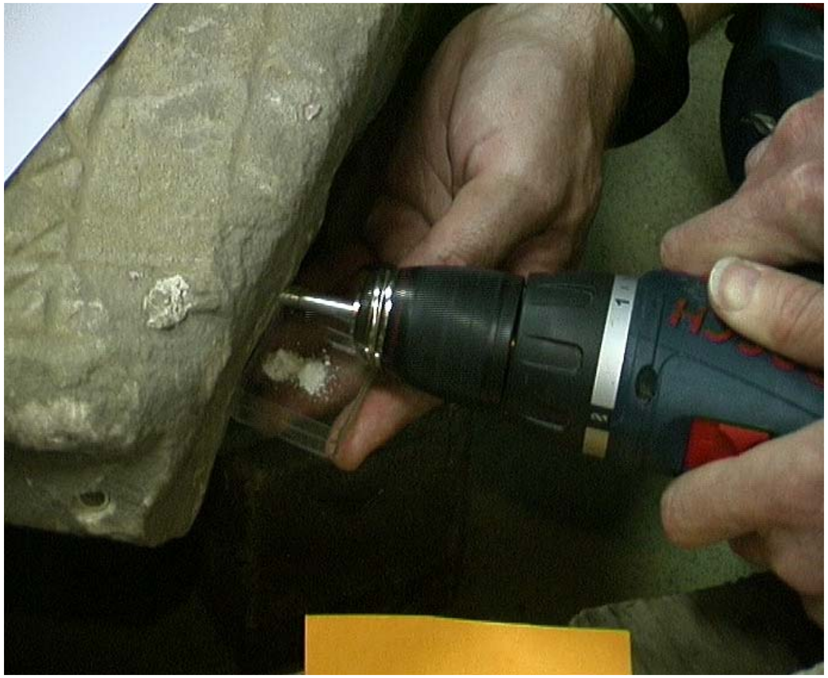
Limestone



Broken grave stone

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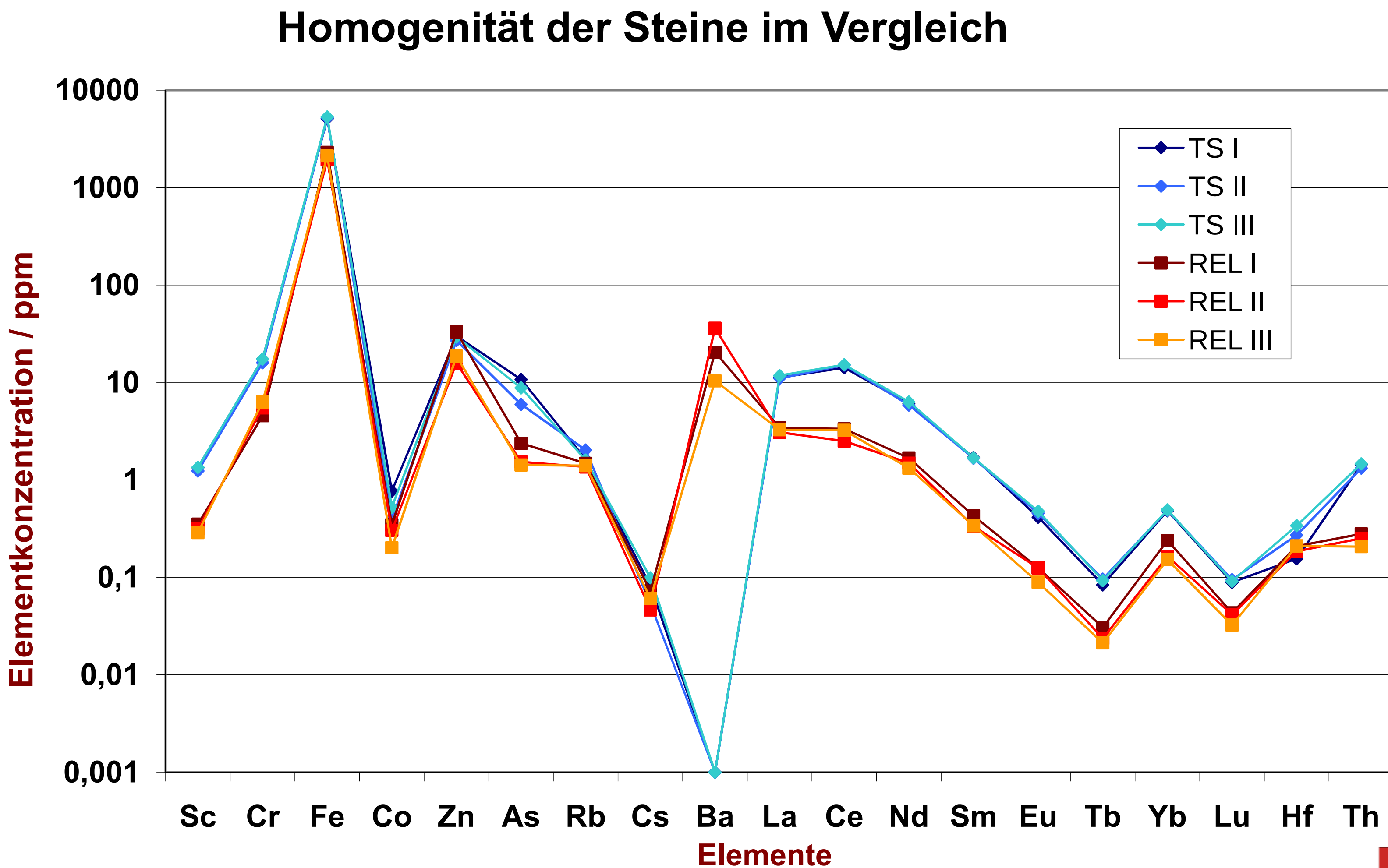
Results



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Reverse paintings of glass in the 18th and 19th centuries

Fig.1 and 2. Daily scenes, hunting scene and a representation of parts from Europe

Fig. 3 and 4. Pictures of Saints, usually they were given as a present: St. Katharina and St. Leonhard

- Important part of the middle European cultural heritage
- Materials changed rapidly in the 18th and 19th centuries (pigments as well as glass)
- Less information about the origin of the glasses
- Are there any differences in the properties of materials in different areas or in different periods?

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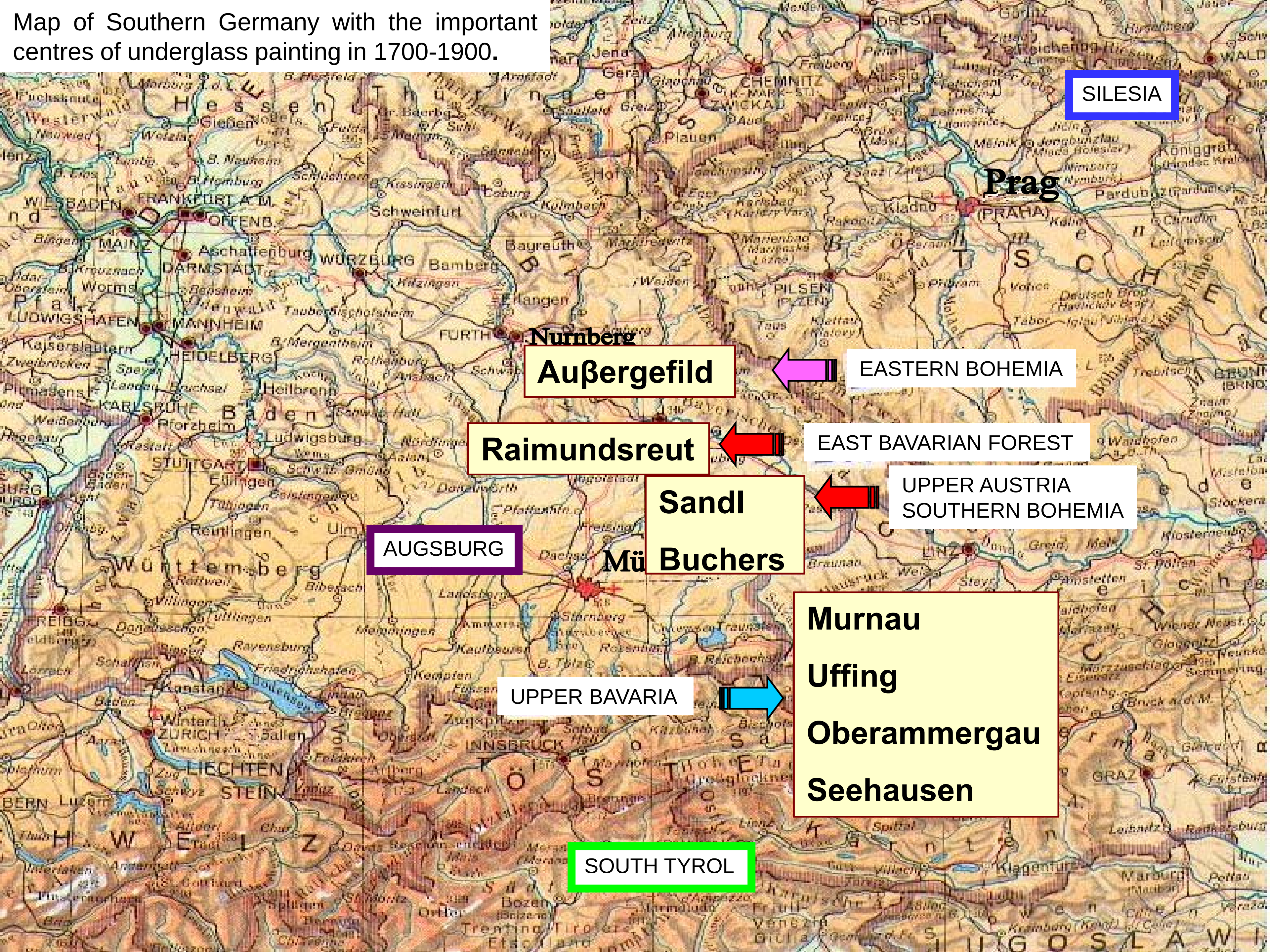
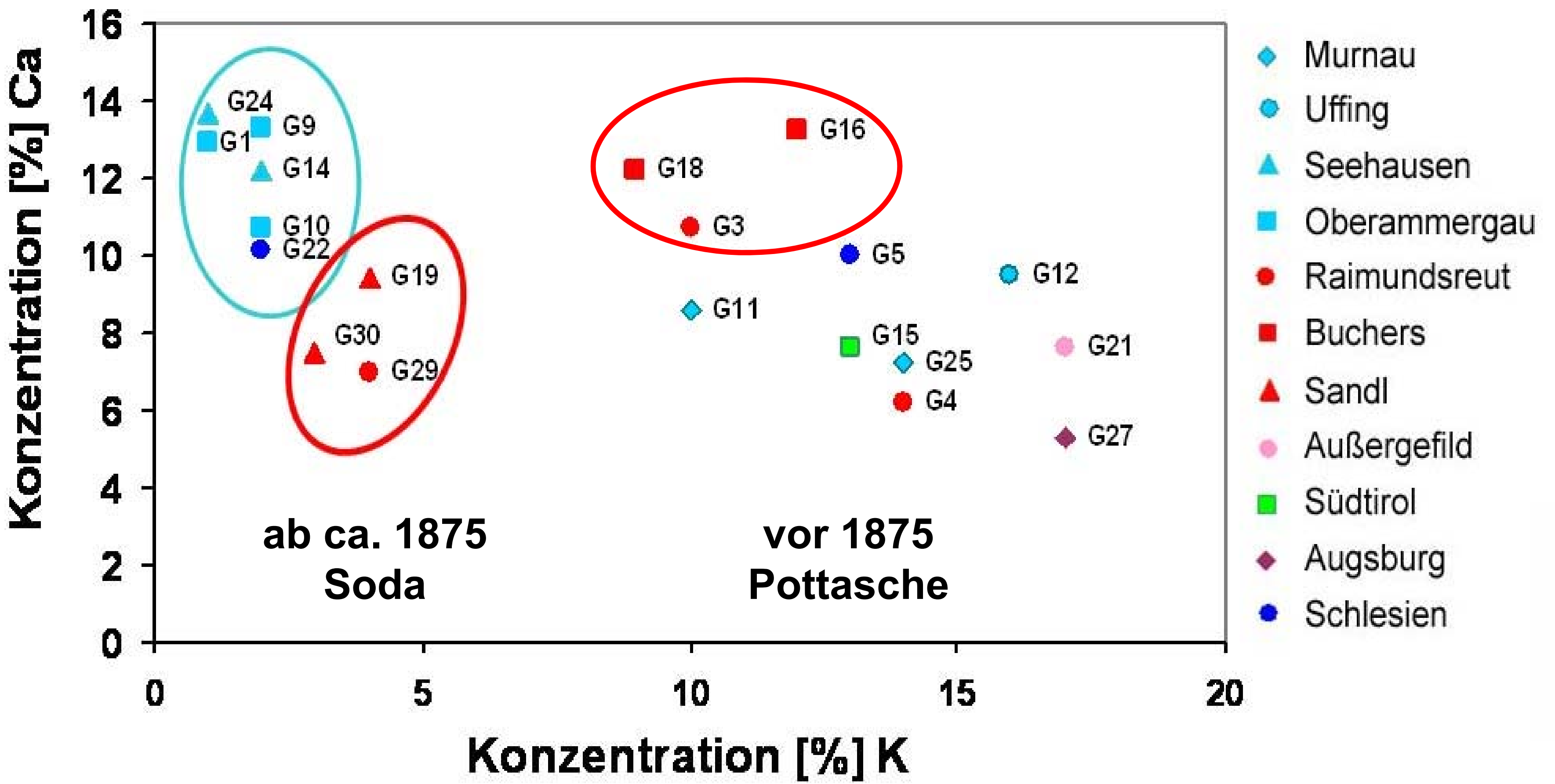
Map of Southern Germany with the important centres of underglass painting in 1700-1900.



Reverse paintings of glass in the 18th and 19th centuries



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Analysis of the elements and trace elements of grapes and wine

Mainz is Germany‘s wine capital.

- **Situated in the heart of Rheinhessen**
- **One of Germany´s largest wine growing areas**
- **a lot of small wine restaurants and wine farms**

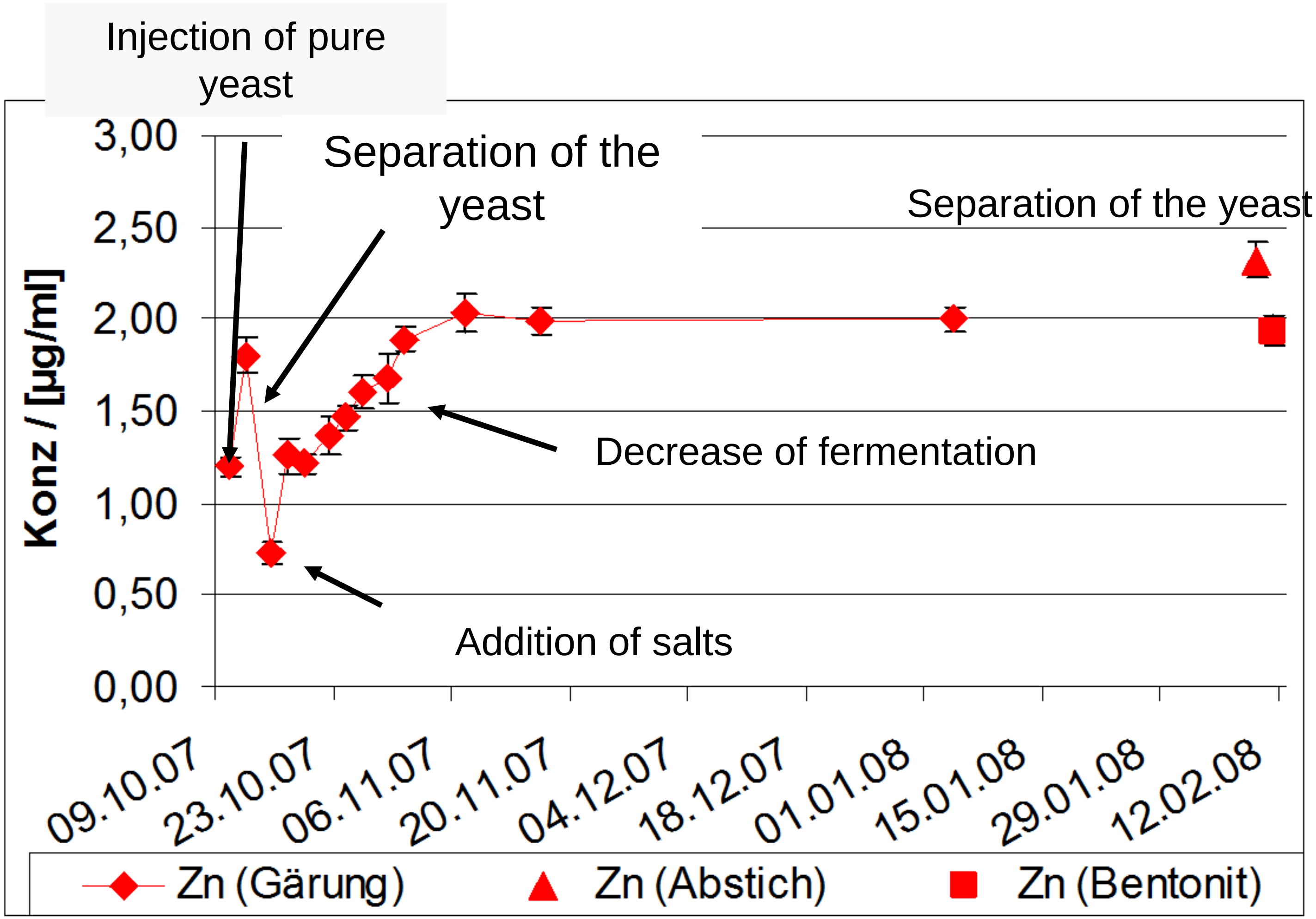
Motivation : High quality of wine

Quality is affected by interruptions in fermentation

- Can the interruptions in fermentation be caused by trace elements ?
- Can the results from the isolated experiment in a laboratory be transferred to a real case in a wine cellar?
- Are the conditions of the grapes important for the fermentation procedure ?
- How is the behaviour of the minerals in the grapes during the time of growing?

Systematic determination of the element and trace element concentration independent of the time for the grapes and the wine during fermentation

Concentration of Zn during the fermentation of the Riesling wine injected with a pure yeast to start the fermentation



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Isotope production

Isotope production at low flux reactors, such as the TRIGAs

Radioisotopes with short decay times such as

^{24}Na, ^{41}Ar, ^{56}Mn, ^{113m}In, ^{82}Br, ^{140}La

Application in the analysis of chemical-technical processes
Determination of fluid-flow, dwell time and volume measurements

Determination of the efficiency of toothpaste

Teeth are irradiated in the roundabout, then cleaned with toothpaste and the total amount of activity in the toothpaste is measured.

Thermal column:

Medical and biological applications

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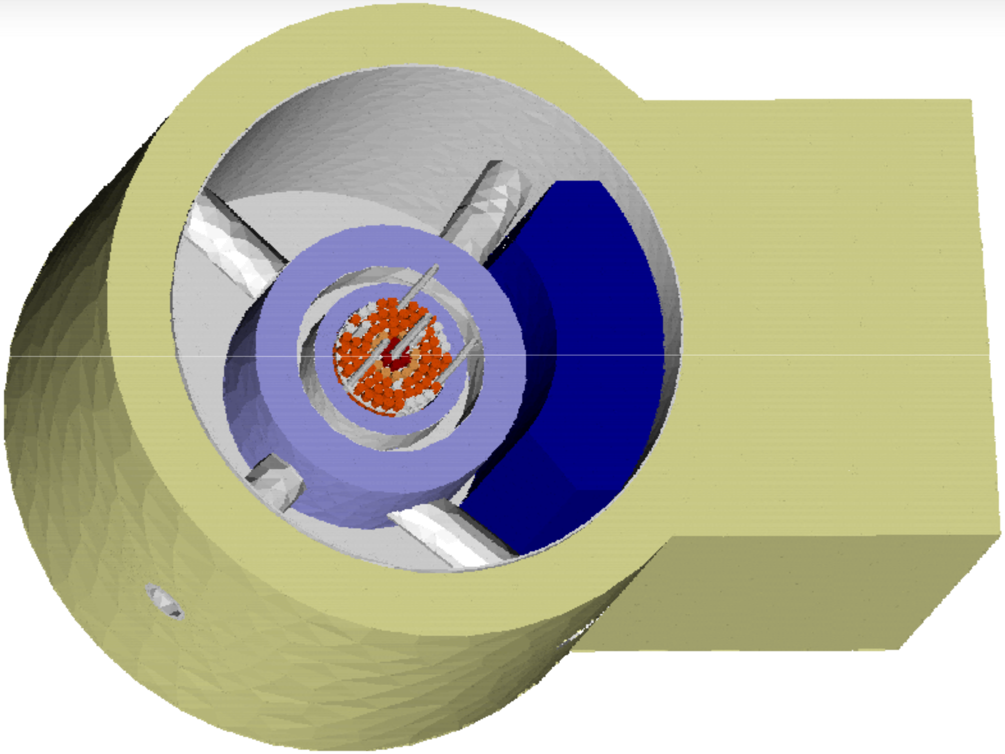
Thermal column: Medical and biological applications



- Enhanced liver tumour therapy applying BNCT
- Determination of Boron using the quantitative neutron capture radiography (QNCR)
- Neutron irradiation of cell cultures
- Dosimetry in mixed neutron and gamma fields

Simuations of the TRIGA Mainz using the 3 dimonsional transport code ATTILA

B. Wortmann (Steag encotec)

BNCT - Groupe

Nuclear Chemistry — G. Hampel, C. Schütz, S. Werner
Pharmacy — C. Grunewald, T. Nawroth, P. Langguth
Transplantation Surgery — G. Otto, S. Minouchehr
Radiology — H. Schmidberger
Pathology — J. Kirkpatrick, C. Brochhausen
Analytical Chemistry — N. Bings

Universidad Católica de Valencia San Vicente Mártir — V. Vicente Vilas, J. Hernández

GSI — M. Scholz

TU Graz

University of Cologne — B. Kuczewski

University of Pavia — S. Altieri, S. Bortolussi

AIT Austrian Institute of Technology — M. Blaickner

HFR Petten — R. Moss

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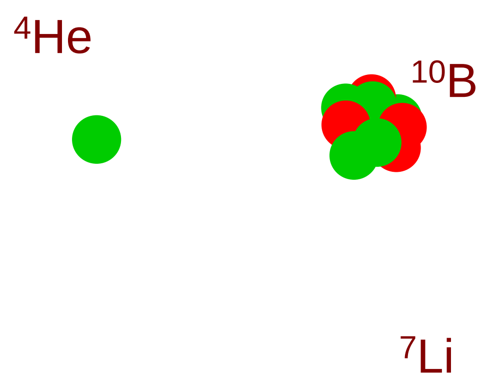
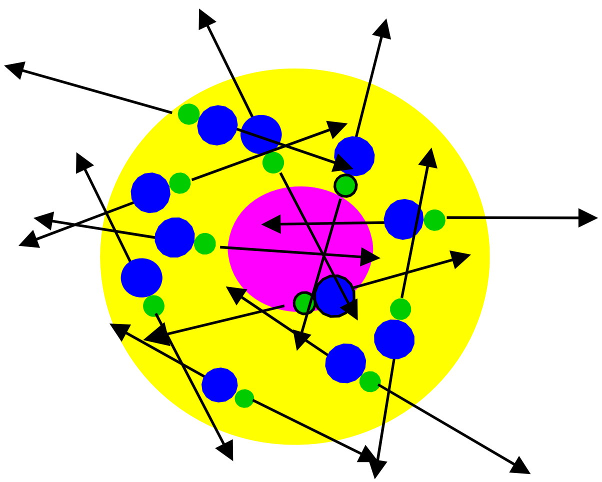
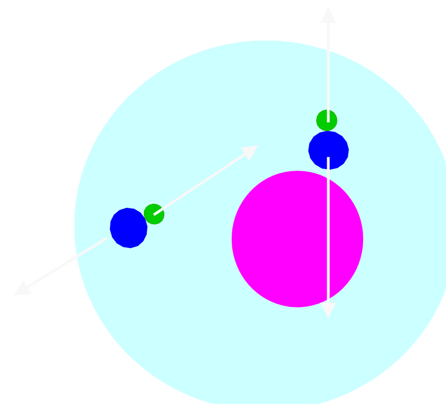
Boron Neutron Capture Therapy (BNCT)



- Thermal neutron capture cross section of ^{10}B: σ = 3840 barn
- High LET: α = 150 keV/μm
  ^{7}Li = 175 keV/μm
- Range in tissue 5 to 8 µm
- Local activation ^{10}B(n,α) ^{7}Li



High enrichment with ^{10}B in the tumour cells (right) and low enrichment in the normal tissue (left) to destroy the tumor.



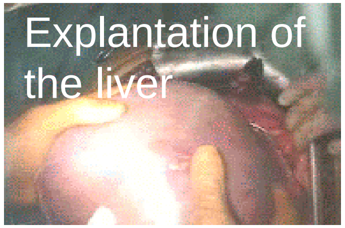
Principal steps:

1. *Application of ^{10}B-containing drug (BPA) preferentially accumulating in tumorous lesions*

2. *Explanting and preservation of the liver as a whole*

3. *Neutron beam irradiation*

4. *Re-implantation of the liver*



Successful Therapy

Target parameter for clinical application:

- B-10 concentration of at least 25 ppm in tumour tissue (≈10^9 atoms per Cell)
- Uptake Ratio B-10 ≥ 2.5
- Maximum dose for healthy tissue: 8 Gy
- Very short anhepatic period of time (< 2 h)

Questions:

- What is the exact boron uptake in tumour vs. healthy liver tissue?
- Are there any wash-out effects concerning the concentration gradient?
- Is the high operative risk justified?

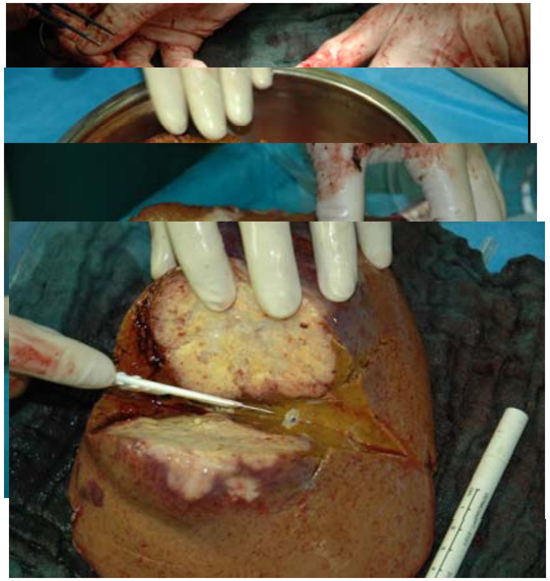
Clinical study:
Determination of the accumulation of BPA in tumour and healthy liver tissue before and after washing the liver specimen with preservation solution.

Licence for 15 patients, 4 done until now

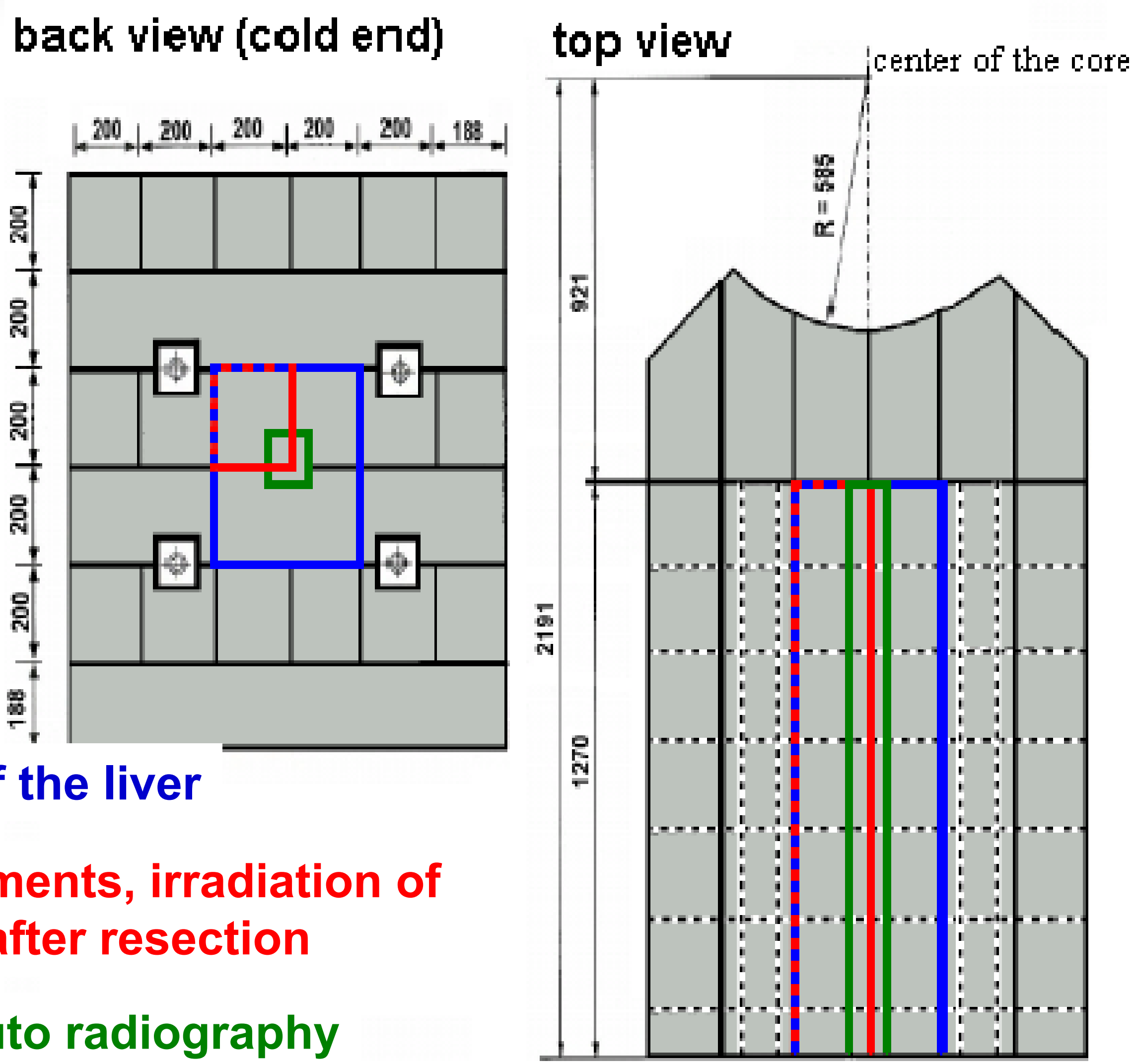
- Surgical treatment of the liver metastases indicated
- Colorectal metastases in one liver lobe

Procedure

- Infusion of BPA bound to fructose in a concentration of 200 mg/kg
- Resection of the liver lobe
- Perfusion and cooling down to 4°C
- Cutting the liver lobe and taking samples
- Installation of dosimeter
- Boron concentration measurements
- Dose measurements



Irradiation positions of the thermal column

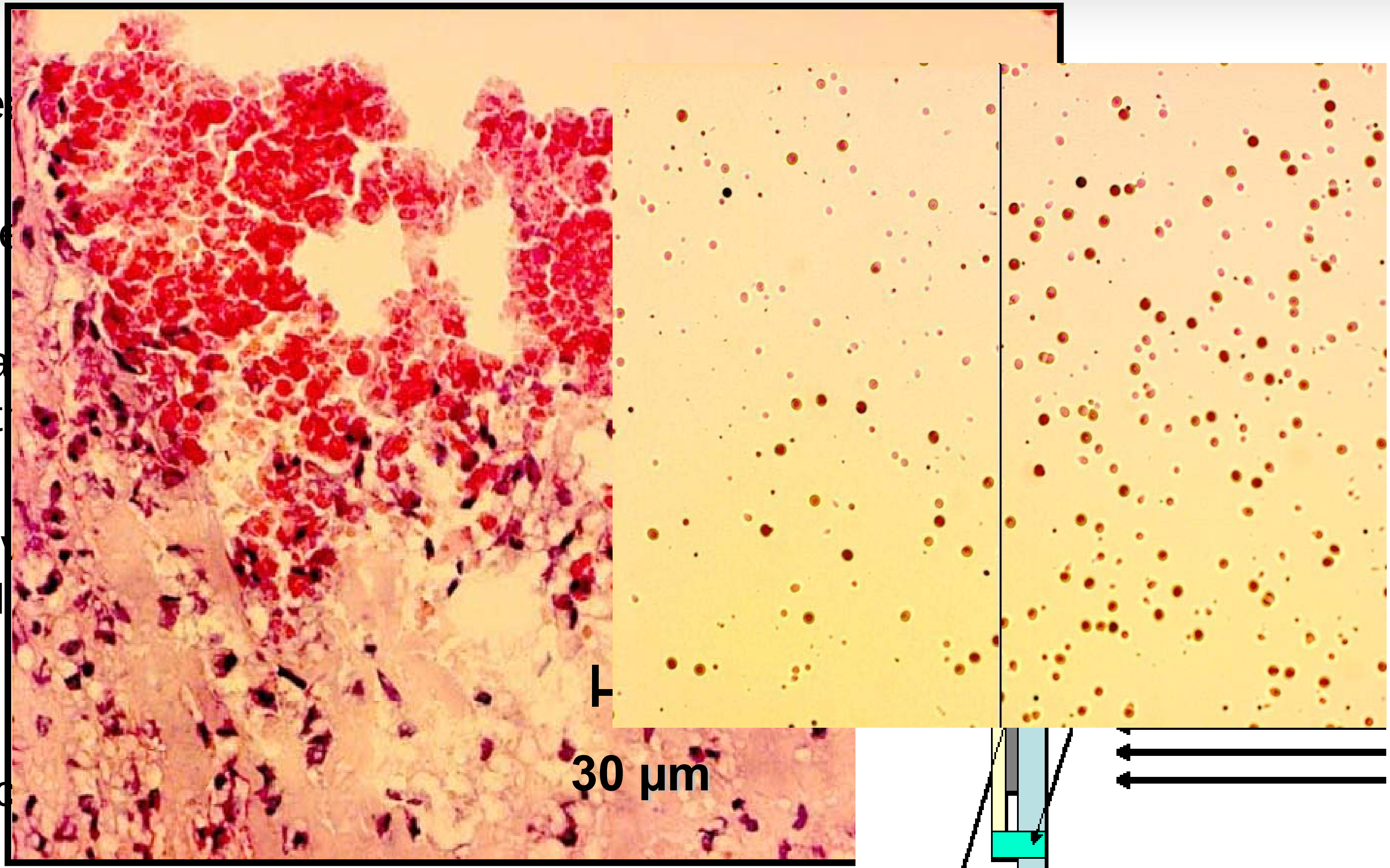


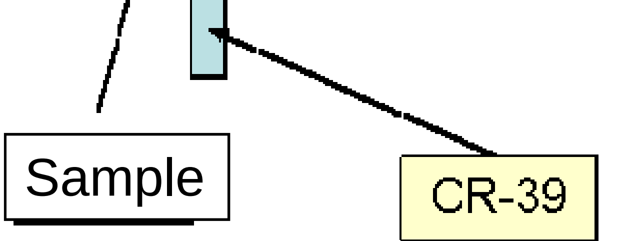
Irradiation of the liver

Cell experiments, irradiation of liver after resection

Auto radiography

- Me
- Use
- Irra
  in t
- De
  7M
- Loc



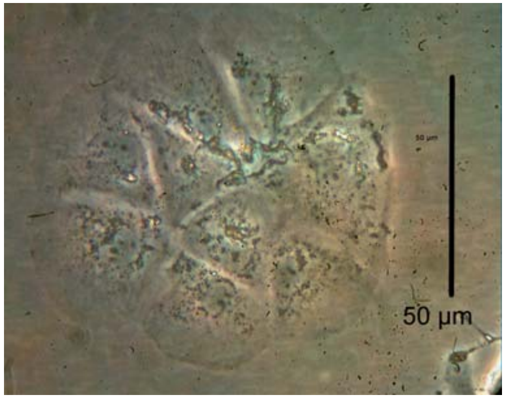


Cell experiments

Aim:

Information about biological effects of neutron radiation

Measurements of survival curves
Determination of relative biological effectiveness (RBE)
Uptake studies



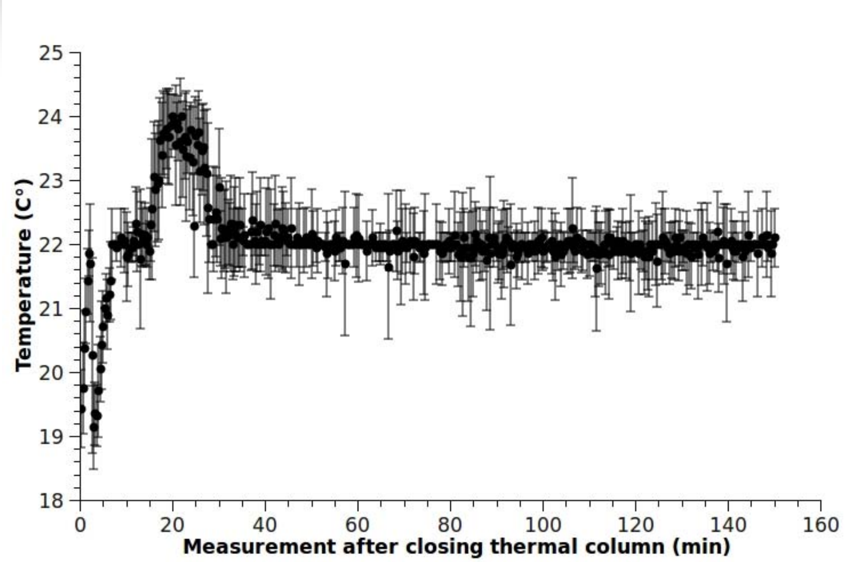
Procedure

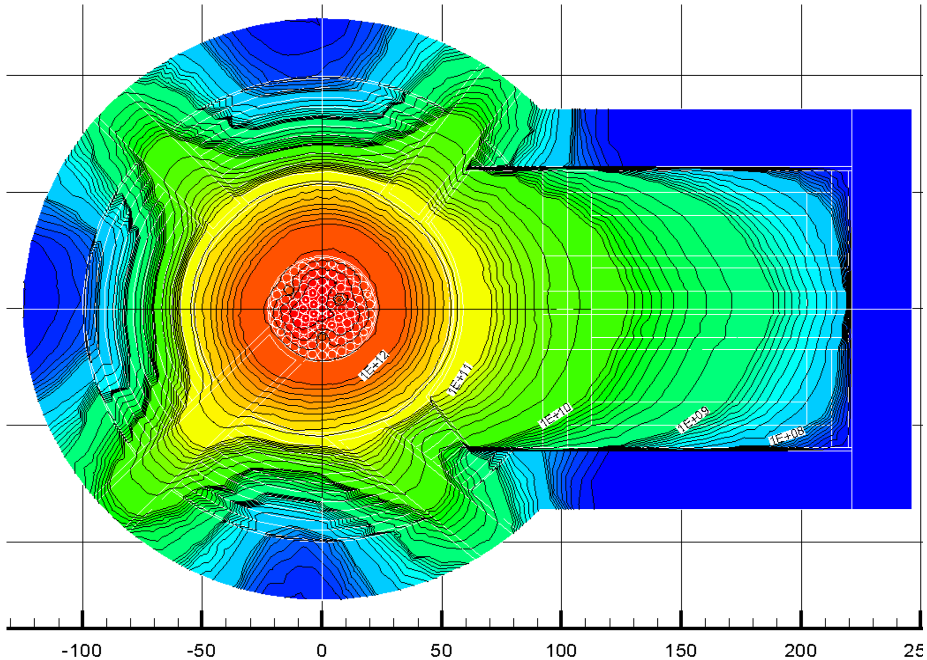
❖ **Irradiation of different cell lines with thermal neutrons using Multi-Well-Plates**

- **HuH7 cells of human hepato cellular liver tumour**
- **Diameter of a tumour cell: About 30 to 50 µm**
- **Age of the cells: 3 day**

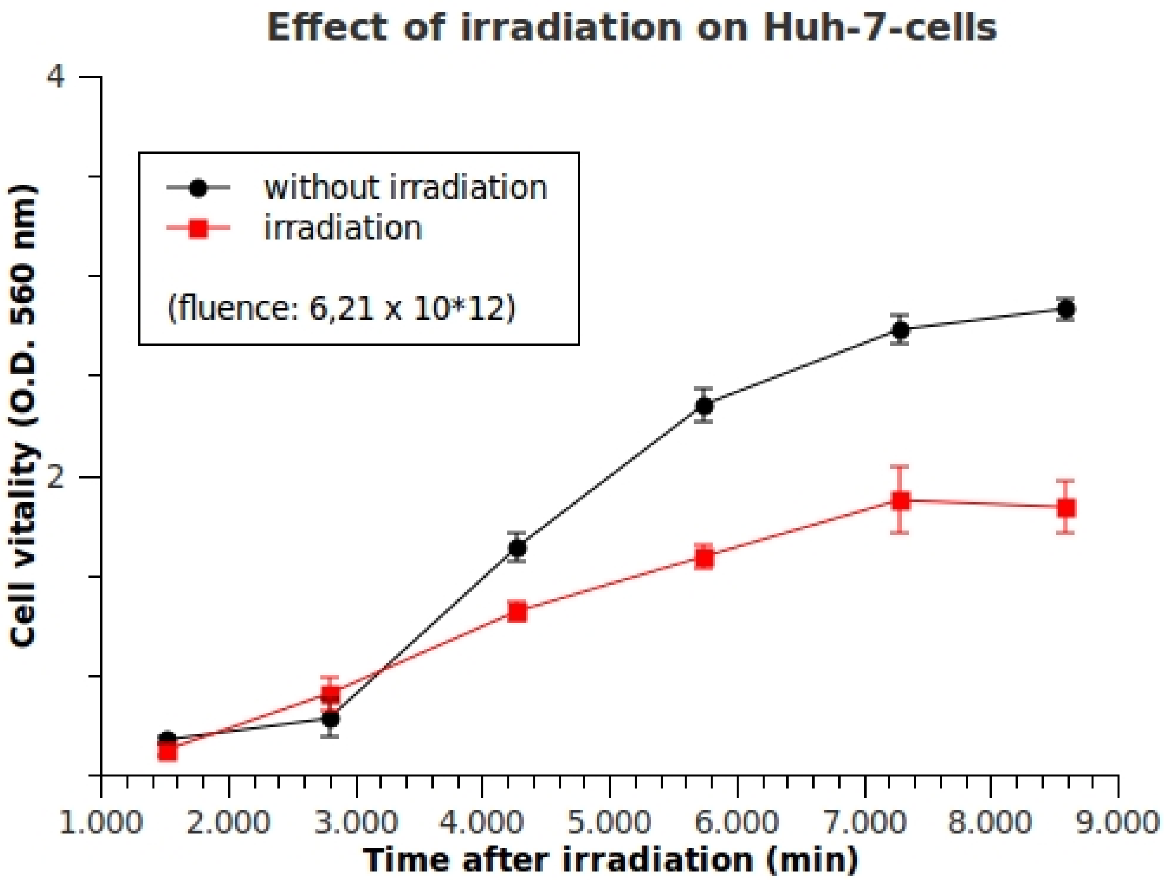
Cell experiments – requiremente for the irradiation

- **Temperature inside the thermal column**
- **Neutron field inside the thermal column**





Cell experiments – results



Applications at the beam ports A, B, C and D

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Applications at the beam port A

Chemistry of the heaviest elements, Transactinide research

Calibration of neutron flux detectors for power reactors

Discovery of nuclear fission (1938)

O. Hahn, F. Strassmann:
Naturwissenschaften (1939):

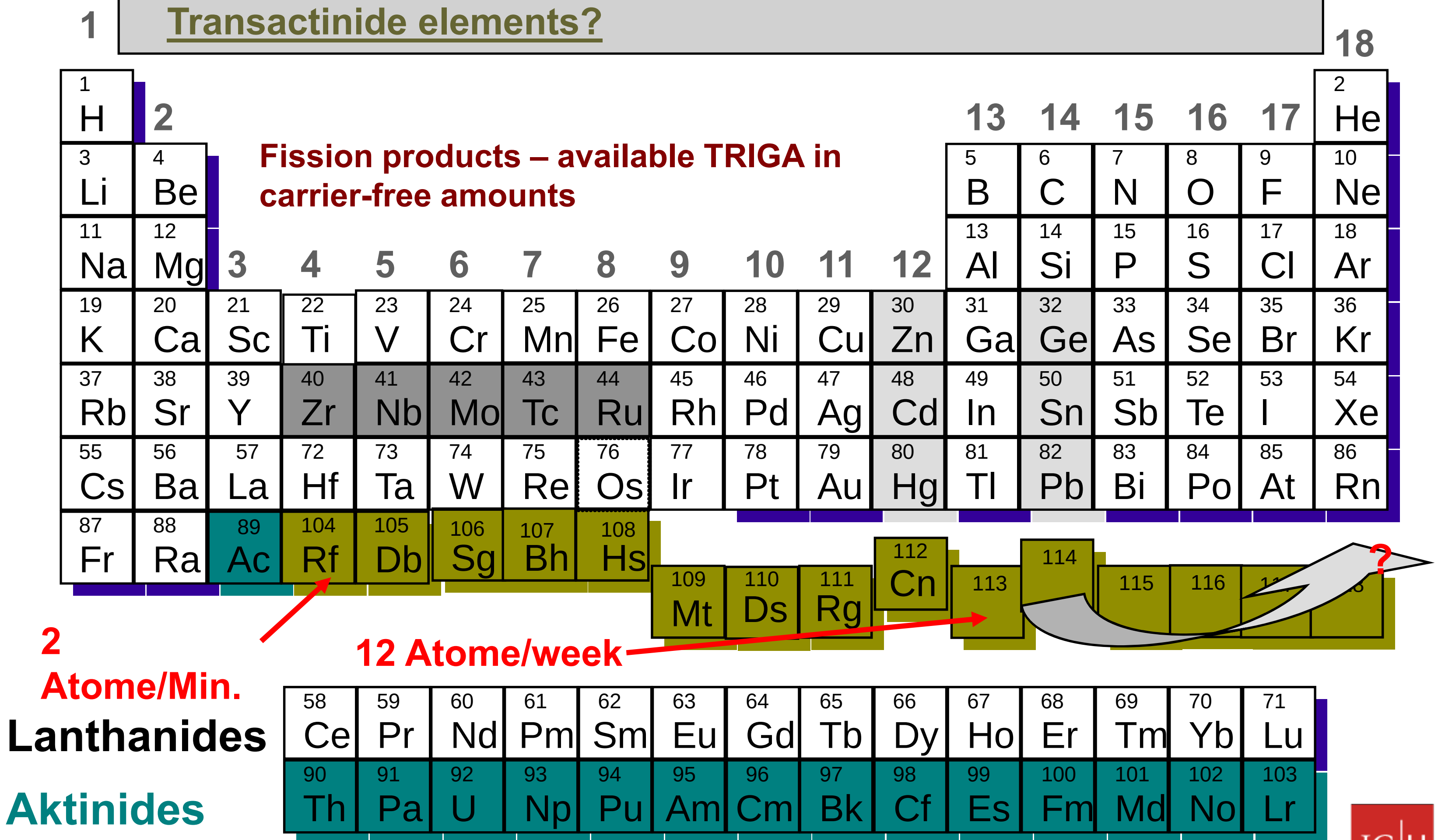
„Als Chemiker müßten wir … statt Ra, Ac, Th die Symbole Ba, La, Ce einsetzen. Als der Physik in gewisser Weise nahestehenden Kernchemiker können wir uns zu diesem, allen bisherigen Erfahrungen der Kernphysik widersprech-enden, Sprung noch nicht entschließen“

↓

L. Meitner, O. R. Fritsch, Nature (1939): *Physik. explanation of fission*

Chemie der schwersten Elemente (Z > 103)

- **Chemistry with single atoms due to low production rates**
- **Do relativistic effects alter the electronic structure of the Transactinide elements?**



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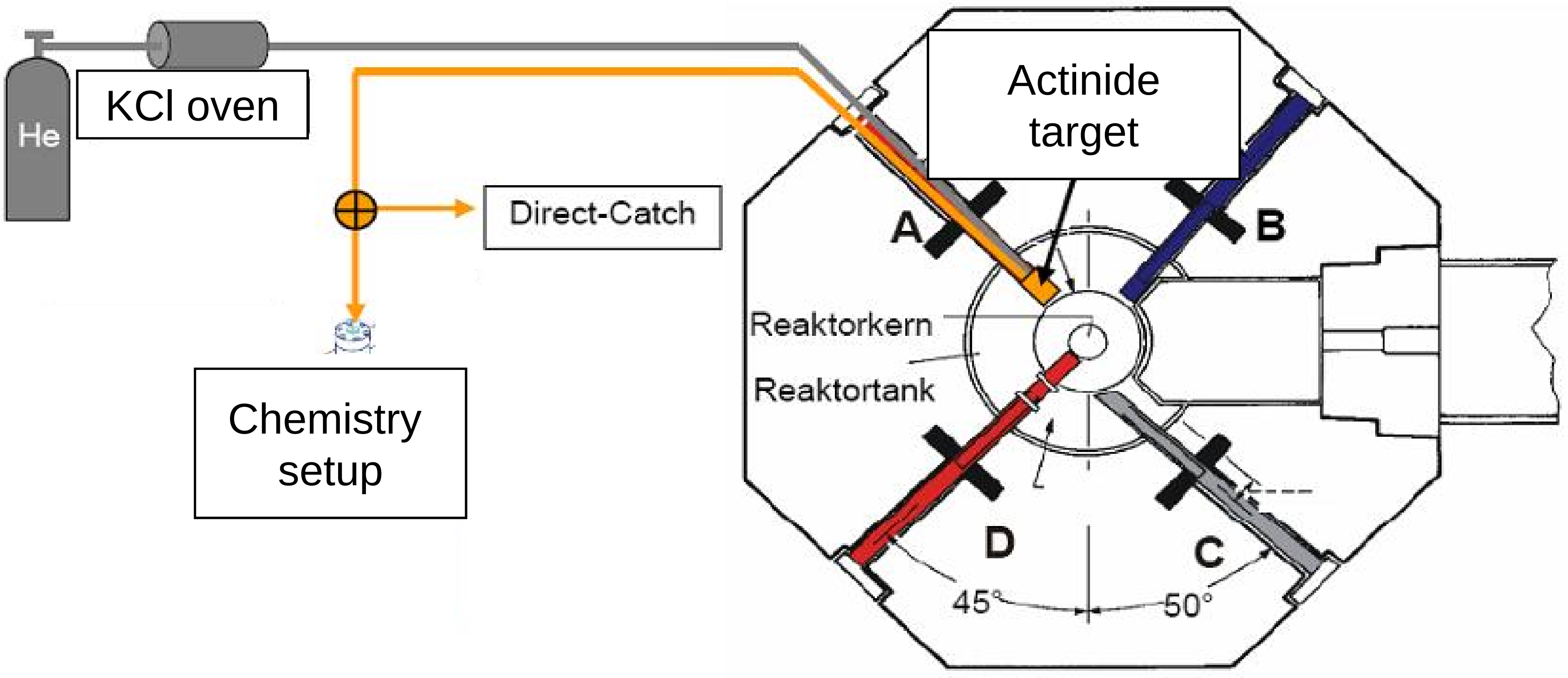
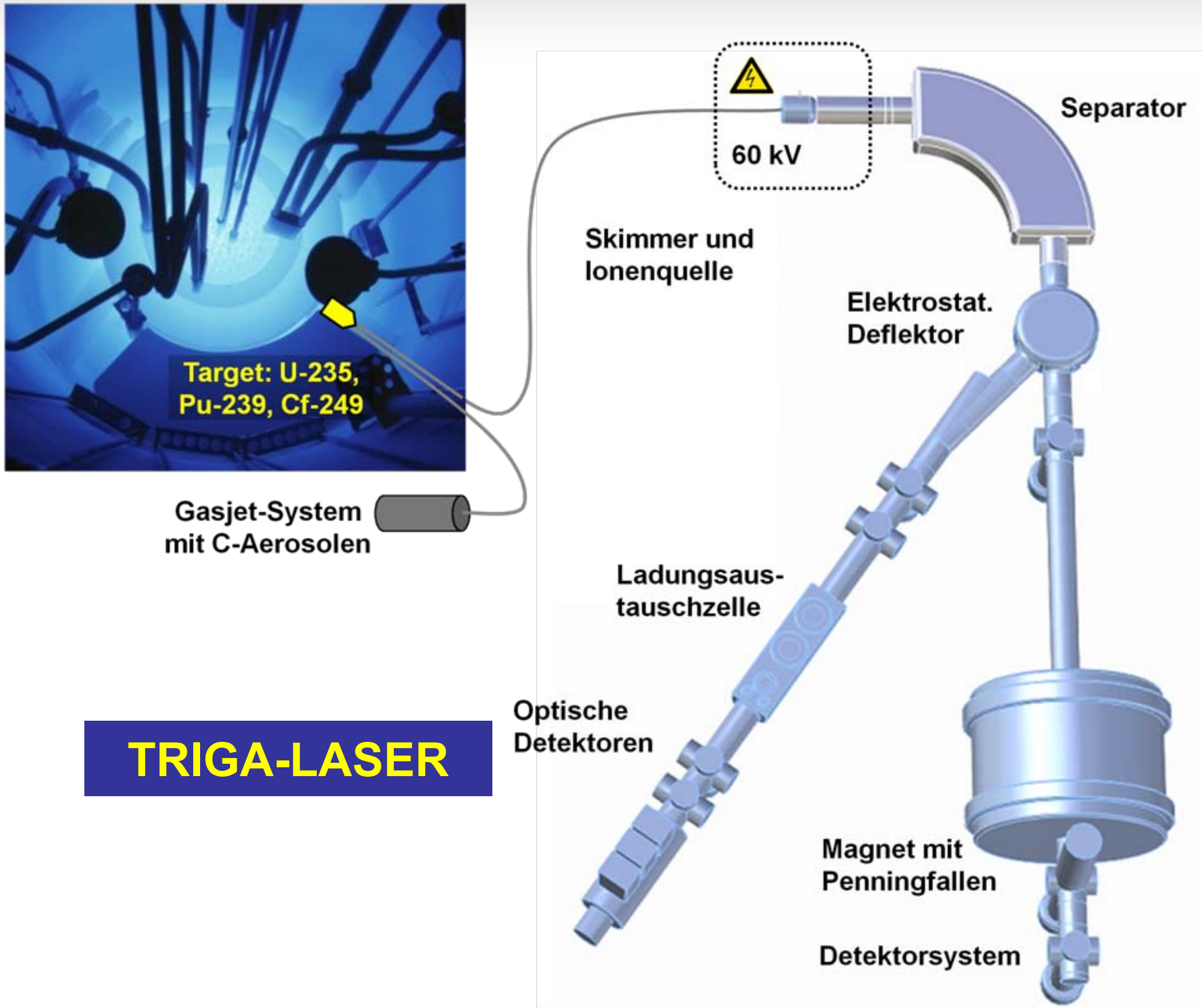

He
KCl oven
Direct-Catch
Chemistry setup
Actinide target
A
B
C
D
Reaktorkern
Reaktortank
45°
50°

TRIGA-SPEC: TRIGA-TRAP and TRIGA-LASER

High-precision measurements of nuclear ground state properties

- Improvement of nuclear models
- A better understanding of the nucleo-synthesis process
- Mass measurements
  - Provide important data for astrophysical calculations - so-called rapid neutron-capture process (r-process) - since the nuclear mass directly reflects the binding energy in the nucleus
  - Serve as test cases for nuclear mass-models in the heavy mass region
- Laser spectroscopy yields information on properties such as
  - nuclear moments and
  - charge-radii of neutron rich nuclides far from stability, which are extracted from the observed hyperfine structure and isotope shift.

TRIGA-SPEC: TRIGA-TRAP and TRIGA-LASER



Measurements on fission products (on-line) like

Mo-42, Tc-43, Ru-44, Rh-45, Pd-46, Ag-47, Cd-48, In-49, Sn 50, Sb-51, Te-52, I-53-Xe-54, Ba-56

⇒ Decay properties of neutron rich fission products

TRIGA-TRAP

Sources for ultra cold neutrons (UCN)

Ultra Cold Neutrons (UCN)

Thermal neutrons

Velocity: v ≈ 2200 m/s

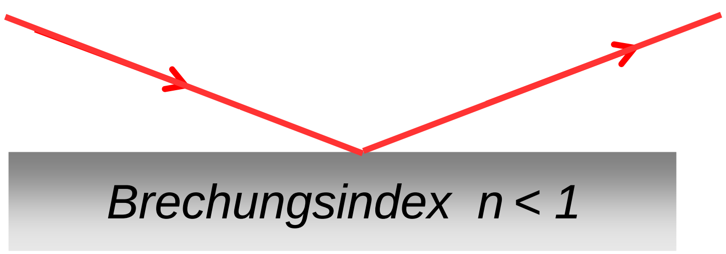
Energy: 1/40 eV

Ultra cold neutrons (UCN)

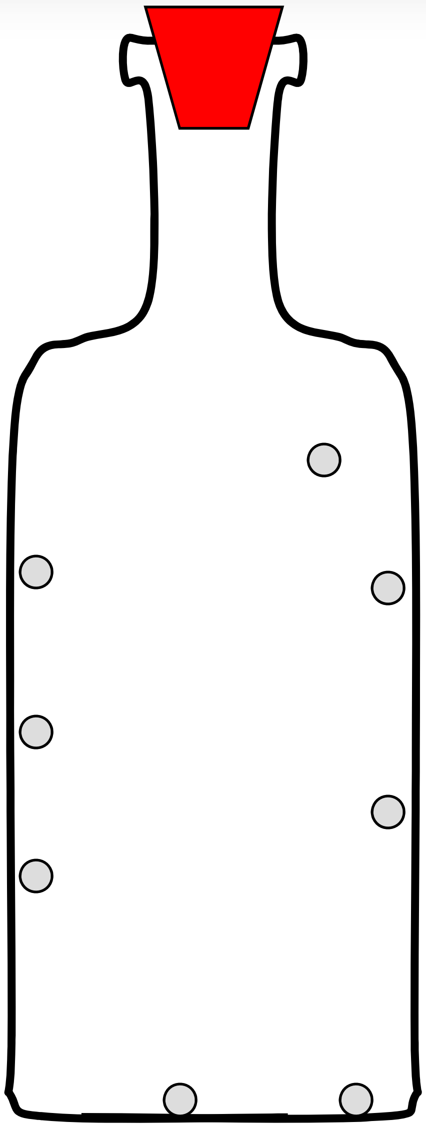
Velocity: v ≤ 7 m/s

Energy: 250 neV

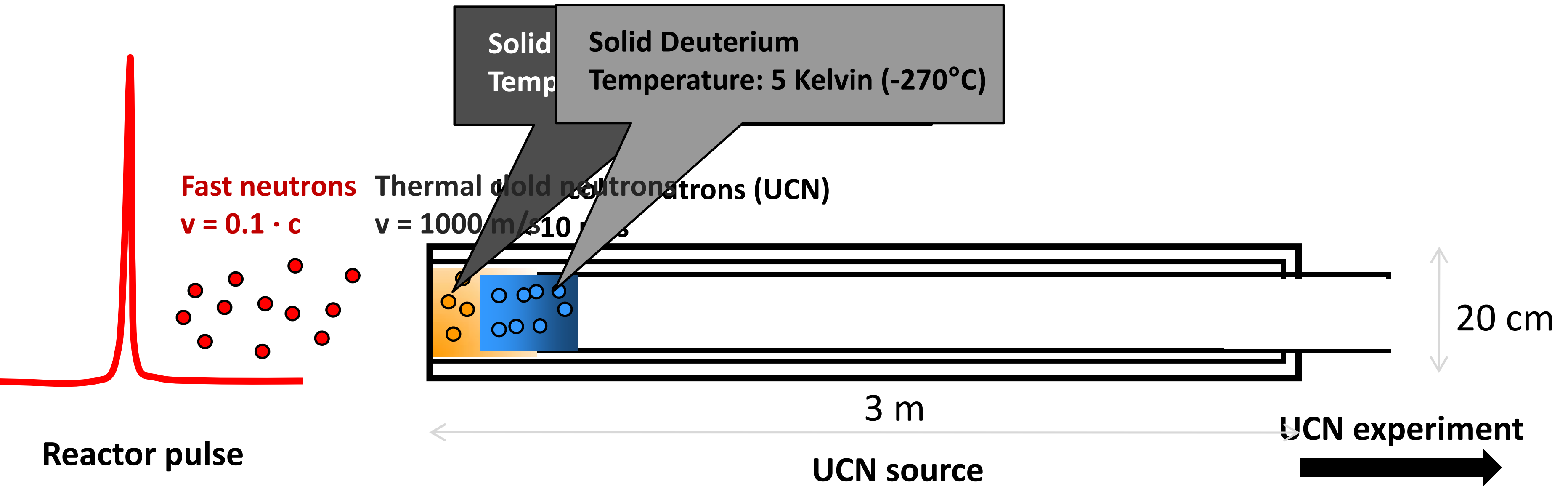
Total reflection at materials like Stainless steal , Ni, Be, Diamand under all angels



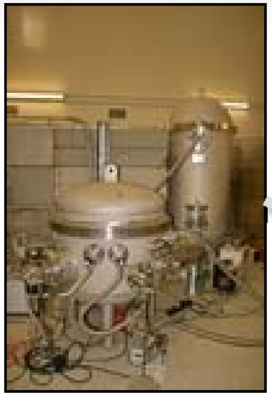
=> UCN can be storied in bottles of these materials



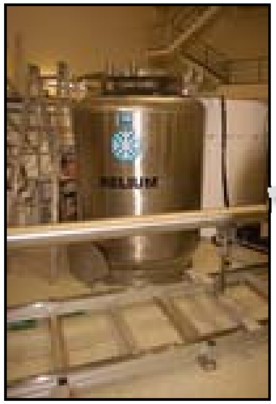
Prinziple of the UCN source at the TRIGA Mainz



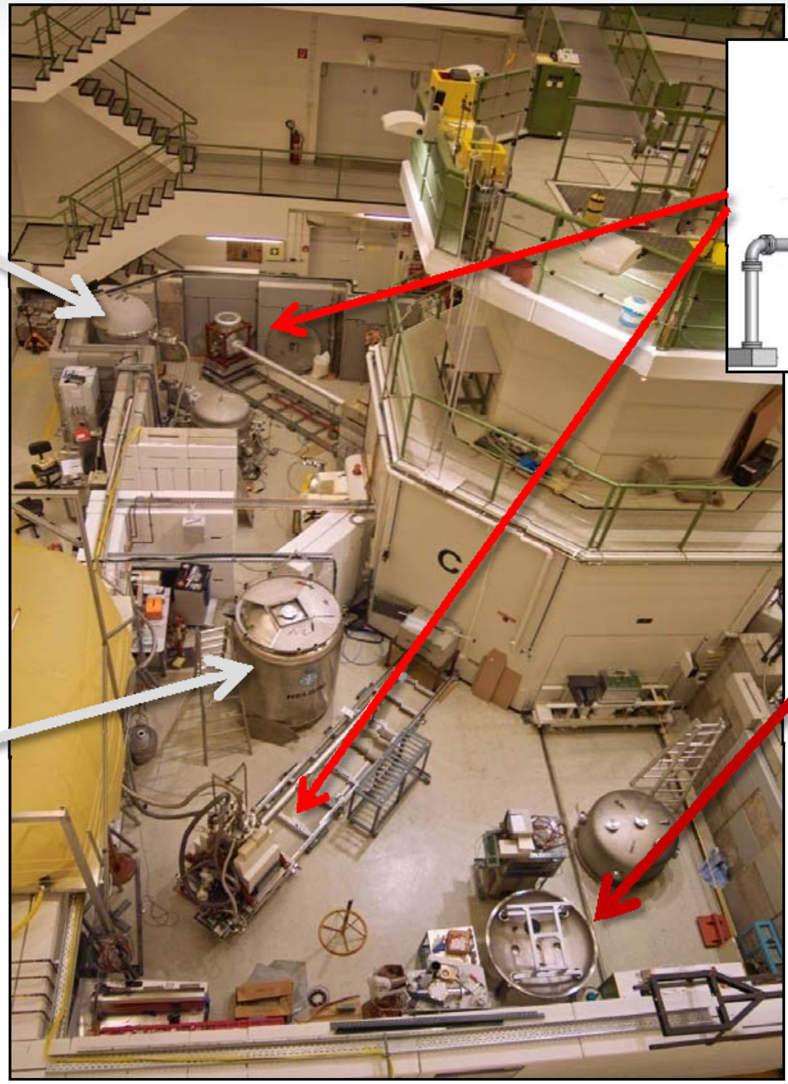
UCN source at the TRIGA Mainz

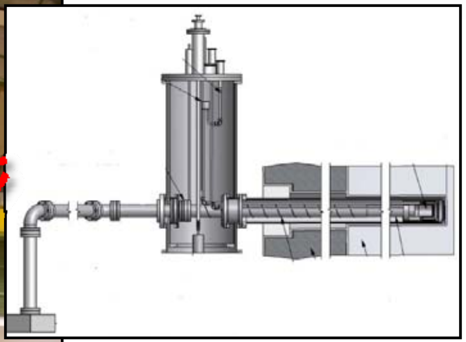


Deuterium/Hydrogen Storage tank



Helium tank





UCN source

UCN storage experiment

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Ultrakalte (ultra-cold) Neutronen (UCN)

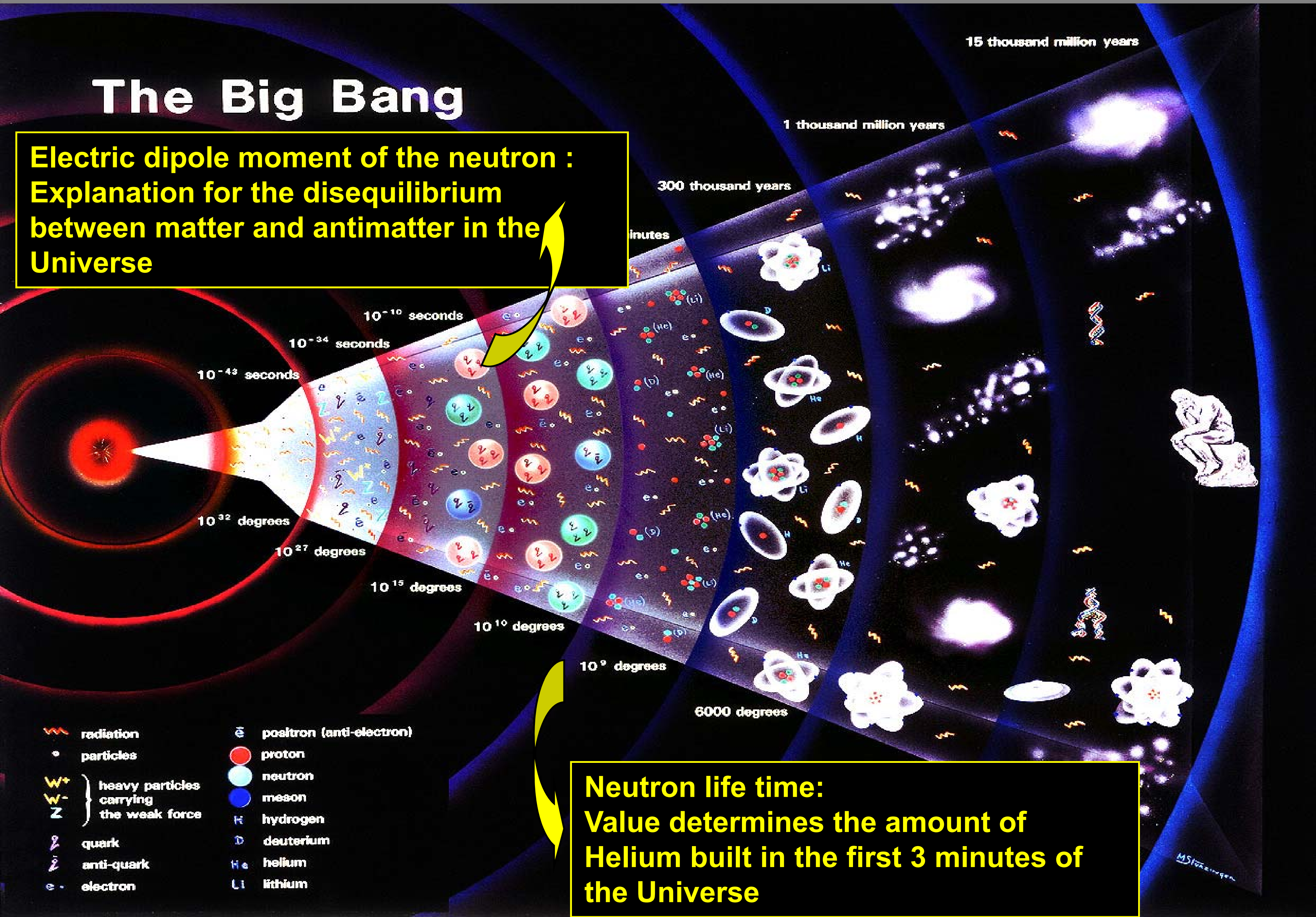
=> High precision experiments with free neutrons !

- **Determination of the live time of the neutrons**
- **Search of the electrical dipole moment of neutrons**

nEDM

⇒ **Answer of fundamental questions of astro-particle physics like the primordial synthesis (i.e. the production of the lightest elements directly after the Big Bang) or the absence of antimatter in the Universe**

Präzisionsexperimente an freien Neutronen



Electric dipole moment of the neutron : Explanation for the disequilibrium between matter and antimatter in the Universe

Neutron life time: Value determines the amount of Helium built in the first 3 minutes of the Universe

Future of the TRIGA Mainz

- TRIGA Mainz is in excellent technical state
- No fuel failure in 45 years of operation
- 7 fresh fuel elements in stock
- Operation at about 200 days per year, more than 17,000 pulses
- Extensive education and training programme
- Extensive research programme **(UCN, TRIGA-SPEC, BNCT, chemistry of the heaviest elements, NAA)**
- Increase of the staff

$\Rightarrow$ **Extension of the reactor operation to at least 2020**

Thank you for your attention !