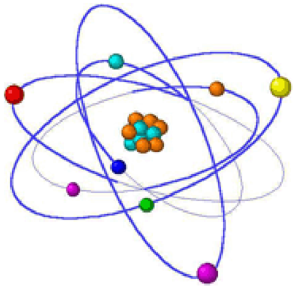
Radioisotope and Radiation Applications (FS2013)



Gamma and Neutron Radiography (Week 6a)

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Gamma and Neutron Radiography: Outline

Gamma Radiography

- Introduction
- Basics: (Supplement)
  - Principle of γ-Radiography
  - Sources and Detectors
- Examples of Industrial Applications:
  - Overview
  - γ-Radiography: Testing of Welds
  - CT: Manufacturer Information

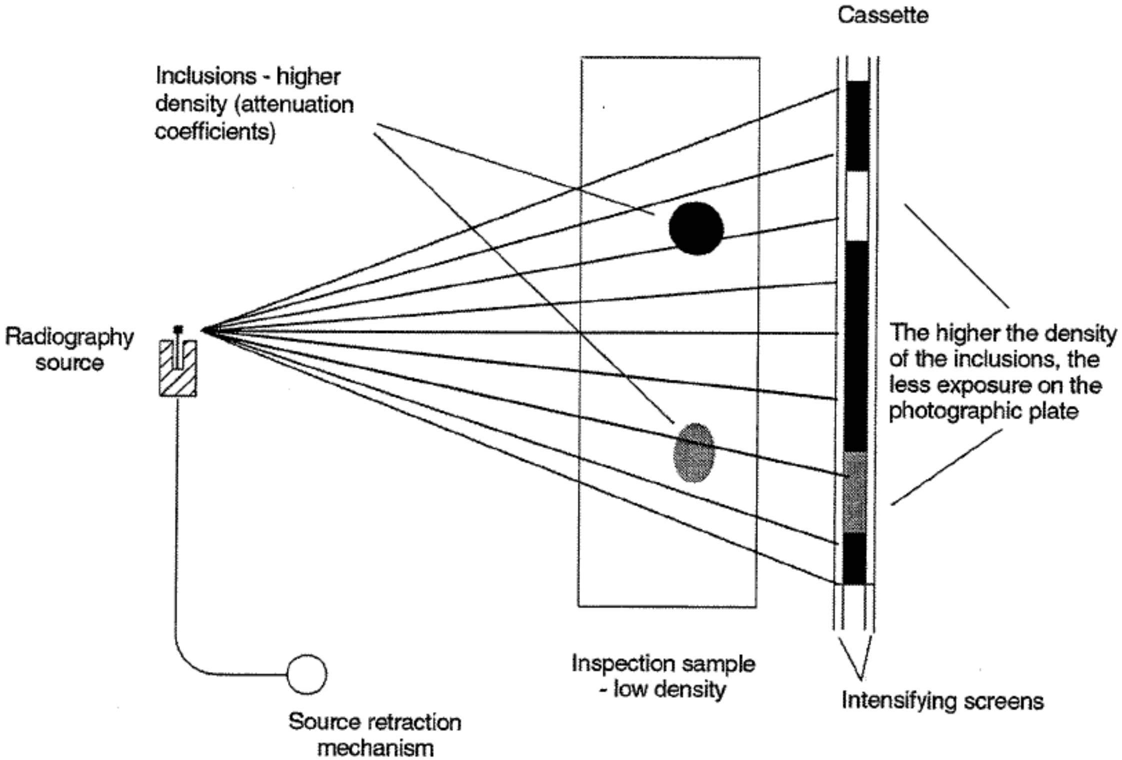
Neutron Radiography

- Basics:
  - Theory of Neutron Interactions:
    - Basic Properties of the Neutron
    - Absorption & Scattering (Suppl.)
    - **Neutron Diffraction**
  - Principle of n-Radiography
  - Principle of CT with Neutrons:
- Complementarity of γ- and n-Radiography
- Special Topics:
  - Time Resolved Radiography
  - Energy-Selective Radiography
  - Phase Contrast
- Examples of Applications

Introduction

- **Definitions:**
  - **Radiography (RG) is the use of certain types of** usually ionizing **radiation to view objects**.
  - (Computerized) Tomography (CT) is imaging by sections or sectioning (sophisticated extension of RG in which the detailed internal structure of a component is obtained in 2D or 3D by analysis of a large number of projections).
- **RG and CT are used both for medical and industrial applications:**
  - Medical radiography (lecture week 3a) and industrial radiography (today).
  - Historically RG and CT were first used in medicine, but are now firmly established in industry.
- **Industrial radiography** has grown out of engineering, and **is a major element of nondestructive testing (NDT)**.
- Depending on the radiation applied one uses the terms: X-ray RG, γ RG, neutron RG (or lately: **neutron imaging**).
- With RG and CT you do NOT want to change or modify the object !

Principle of Projection Gamma Radiography (Supplement!)



- Principle: attenuation by absorption and scattering.
- Processes of interaction:
  - **Photoelectric effect** (low energy < 0.5 MeV), σ_{pe}~Z^n (n=4-5)
  - **Compton Scattering** (medium energy 0.5-1.0 MeV), σ_C~Z
  - **Pair Production** (high energy > 1.022 MeV), σ_{pp}~Z^2 (above threshold)
- Attenuation law:
  - $I(x) = I(0) \exp(-\mu_{tot} \cdot x)$
  - with $\mu_{tot}=\mu_{pe}+\mu_C+\mu_{pp}$

Gamma Radiography: Sources and Detectors (Supplement!)

Sources:

- For X-ray RG: high voltage X-ray tubes, betatrons, LINACs
- For gamma RG the following radionuclides are commonly used:
  - ^{60}Co ($T_{½}$=5.27a, E_{γ}=1.17, 1.33 MeV),
  - ^{137}Cs ($T_{½}$=30.2a, E_{γ}=662keV),
  - ^{192}Ir ($T_{½}$=73.8d, E_{γ}=296, 308, 316, 468 keV)
  - ^{169}Yb ($T_{½}$=32.03d, E_{γ}=63, 110, 131, 177, 198, 308, ... keV)

Detectors:

- Photographic film
- Scintillators
- Semiconductor diode arrays

Examples of Industrial Applications: Overview

- Applications of gamma radiography:
  - Inspection of welds **(first example)**.
  - Study of metal castings.
  - Generally: monitoring the internal structure of manufactured components.
- Applications of computerized tomography:
  - Study of machine components and the condition of castings (including measurements of the dimensions) **(second example)**.
  - With high-resolution (5μm) micro-tomographic systems detailed information on the internal structure of materials such as wood and polymers can be obtained.
  - In the steel industry to control products that are manufactured in a continuous process.
  - For the examination of rocket motors.
  - To optimize the milling of timber.

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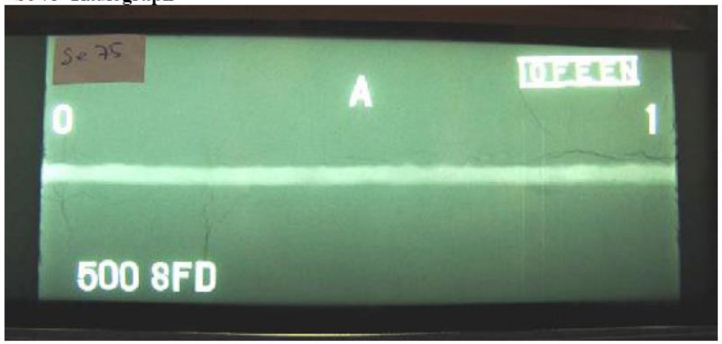
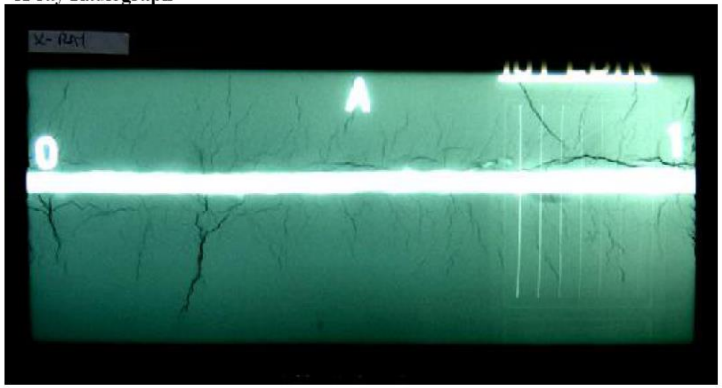
RG Examples: Inspection of Welds

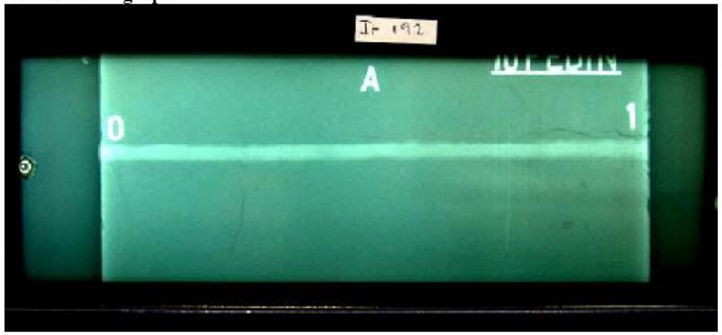
Item 1 – Se 75 Radiograph



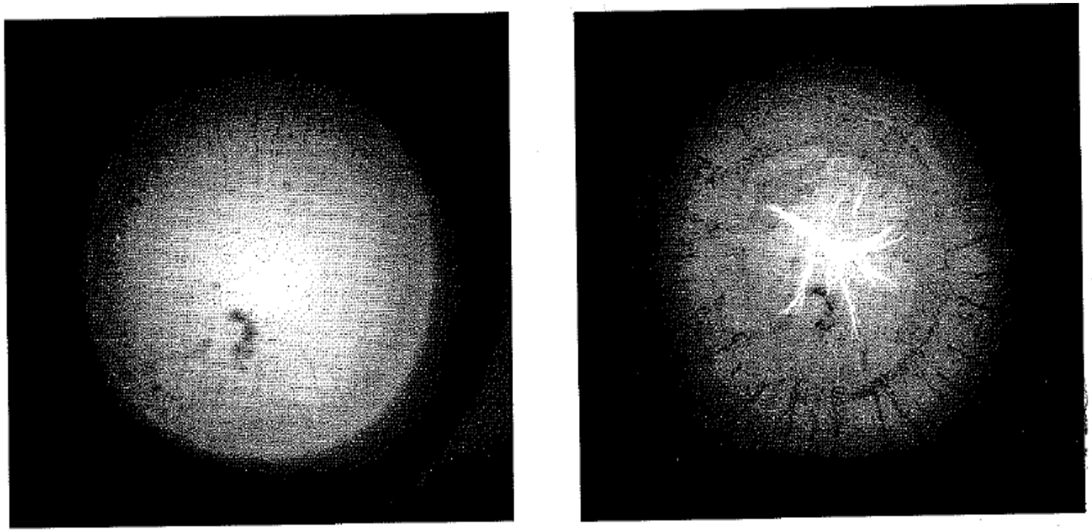
Item 1 – X-ray Radiograph



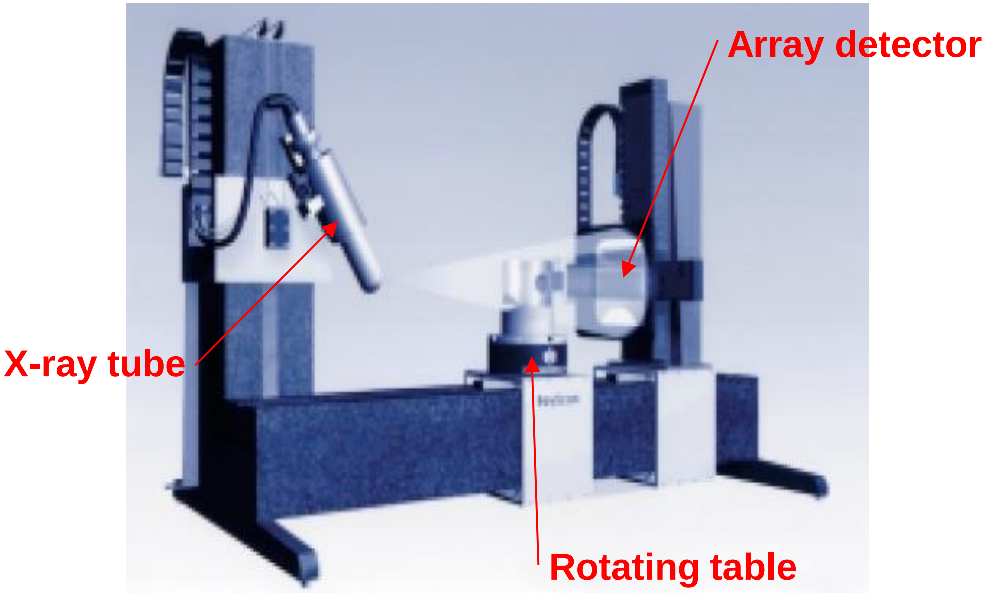
Item 1 – Ir 192 Radiograph



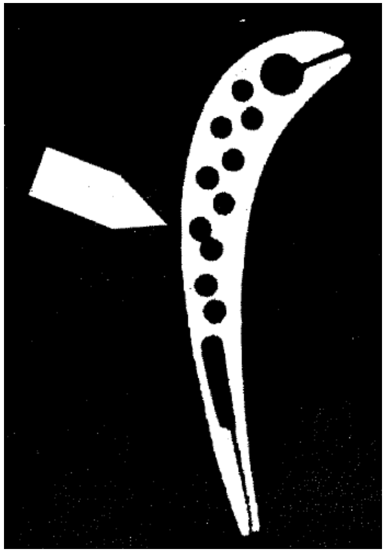
- On the left: welding imperfections of a 3.4mm thick stainless steel plate as seen in RG using a ^{75}Se ($T_{½}$=120d, E_{γ}=121 ... 401 keV), X-ray, and ^{192}Ir source ($T_{½}$=73.8d, E_{γ}=296 ... 468 keV).
- Below: X-ray RG of welding spots on a thin aluminum sheet, faultless and with cracks.



CT Example: X-ray CT Manufacturer Information



Material	additive wall thickness
Plastics	200 mm – 250 mm
Light metal alloys	approx. 150 mm
Model mate-rials (plaster, wood, resin)	200 mm – 250 mm
Glass, ceramics	on request
Steel	approx. 25 mm



- Computer tomographs for industrial applications are commercially available, see, e.g., http//:www.hwm.com (Wälischmiller GmbH).
- CAD data can be generated from the results of the CT.
- Some materials suitable for CT analysis with a maximum additive wall thickness are listed in the table.
- In the figure a faulty turbine blade is shown.

Basic Properties of the Neutron

- According to **Quantum Mechanics**, **all elementary particles** have properties that are **wave-like** (interference) **and** properties that are **particle-like** (localization).

- A neutron seen as a (non-relativistic) particle is characterized by properties like:
  - its zero charge and its (rest) mass of $m_N = 1.6749 \cdot 10^{-27}$ kg,
  - its momentum $\mathbf{p} = m\mathbf{v}$ and kinetic energy $E = ½ m_N \mathbf{v}^2 = \mathbf{p}^2/(2m_N)$,
  - its spin of 1/2 and magnetic moment $\mu_N = -1.913\mu_N$ ($\mu_N = e\hbar/2m_P$= nuclear magneton).

- Neutron beams seen as waves may show diffraction and interference can occur:
  - By the **De Broglie relation $\lambda = h/p$** (λ=wavelength, h=Planck constant, p=momentum) a wavelength can be attributed to a neutron.
  - For low energy neutrons with momentum $\mathbf{p}=m\mathbf{v}$ one can write: $\lambda = h/(2mE)^{½}$ or $E = h^2/(2m\lambda^2)$.

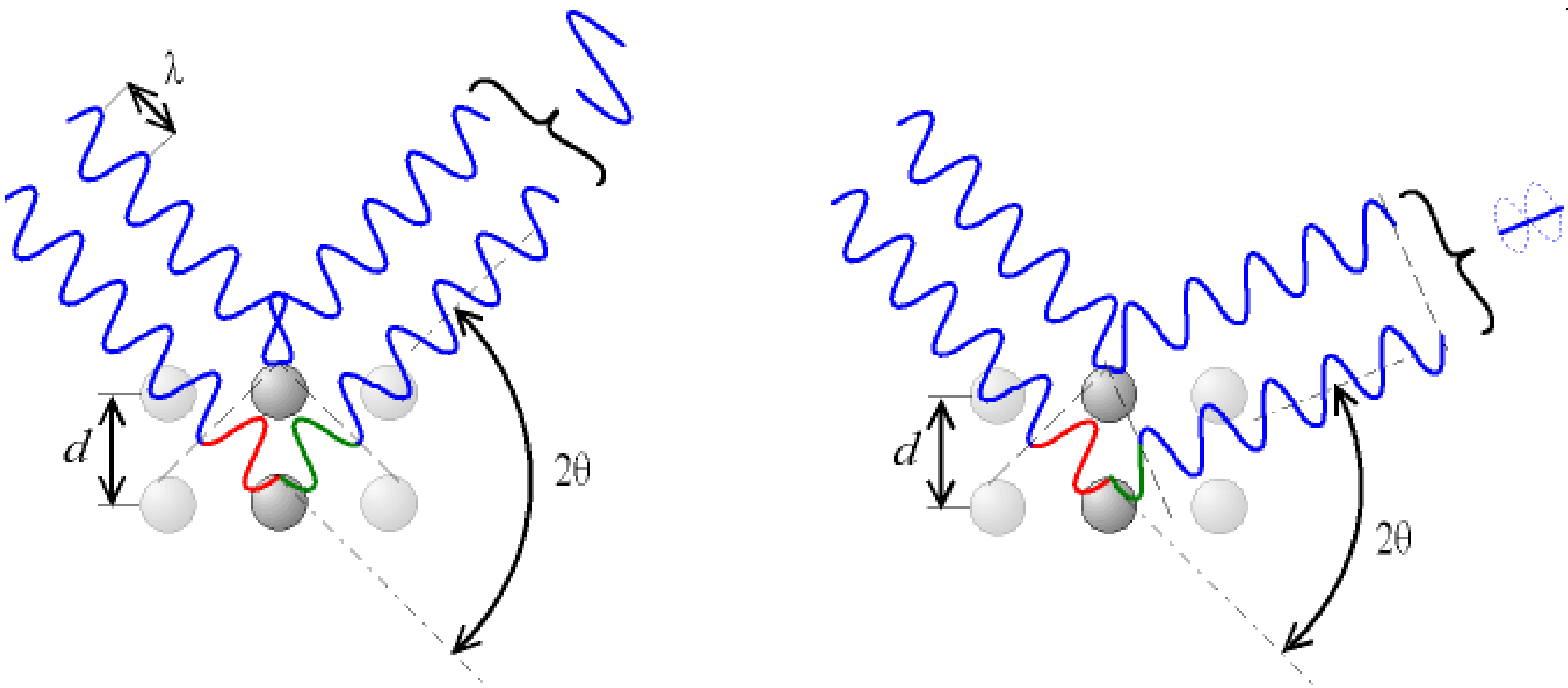
category	energy range	wavelength [Å]	velocity [m/s]
ultra cold	≤ 300 neV	≥ 500	≤ 8
cold	0.12 meV – 12 meV	26.1 – 2.6	152 – 1515
thermal	12 meV – 100 meV	2.6 – 0.9 (~ interatomic distance)	1515 – 4374
thermal (average)	25.3 meV	1.8	2'200
epithermal	100 meV – 1 eV	0.9 – 0.28	$4374 – 13.8 \cdot 10^3$
intermediate	1 eV – 0.8 MeV	0.28 – 0.00032	$13.8 \cdot 10^3 – 12.4 \cdot 10^6$
fast	> 0.8 MeV	< 0.00032	$> 12.4 \cdot 10^6$

Neutron Interaction with Matter (Supplement!)

- Generally neutron interactions with matter may be divided into:
  - Absorption-reactions:
    - Radiative capture: $^{A}Z(n,\gamma)^{A+1}Z$
    - Nuclear reactions: $^{A}Z(n,p)$, $^{A}Z(n,\alpha)$, $^{A}Z(n,2n)$, ...
    - Fission of heavy nuclei: $^{A}Z(n,f)$
  - Scattering-reactions, in which the neutron loses kinetic energy and changes direction:
    - Elastic scattering: $^{A}Z(n,n)^{A}Z$; energy loss of neutron is highest for light nuclei
    - Inelastic scattering: $^{A}Z(n,n')^{A}Z$
  - Diffraction: the neutron changes its direction only.
- Attenuation: $\mathbf{I(x) = I(0)\cdot exp(-\Sigma_t\cdot x)}$, $\mathbf{\Sigma_t = N\cdot\sigma_t = N\cdot(\sigma_e+\sigma_i+\sigma_\gamma+\sigma_r+...)}$
- The magnitude of the cross sections for the various neutron induced processes depend on E_n and on the structure of the target (nucleus and crystal lattice).
- Due to the high interaction probability of thermal neutrons with hydrogen containing materials, neutron RG delivers high contrast images for thin layers of organic substances or samples partly consisting of hydrogen rich components.

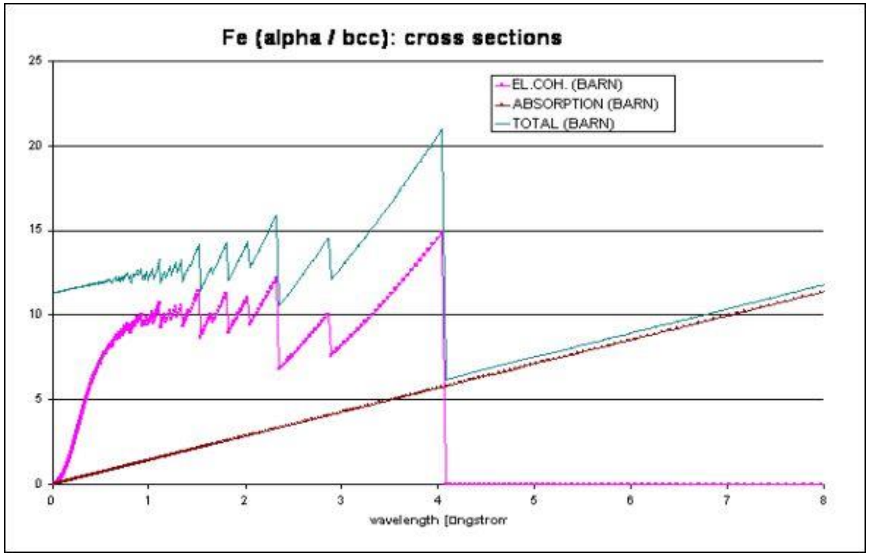
Neutron Diffraction (1): Basics

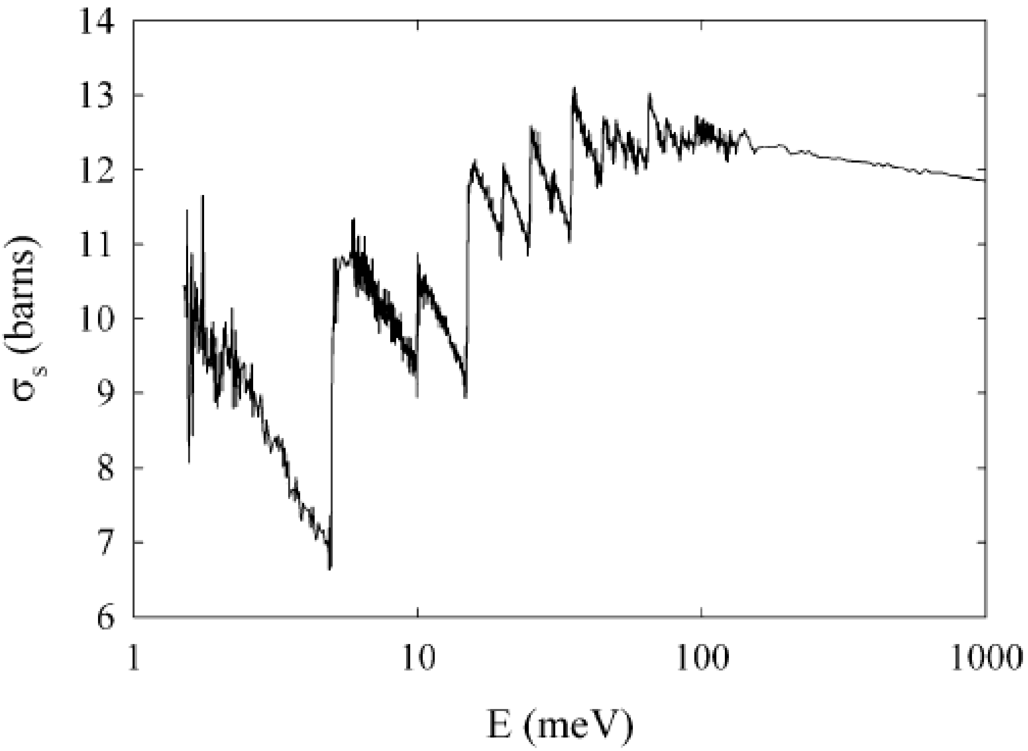
- **Bragg's law** for scattering of waves on crystal lattices:
  - **interference is constructive** when the phase shift is a multiple of 2π, or
  - Bragg's equation is fulfilled: **$n \cdot \lambda = 2d \cdot \sin(\theta)$** with:
    - θ = angle between incident ray and scattering plane
    - *d* = spacing between lattice planes
    - n = integer



Neutron Diffraction (2): Bragg's Edges

- The figure on the left shows the neutron cross sections in barn for scattering, absorption, and the total for Fe (bcc structure) in the wavelength range from 0 to 8 Å.
- Above 4 Å the run of the curve is dominated by absorption and increases with wavelength. At and below 4 Å the so-called "Bragg edges" appear due to the diffraction of neutron waves.
- The figure on the right shows the same features for scattering on polycrystalline iron.





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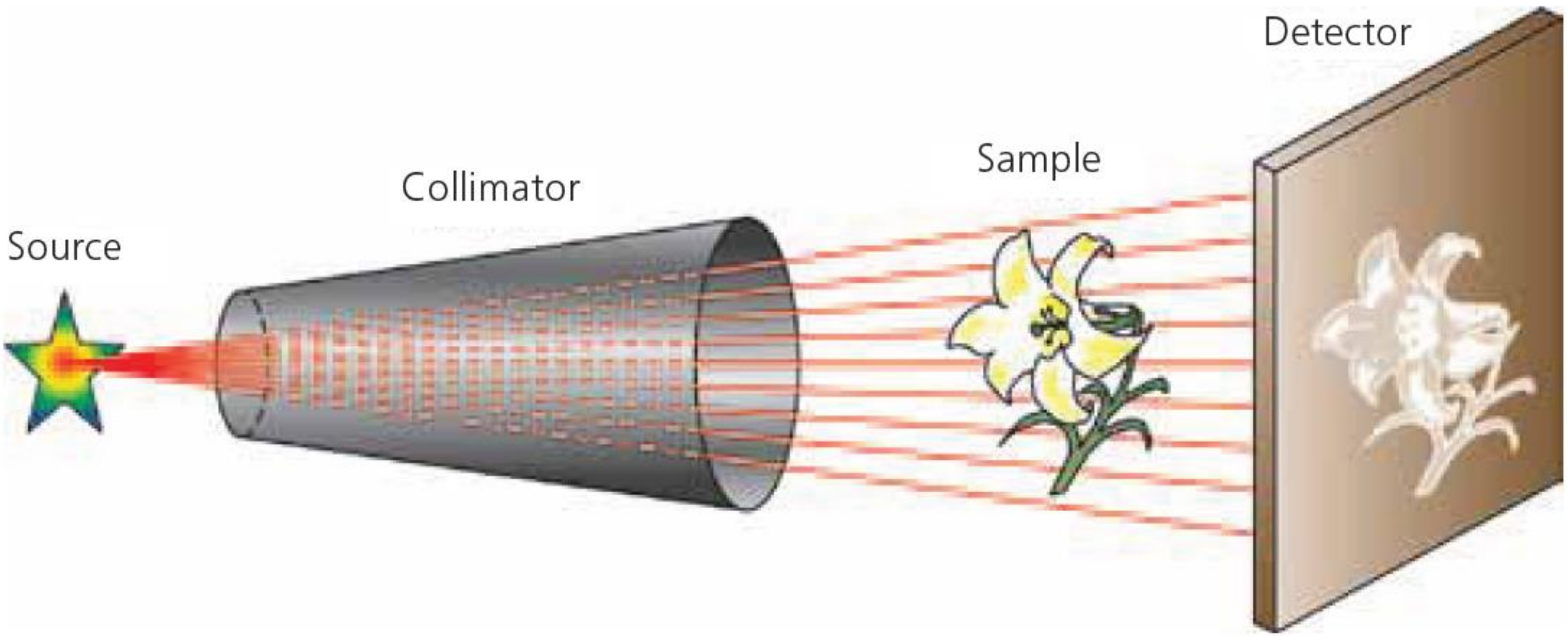
Applications due to Distinctive n-Properties

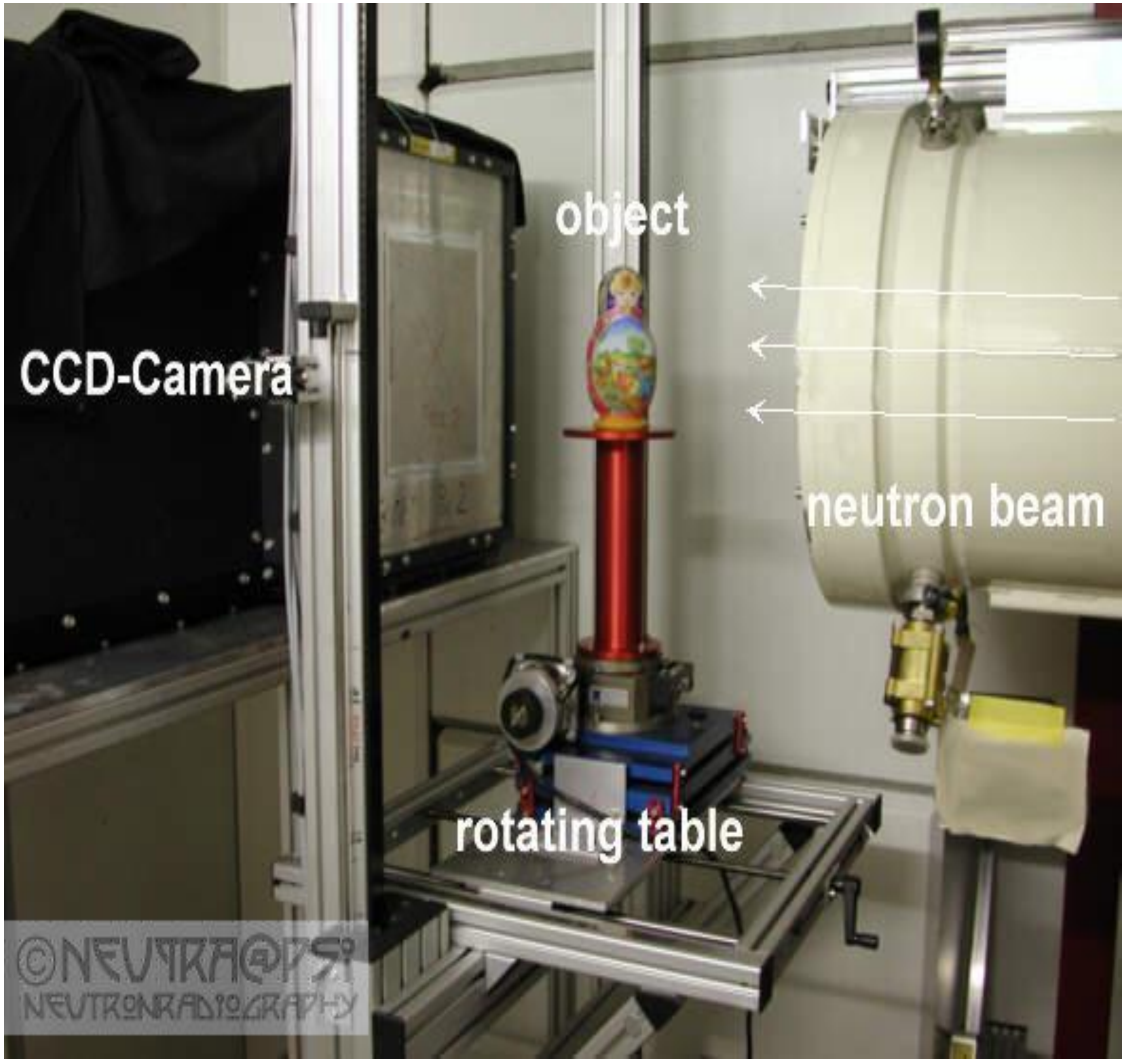
- Neutrons are weakly interacting neutral particles that penetrate deeply into most materials, so they can be used to internally image large objects, e.g., a full-size operating internal combustion engine, non-destructively.
- The amount of scattering or absorption of neutrons by atomic nuclei varies in an apparently random fashion through the periodic table. Hydrogen in particular has a very large scattering cross-section. Neutrons can therefore provide good contrast for light atoms in the presence of heavy atoms. This makes neutron imaging highly complementary to X-ray imaging.
- The amount of scattering or absorption can also vary significantly between isotopes of the same chemical element, e.g., hydrogen has a very different scattering cross-section from that of its isotope deuterium. The contrast of particular elements/materials in an image can therefore be enhanced by substituting one isotope for another.
- "Thermal" neutrons have wavelengths similar to inter-atomic distances, so mechanisms such as refraction or diffraction can be used to enhance images or to produce indirect images.
- Neutrons have a magnetic moment and a magnetic scattering cross-section that is comparable to the nuclear cross-section for many atoms. They can therefore be used to image magnetic structures.

Principle of Projection Neutron Radiography

- The collimator selects a straight neutron beam that passes through the object. A neutron area detector measures the attenuation.
- The principles of neutron and γ radiography are the same, except for the different sources and interactions.

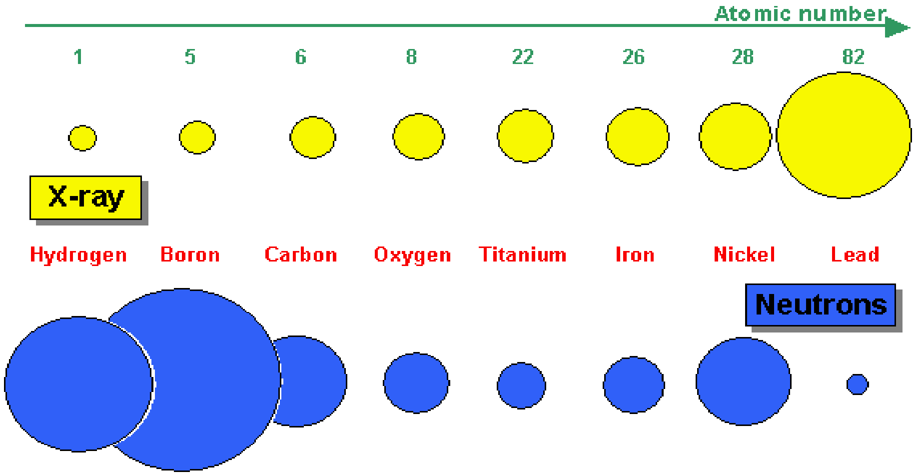


Principle of Neutron Computerized Tomography

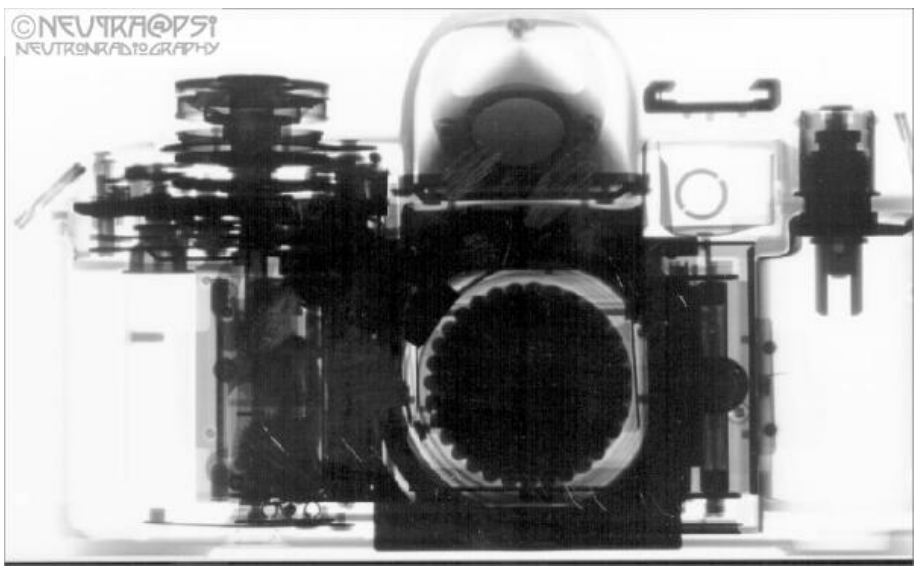


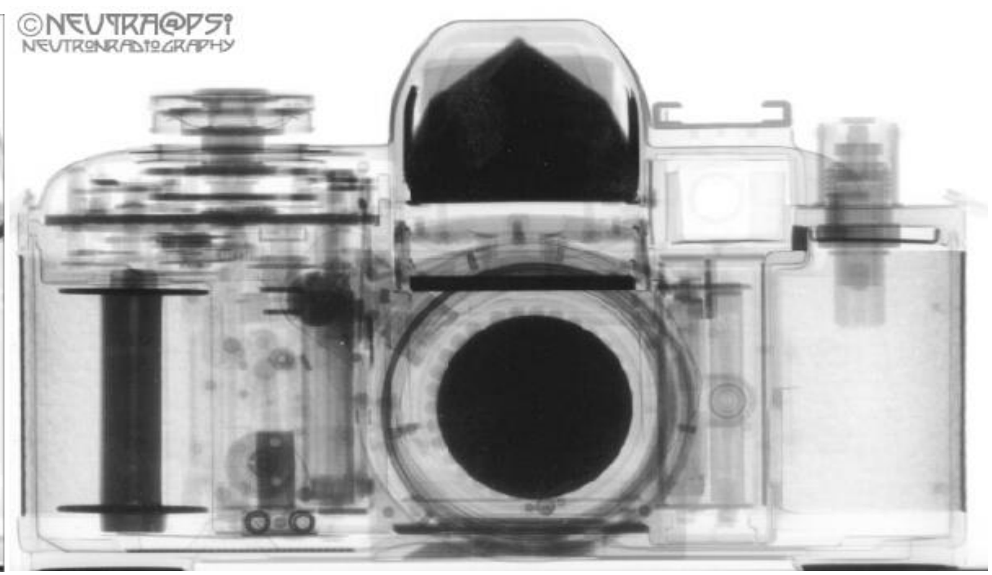
- ❑ Same principle as in X-ray CT, except that the sample is rotated in neutron tomography.
- ❑ Neutron RG and CT have been further developed during the last decades:
  - Time-resolved neutron RG.
  - Energy-selective RG, especially ultra cold neutrons.
  - Using phase contrast to obtain better images.
  - Better detectors.

Complementarity of Gamma (X-ray) and Neutron RG (1)

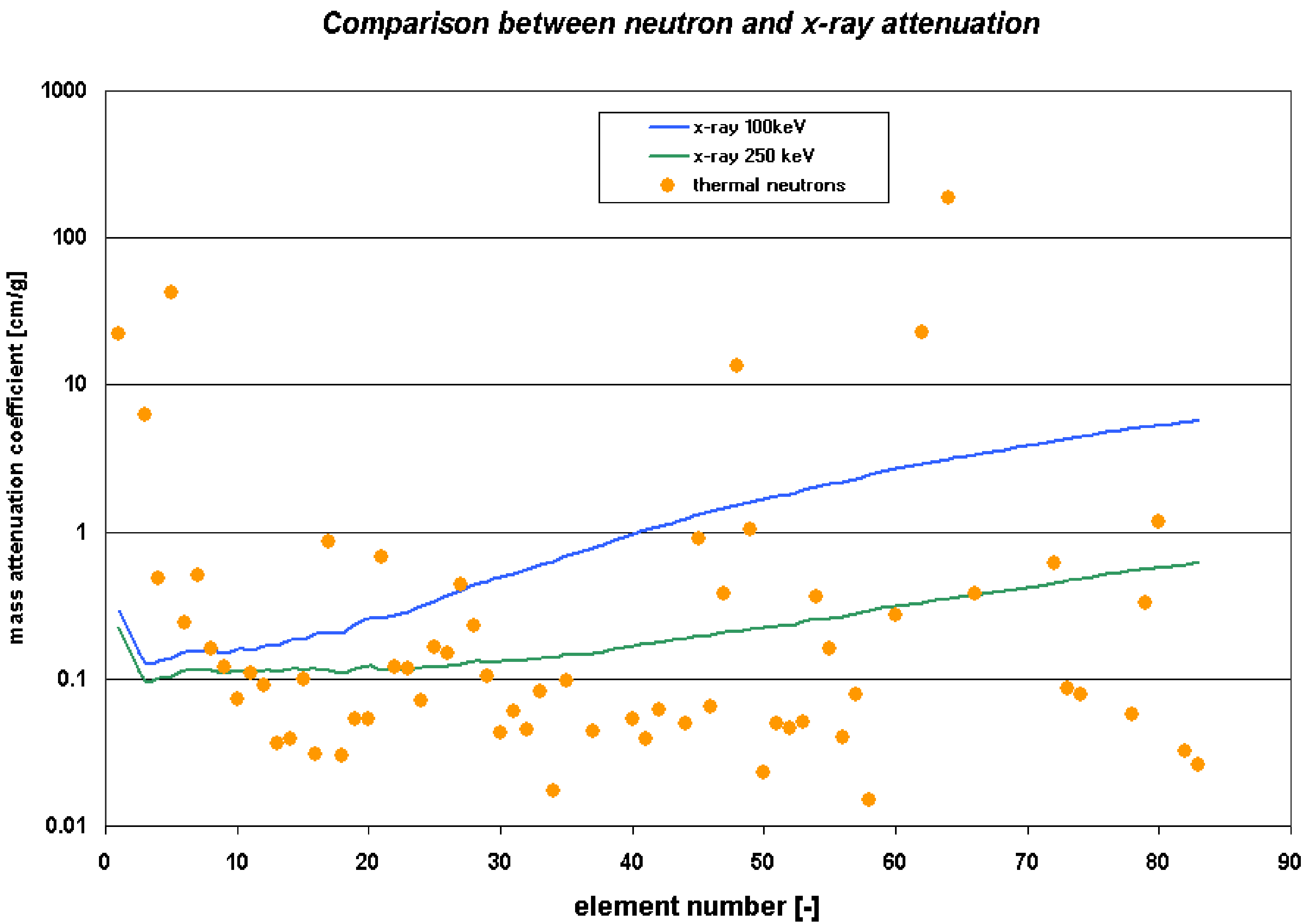


- X-rays and gamma rays mainly interact with the electronic shell of the atom and therefore increase ~Z^n.
- Neutrons interact with the atomic nucleus.
- The figure on the left illustrates the gamma and neutron interaction probabilities for selected nuclei.
- The figures below show radiographs of a camera (left: X-ray, right: neutron).

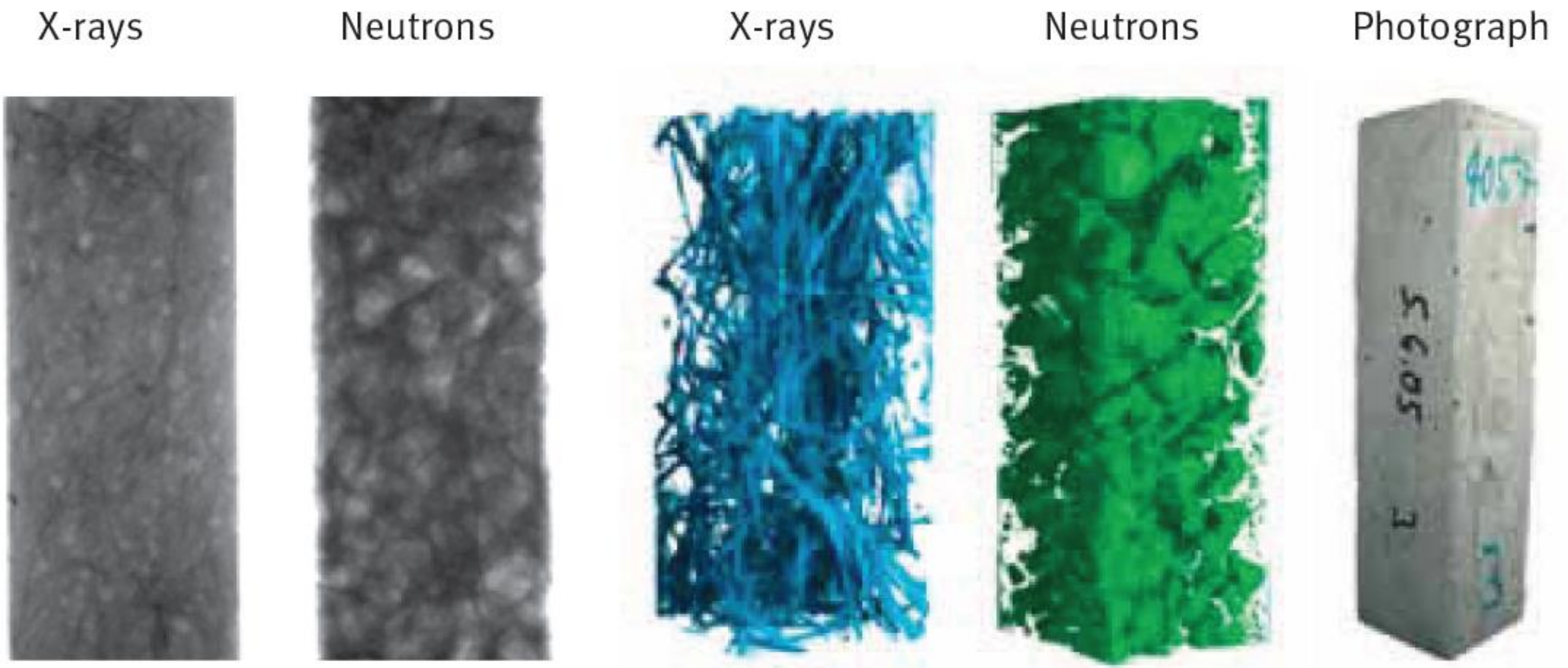




Complementarity of Gamma (X-ray) and Neutron RG (2)



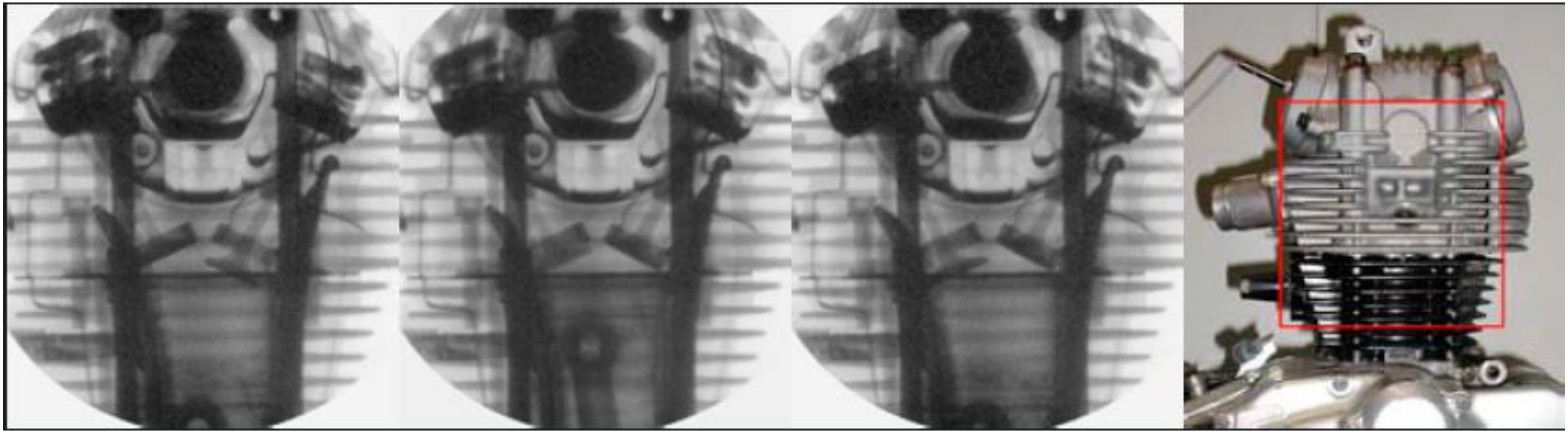
Complementarity of X-ray and Neutron Tomography



- “Pictures” of a reinforced concrete sample. The two images on the left are radiographs, on the right there is a photograph. The blue and green images are tomograms.
  - In the green image it is possible to recognize the hydrogen-containing components of the concrete (sand, gravel, etc.), though nothing can be seen of the reinforcing iron.
  - In the blue image, an X-ray tomogram, on the other hand, the structure of the reinforcing iron is practically all that can be recognized.

Time Resolved Radiography

- The propagation of small amounts of hydrogenous substances can be traced (in soil, rock or metallic castings).
- Tomographic acquisition of fluid transport at one minute intervals yielding complete 3D image volumes possible with Si flat-panel detector (frame rates up to 30 frames per sec).
- Picture shows snapshots of a motor-bike engine operating at 1200 rpm.



Energy Selective Radiography

- Many materials (e.g. metals) show steep steps in their neutron interaction probabilities at low neutron energies (E_n).
- By means of energy selective RG measurements, these Bragg edges can be used to enhance contrast or elucidate changes in material properties.
- Narrow bands of E_n are selected by a spinning turbine wheel with strongly absorbing lamellas.
- Figure below shows a photograph (left) and three RGs of a thick steel weld taken with three energy bands at 2.8, 5.1, and 8.0 meV.

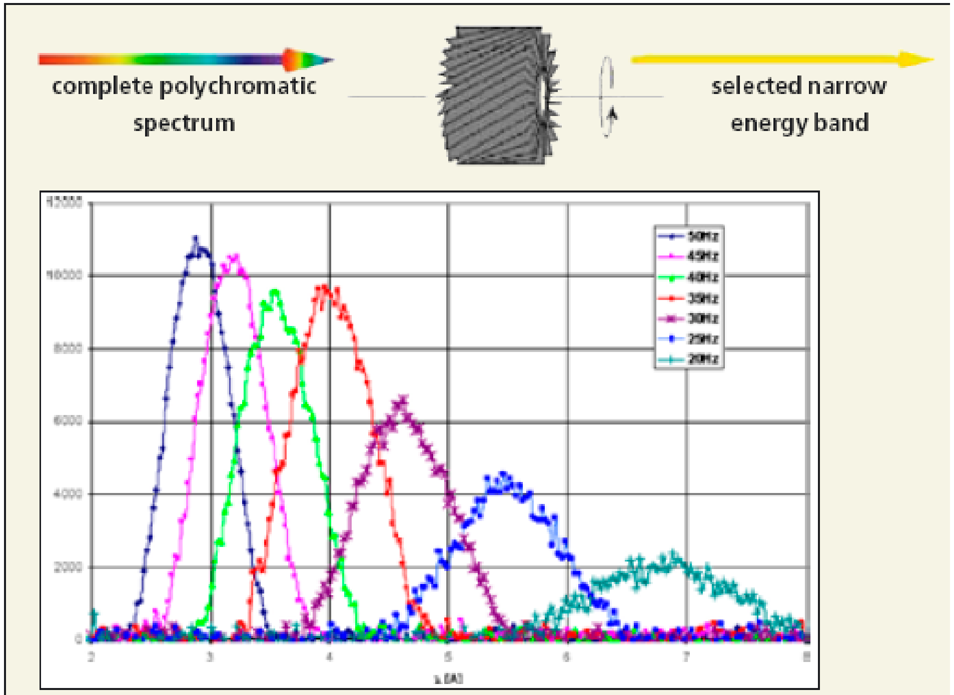
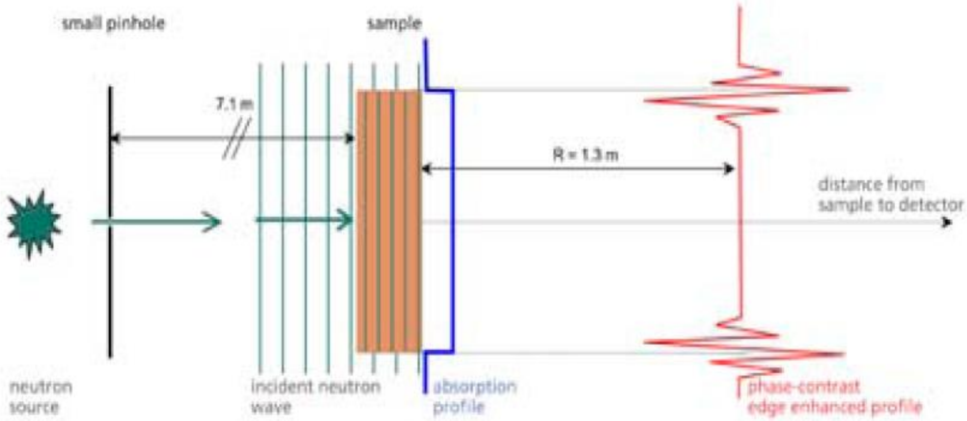
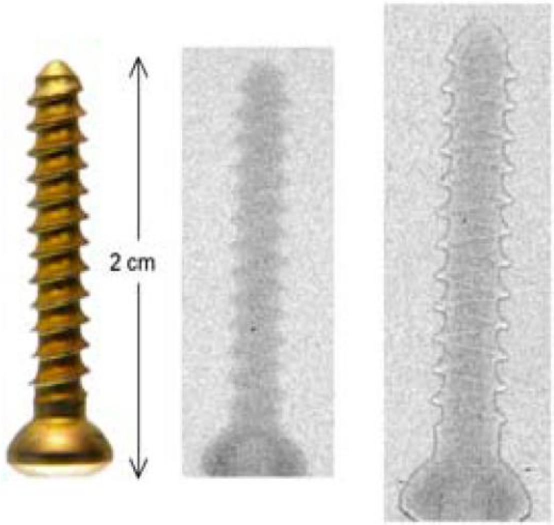


Figure 19: Selecting a neutron energy range by a spinning turbine wheel set up in the neutron flight path. The polychromatic spectrum is transformed into a narrow energy band.

Phase Contrast Enhancement

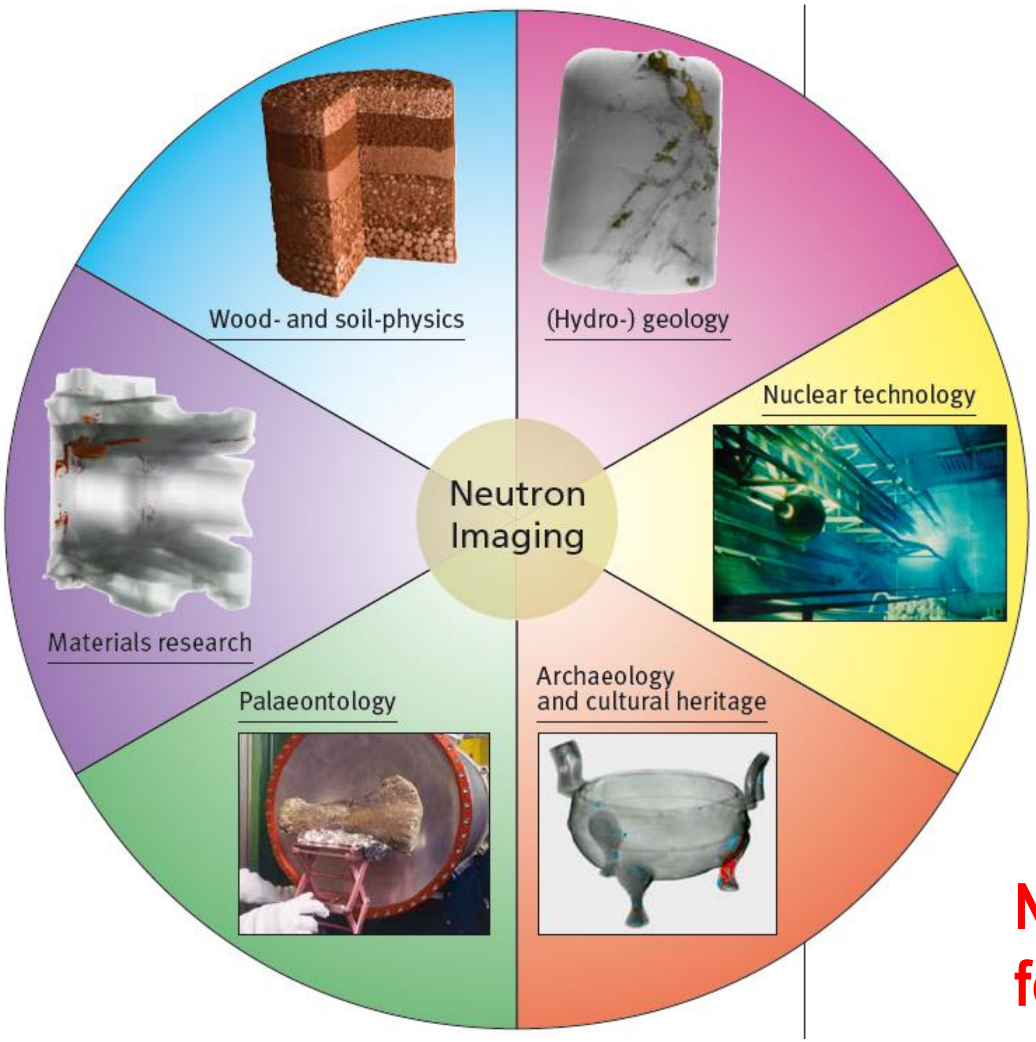




photograph absorption radiograph phase contrast enhanced radiograph

- Neutrons are diffracted by objects and exhibit superposition or interference.
- Neutron waves pass through different media at different speeds and wavelengths, which causes phase shifts.
- **Such phase shifts can lead to image contrast, which then is called phase contrast.**
- Especially at the edges of weakly absorbing objects such contrast enhancements become visible.

Examples of Applications: Overview



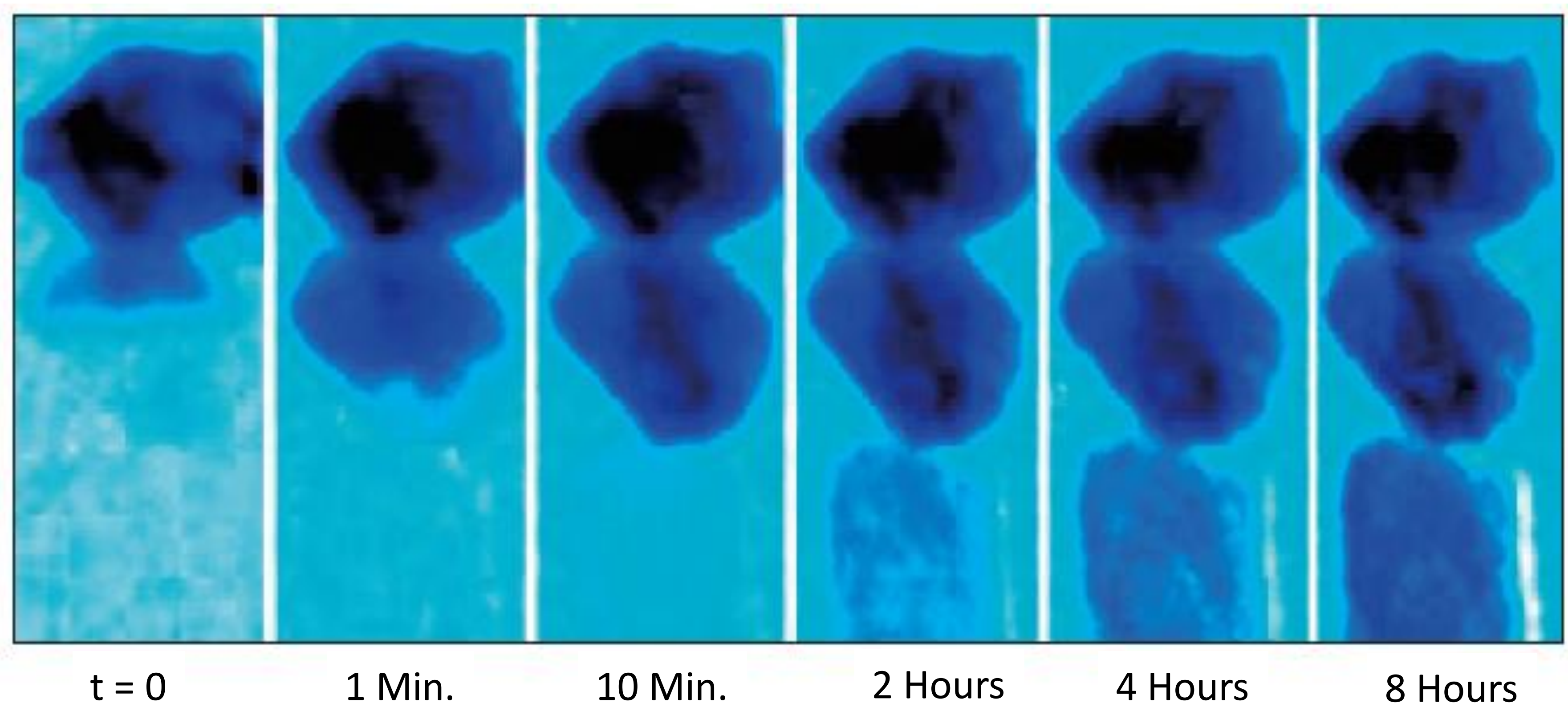
Application fields of n-RG and n-CT:

- Civil engineering (wood & soil)
- Archeology, Paleontology
- Automobile industry (bonding)
- Energy storage (fuel cells)
- Nuclear industry (fuel elements)
- Turbine engines (blades)
- Air and Space industry
- Armaments industry (igniter)
- Material science

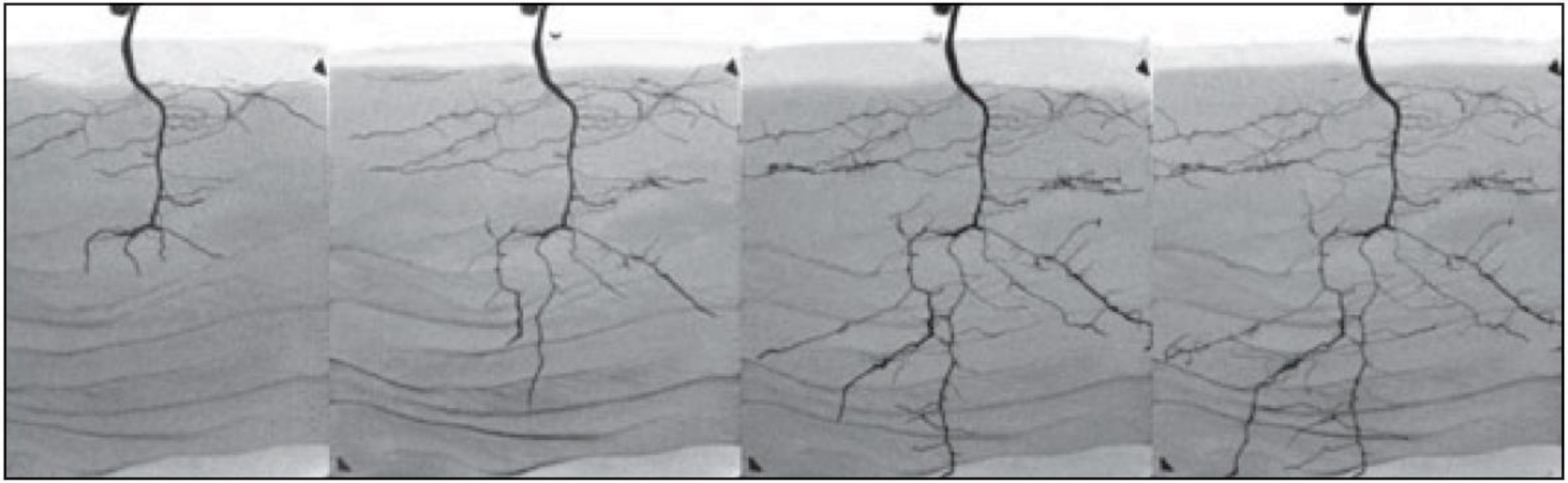
Neutron imaging is mainly used for safety related objects or for expensive and unique objects.

Civil engineering: Soil Structure and Humidity Transport

- **Due to its high sensitivity to small amounts of hydrogenous compounds in a matrix, neutron RG and CT can be used to measure humidity transport in soil.**
- **Measurements are needed for the validation of simulation models used to analyze the mobility of nutrients, pesticides, contaminants ... in soil.**
- **The figure shows humidity transport in small soil agglomerates of 5mm in diameter.**



Civil engineering: Examination of Root Growth



- The figure shows an examination of root growth in a lupine over a period of about four weeks.

Archeology: Renaissance Bronzes

- At PSI renaissance bronzes from the Rijksmuseum Amsterdam were investigated by neutron CT in order to study their castings. The inside of the bronze could be revealed.
- The shape and size of bronze hollows or additional filling materials yielded conclusions about the casting process. Resins or varnish used for the conservation of sculptures appear with high contrast.

Photo: Rijksmuseum Amsterdam

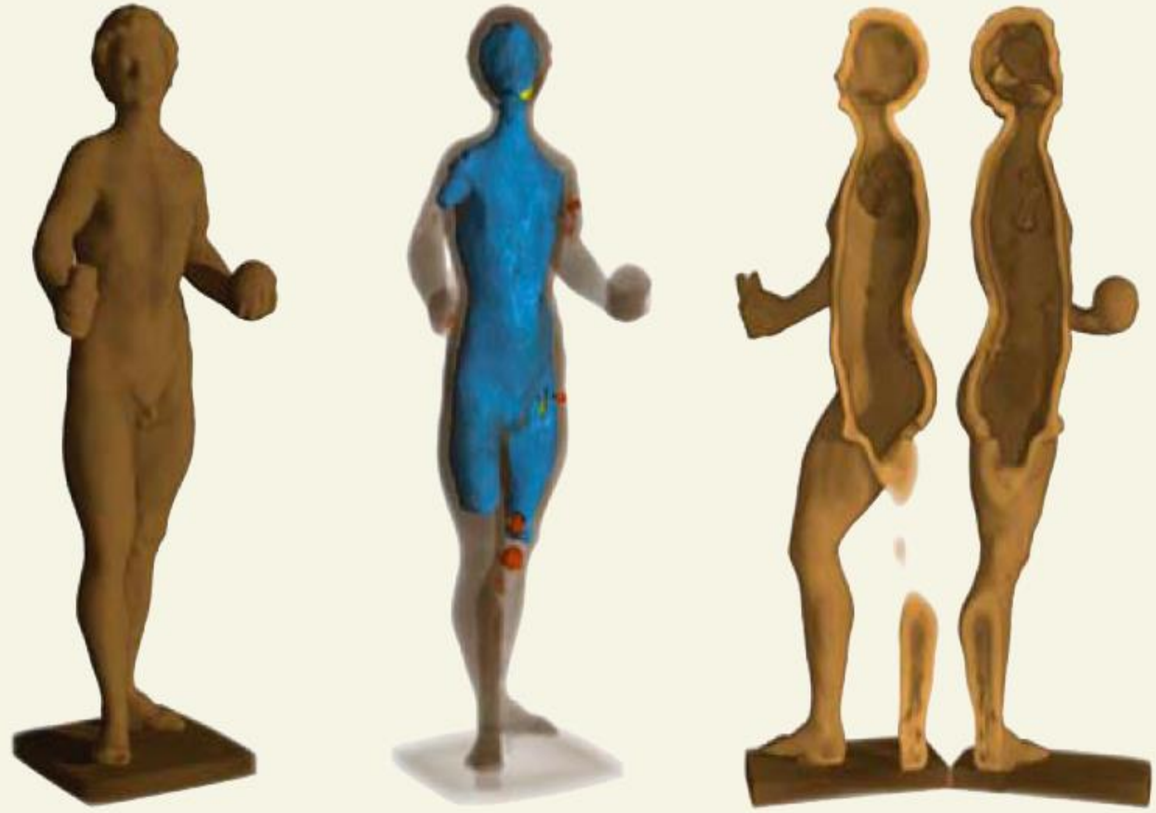
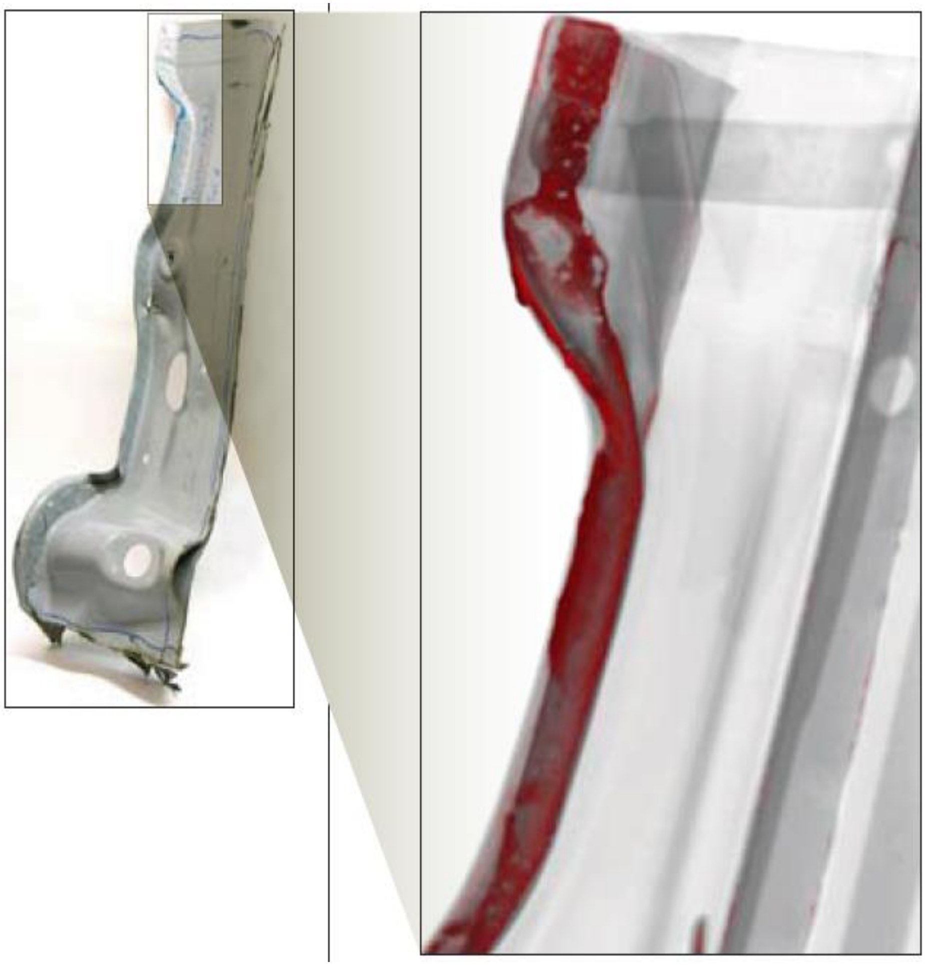


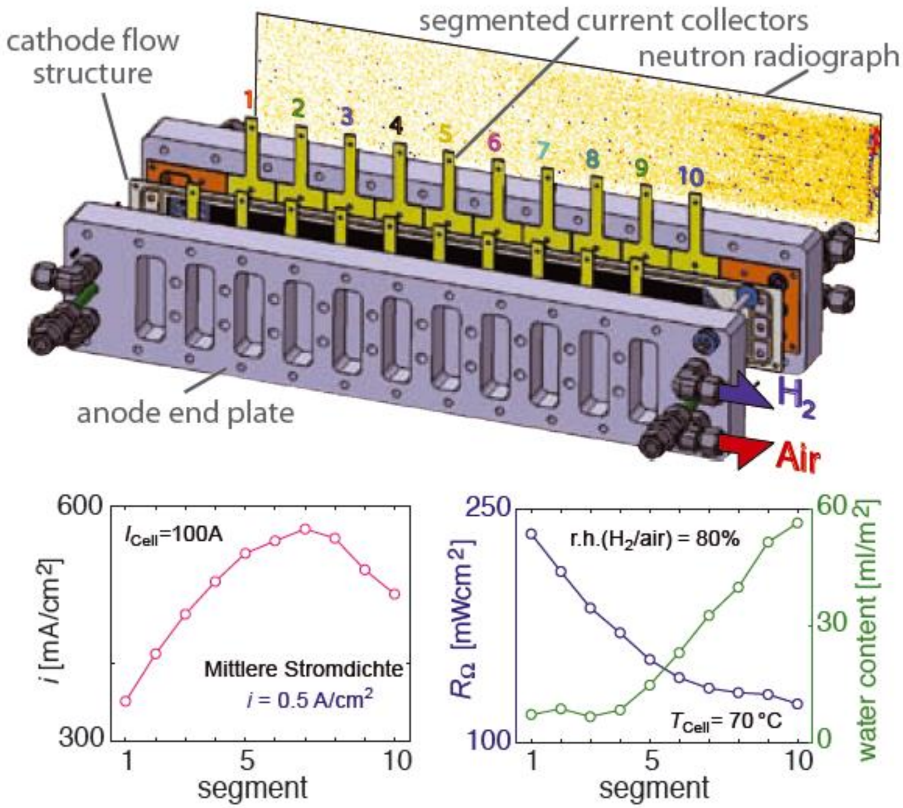
Figure 24: **Tomographic views of a bronze sculpture: virtual slices can be created without damaging this unique object.**

Automobile Industry: Metal Bonding



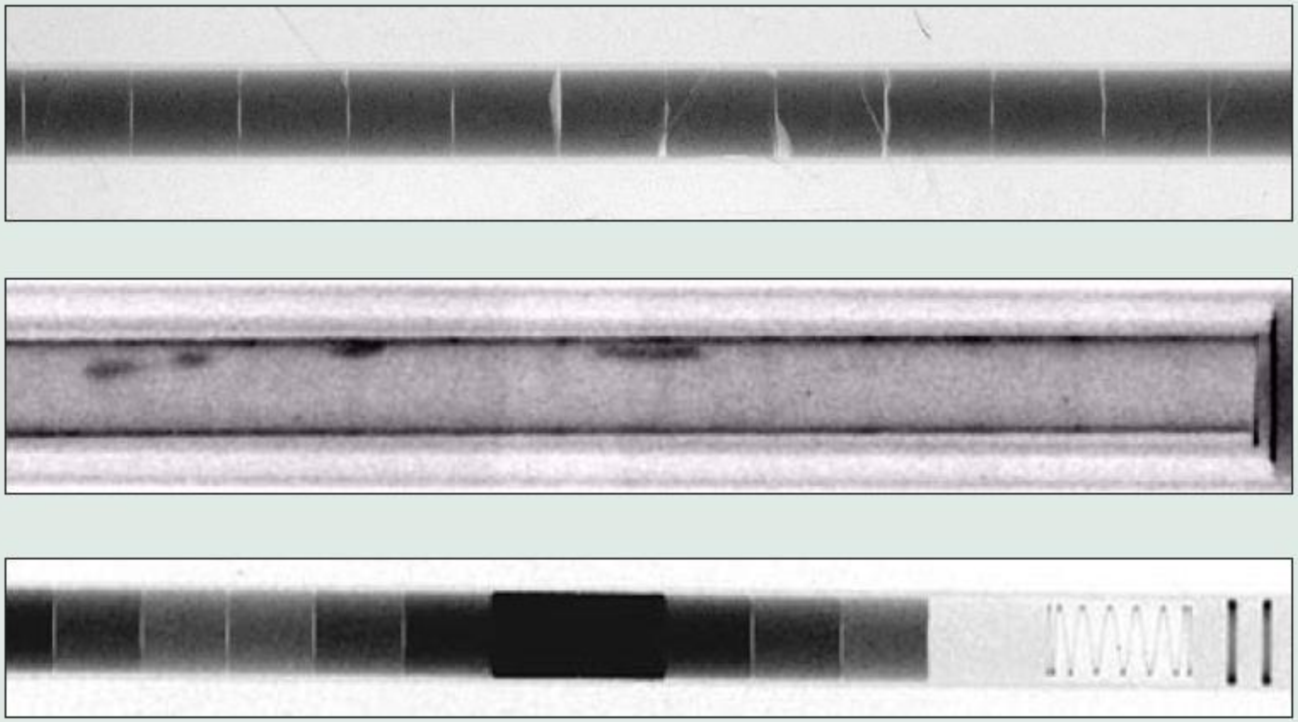
- Adhesives used for metal bonding are hydrogenous epoxy resin compounds.
- Due to the high sensitivity of neutrons to small amounts of hydrogen, even very thin layers of adhesives applied in metal bonding become visible.
- The figure shows part of a bonded automobile frame and reveals bonding inhomogeneities.

Energy Storage: Fuel Cell Investigations



- Changing water content of the fuel cell membrane affects fuel cell performance.
- By neutron RG the water distribution within a working fuel cell can be monitored non-invasively.
- In combination with other spatially resolved characterization methods of the cells electrochemistry, important insight into fuel cell operation can be obtained.

Nuclear Industry: Imaging of Nuclear Fuel

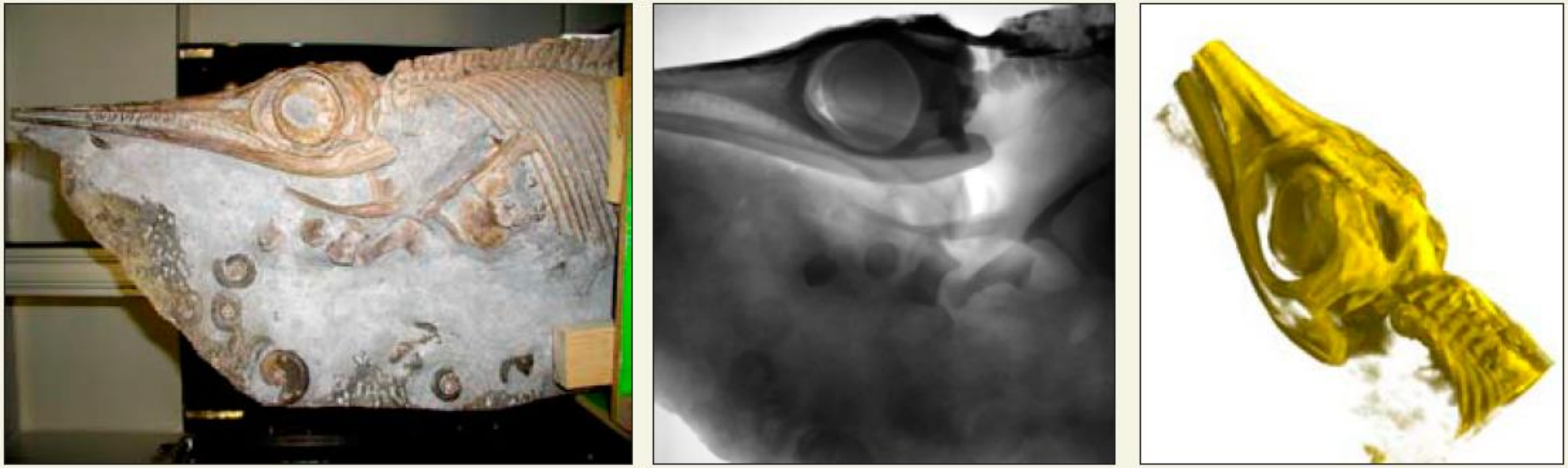


Radiographic inspection of nuclear power plant fuel rod segments: single fuel pellets show fractures and chips (top), zirconium hydride lenses due to cladding corrosion (middle), or fresh fuel pellets with varying isotopic enrichment (lower).

- Traditional X-ray RG of nuclear fuel elements are almost impossible, since irradiated fuel is a strong γ-ray emitter.
- At PSI fuel rod segments can be investigated in collaboration with the PSI Hot Laboratory.
- The aim of the studies of nuclear fuel is to check the integrity of the fuel pellets after long term irradiations and to evaluate the corrosion of the zircaloy cladding.

Paleontology: Investigation of Fossils

- Neutron RG permits non-destructive evaluation of large fossils.
- In the tomographic study of the head section, the skeleton can be segmented from the surrounding sediment.
- Insight into the development of ichthyosaurs can be gained and further restoration steps can be envisaged.

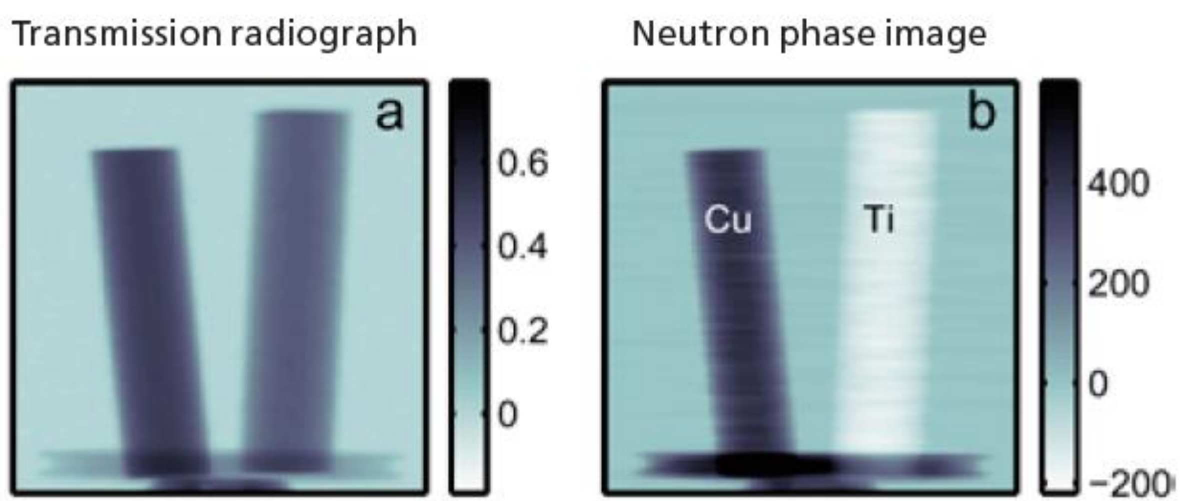


Fossilised skeleton of an ichthyosaur partially dissected by U. Oberli, St Gallen. Photograph (left), radiograph (middle), and tomographic view of head section (right).

Outlook on the development of neutron RG Methods

- Installation of an ultra cold neutron source.
- Implementation of a setup for neutron phase contrast imaging.
- Implementation of an X-ray source setup in the NEUTRA facility at PSI to allow for dual-modality investigations.
- In comparison to synchrotron-based micro-tomography, the spatial resolution of neutron tomography is low (several hundred µm). Goal: 20µm resolution.
- In the figure comparison of:
  - neutron absorption with
  - neutron phase imaging

  of a copper and titanium rod.



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Summary

- Historically **radiography and CT with X-rays and gammas** were first used in medicine, but **are now firmly established in industry**.
- X-ray radiographs and tomographs are commercially available.
- **Industrial radiography is a major element of nondestructive testing** (NDT). Often testing in operation is possible.
- Both gamma and neutron radiography have a broad range of applications.
- **Gamma (X-ray) and neutron radiography are complementary**.
- There is a strong group at PSI that performs neutron radiography for science and industry and that is intensively developing the method.

Literature / WWW-references

- G.C. Lowenthal, P.L. Airey, *“Practical Applications of Radioactivity and Nuclear Reactions”*, Cambridge University Press (2001), **Chapter 7**
- Hassina Z. Bilheux, Robert McGreevy and Ian S. Anderson, *“Neutron Imaging and Applications”*, Springer (2009)
- *PSI-Brochures:*
  - **Neutron Imaging** / How neutrons create pictures, (Villigen PSI, November 2007)
  - **Neutrons for Research** / The Spallation Neutron Source SINQ at the Paul Scherrer Institute, (Villigen PSI, January 2009)
- Neutron Imaging and Activation Group at PSI: http://neutra.web.psi.ch