Neutrons.

Sources and theory basics.

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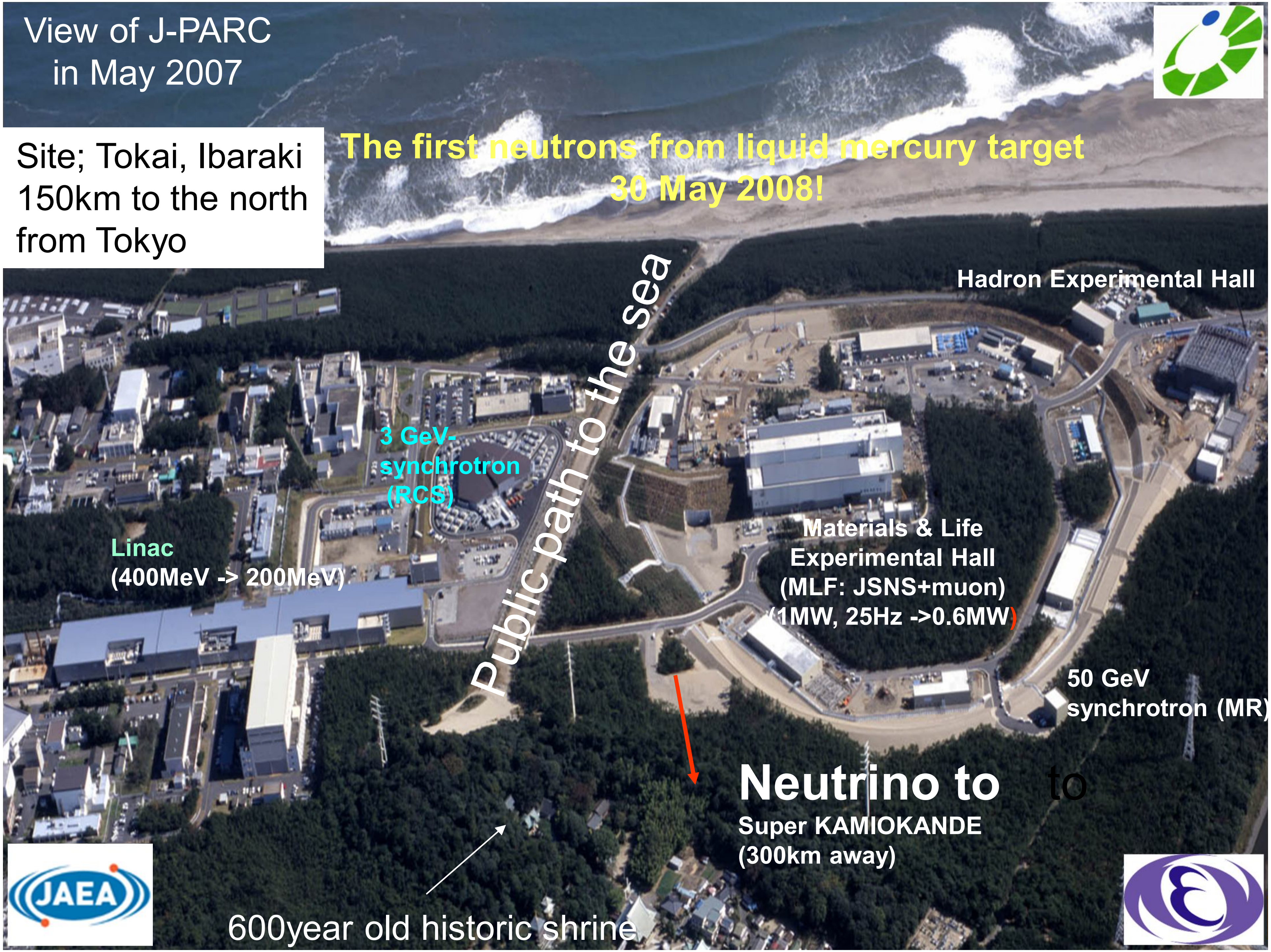
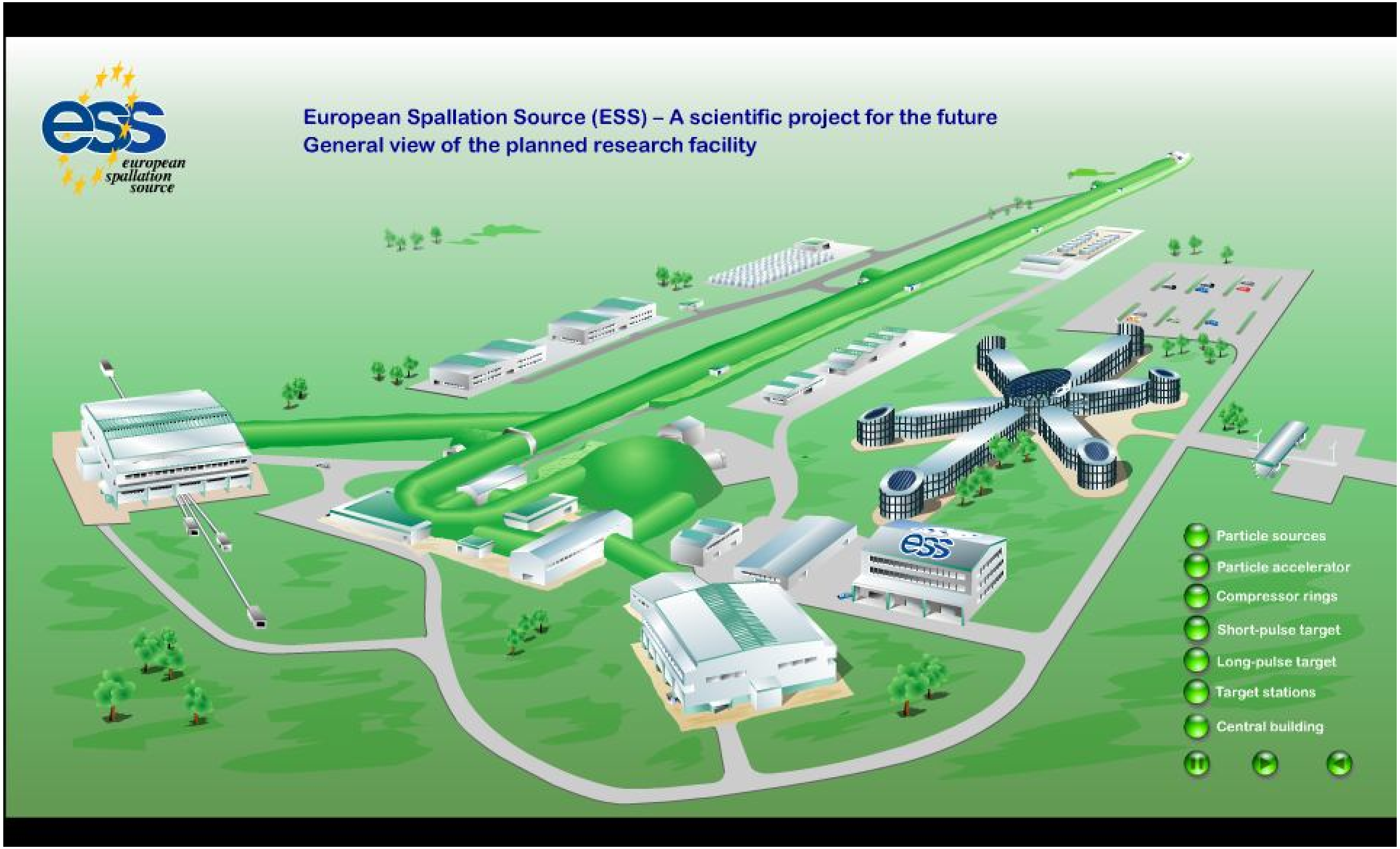
SNS (Oak Ridge, USA)

First neutrons on 28 April 2006!

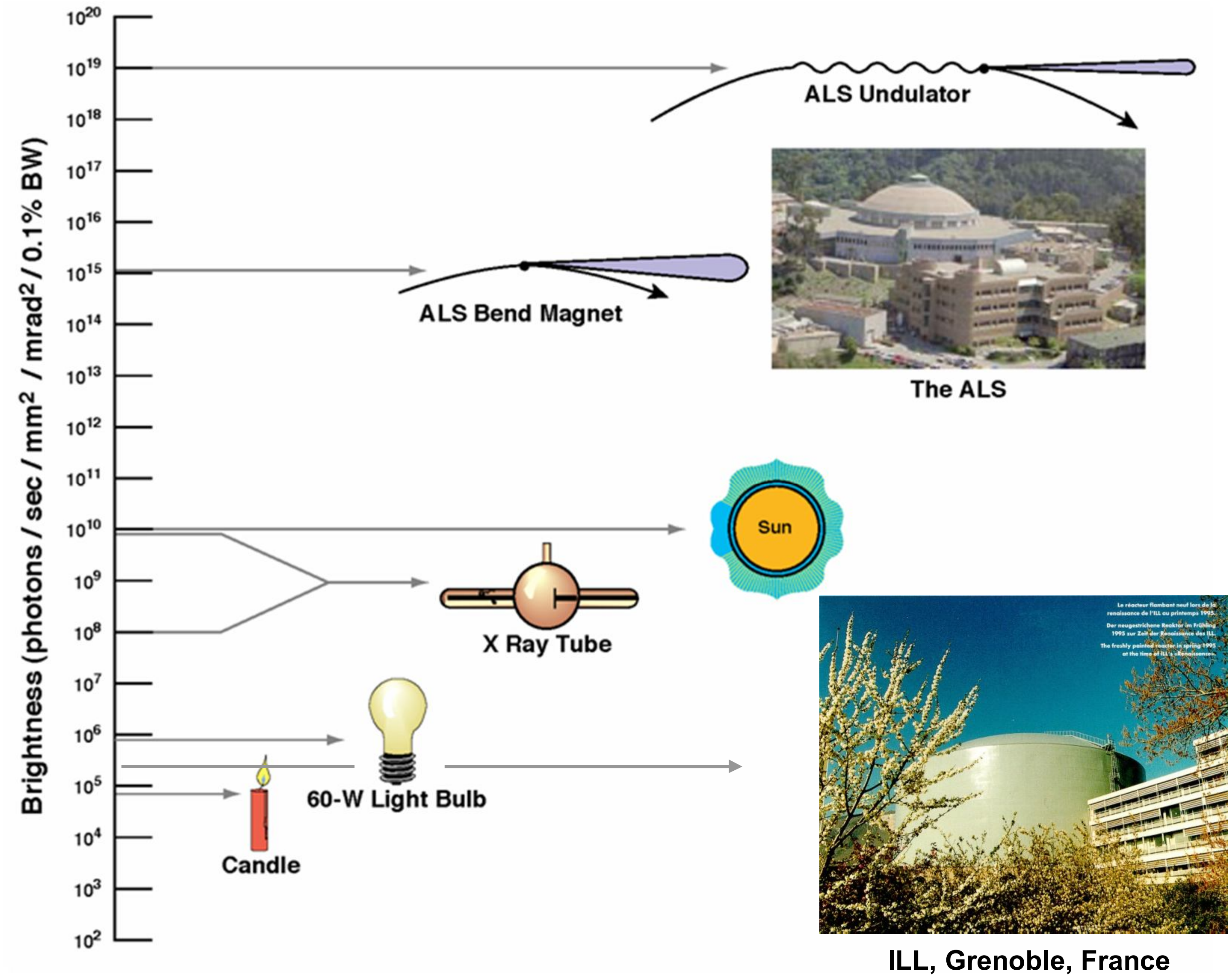
Today SNS is operating with beam to target. Power on target during January 2008 reached a world record of 305 kW.


View of J-PARC
in May 2007
Site; Tokai, Ibaraki
150km to the north
from Tokyo
The first neutrons from liquid mercury target
30 May 2008!
Hadron Experimental Hall
Public path to the sea
3 GeV-
synchrotron
(RCS)
Linac
(400MeV -> 200MeV)
Materials & Life
Experimental Hall
(MLF: JSNS+muon)
(1MW, 25Hz ->0.6MW)
50 GeV
synchrotron (MR)
Neutrino to
to
Super KAMIOKANDE
(300km away)
600year old historic shrine

The European Spallation Source



Brightness comparison of different radiation sources

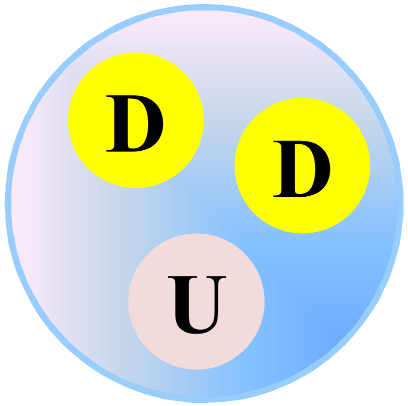


Neutron as a particle

According to quark theory, neutron consists of two down (d) and one up (u) quarks.

Quarks	Charge / e	Mass / m_e
‘down’ d	- 1/3	600
‘up’ u	+ 2/3	600

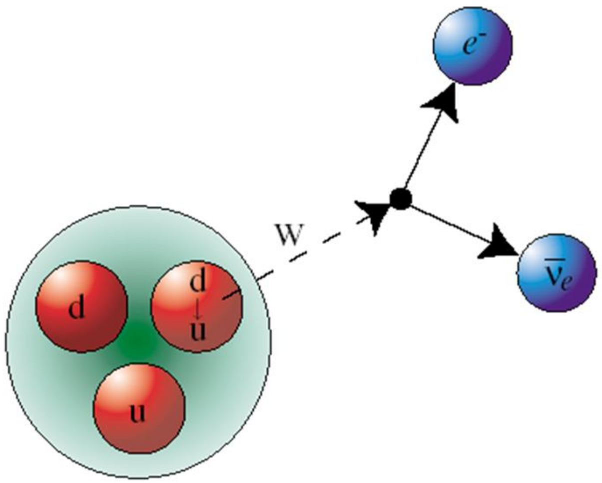
Neutron



mass m_n= 1.175×10^{-27} кг
el. charge = 0; спин = ½
magnetic dipole moment μ_n = -1.913 μ_N, where
nuclear magneton μ_N = eh/4πm_p = 5.051×10^{-27} JT^{-1}

Neutron as a particle

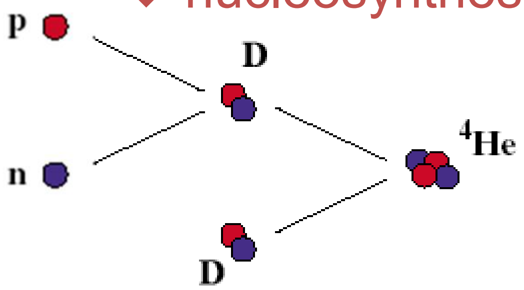
Neutron Beta Decay



$$n \rightarrow p^{+} + e^{-} + \overline{\nu}_e + 782\ \text{keV}$$

Why it is important to know precisely the neutron life-time?

- verification of Standard model: matrix element V_{ud}
- parameters of weak interactions
- nucleosynthesis during the Big Bang

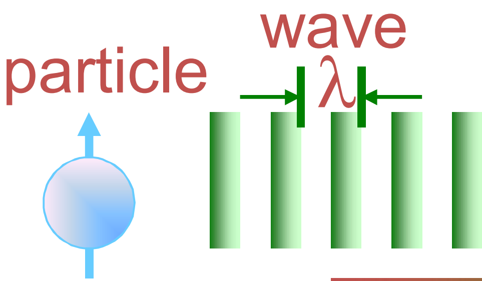


$$\tau_n = 885.7 \pm 1.0\ \text{sec}$$

Neutron as a particle and a wave

Neutron possesses properties of both particle and a wave:

$$E = m_n v^2/2 = k_B T = (hk/2\pi)^2/2m_n; \quad k = 2\pi/\lambda = m_n v/(h/2\pi)$$



λ (nm) = 395.6 / v (m/s)

E (meV) = 0.02072 k^2 (k in nm^{-1})

1 meV = 8.066 cm^{-1} = 11.6 K = 1.6×10^{-22} J

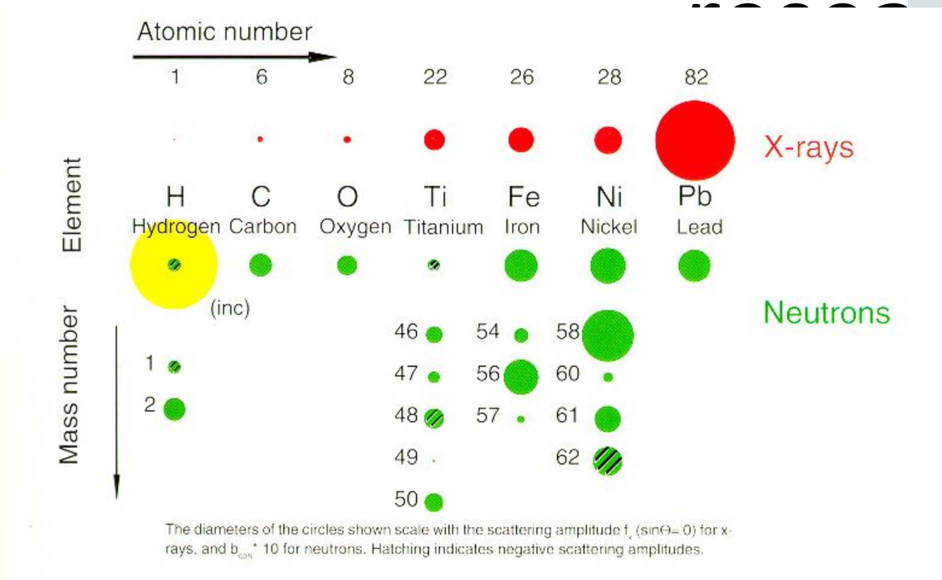
Ultra-cold **cold** **thermal** **hot**

Energy (meV)	**<0.0001**	**0.001 - 10**	**5 - 100**	**100 - 500**
Wavelength (Å)	**~ 900**	**4 - 300**	**1 - 4**	**0.4 - 1**
Temperature (K)	**~ 0.001**	**0.01 - 120**	**60 - 1000**	**1000 - 6000**

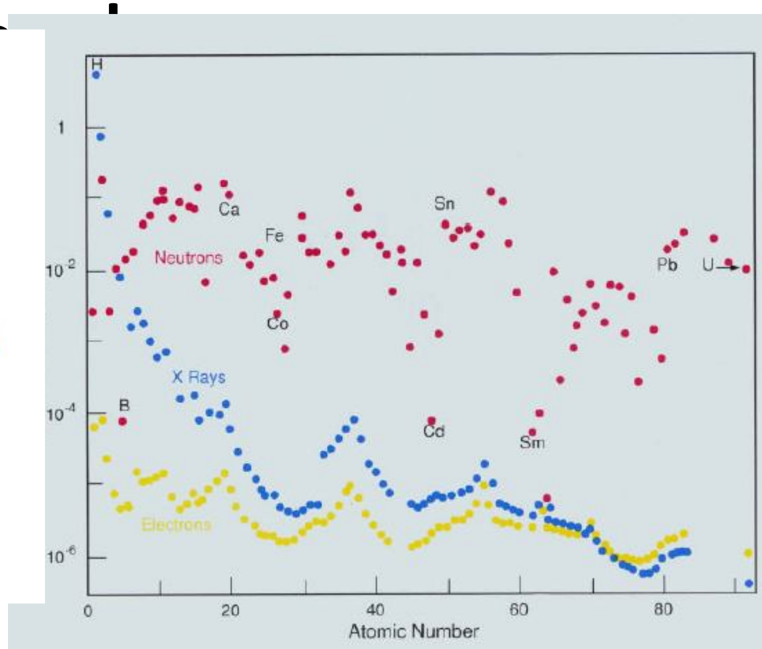
Neutrons for condensed matter research

Property	Applicability
No charge, small cross sections	• can investigate bulk material • can treat scattering in first Born approximation • complex sample environment • no damage to biological samples
Wavelength of thermal neutrons in the range of interatomic distances	• can determine crystal structures and atomic positions
Magnetic moment	• can examine magnetic properties on microscopic scale
Kinetic energy in the range of elementary excitations	• can investigate dynamical properties and excitation energies
Scattering by nuclei	• can "see" hydrogen, can distinguish isotopes → contrast variation
Coherent and incoherent scattering	• collective phenomena as well as single atom effects

Neutrons for condensed matter research



The diameters of the circles shown scale with the scattering amplitude f_x (sinθ=0) for X-rays, and $b_{coh}\times 10$ for neutrons. Hatching indicates negative scattering amplitudes



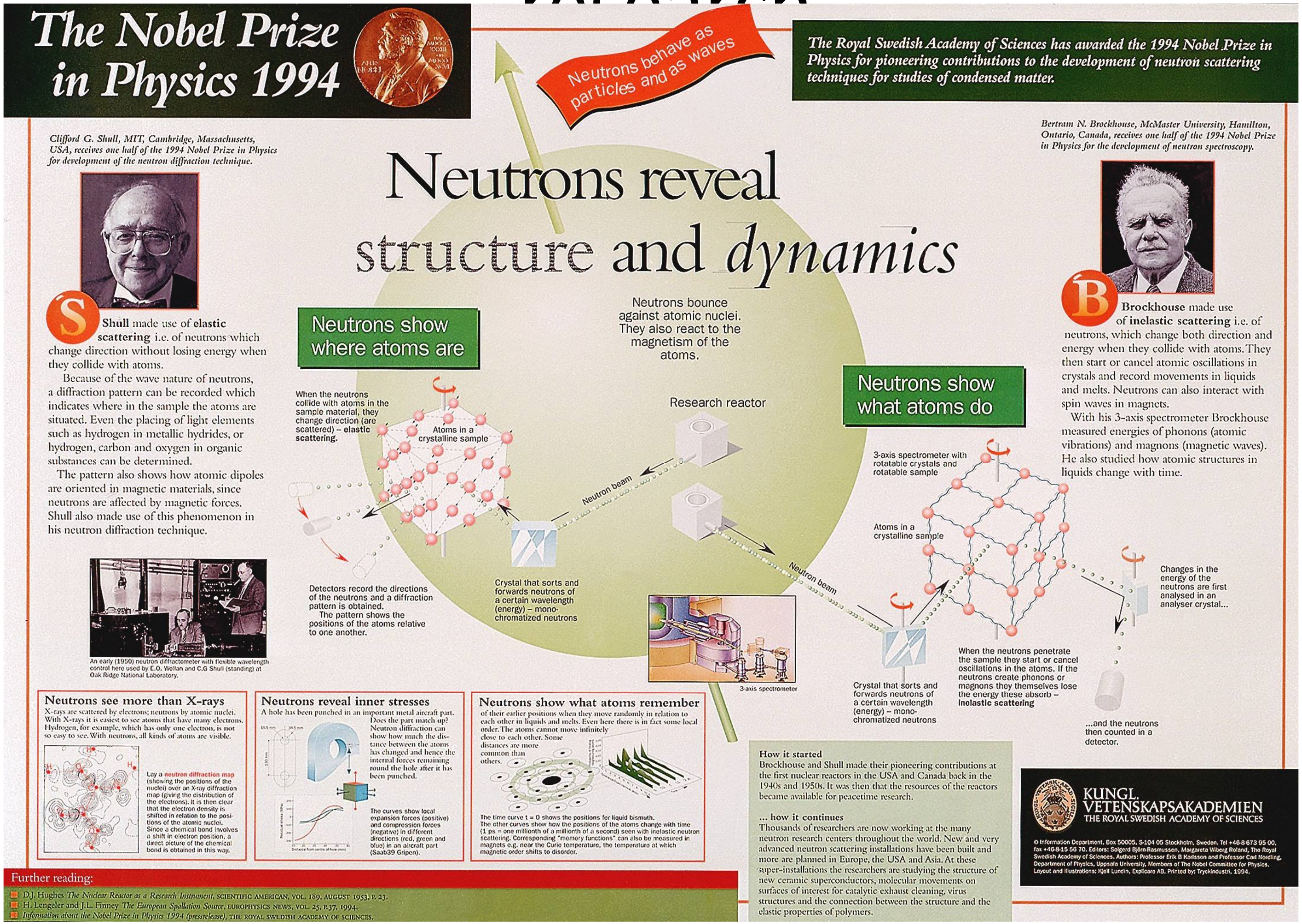
Penetration depth of thermal neutrons, low energy electrons and 8 keV X-rays into different elements

For neutrons: no regular wavelength dependence of scattering length (which is just a number, not the function of the scattering angle as in the case of X-rays!) and absorption coefficient from atomic number; enormous difference in scattering legths and absorption coefficients for H and D; huge absorption for Cd, B, Sm, Gd

Disadvantages

Relatively low intensity of neutron sources ⇒ weak signal, large sample volumes required etc.
Strong absorption of some elements, but isotope substitution can cure the problem.
Kinematical restrictions limit the achievable energy-momentum range..

Neutrons for condensed matter research



Neutrons for condensed matter research

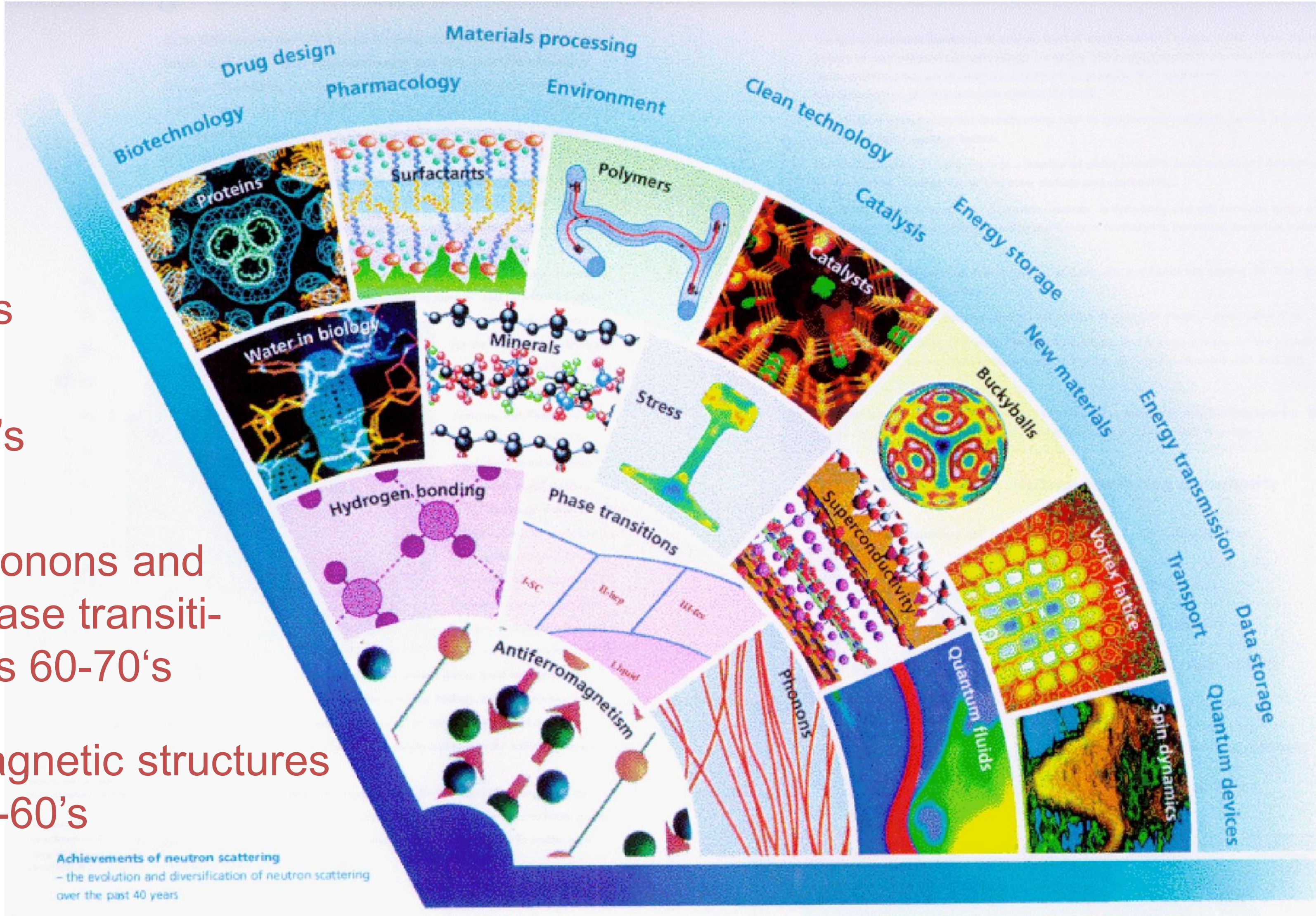
Interdisciplinary character of research with neutrons

90's

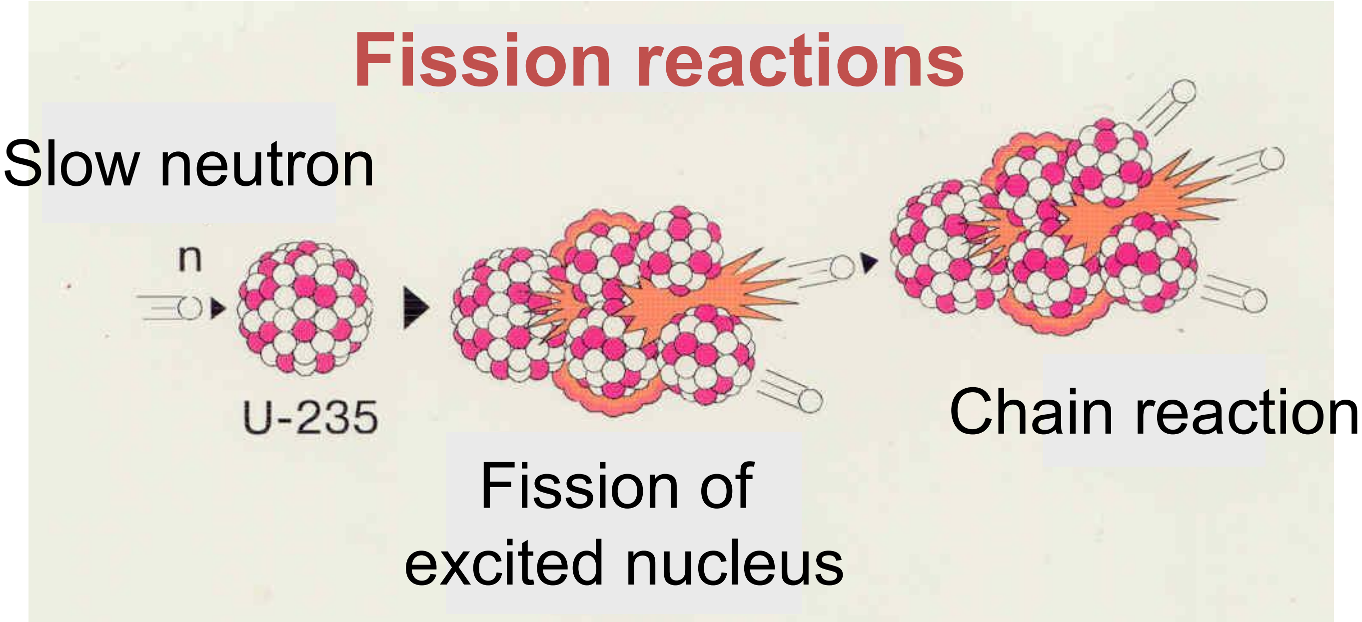
80's

Phonons and phase transiti-ons 60-70's

Magnetic structures 50-60's



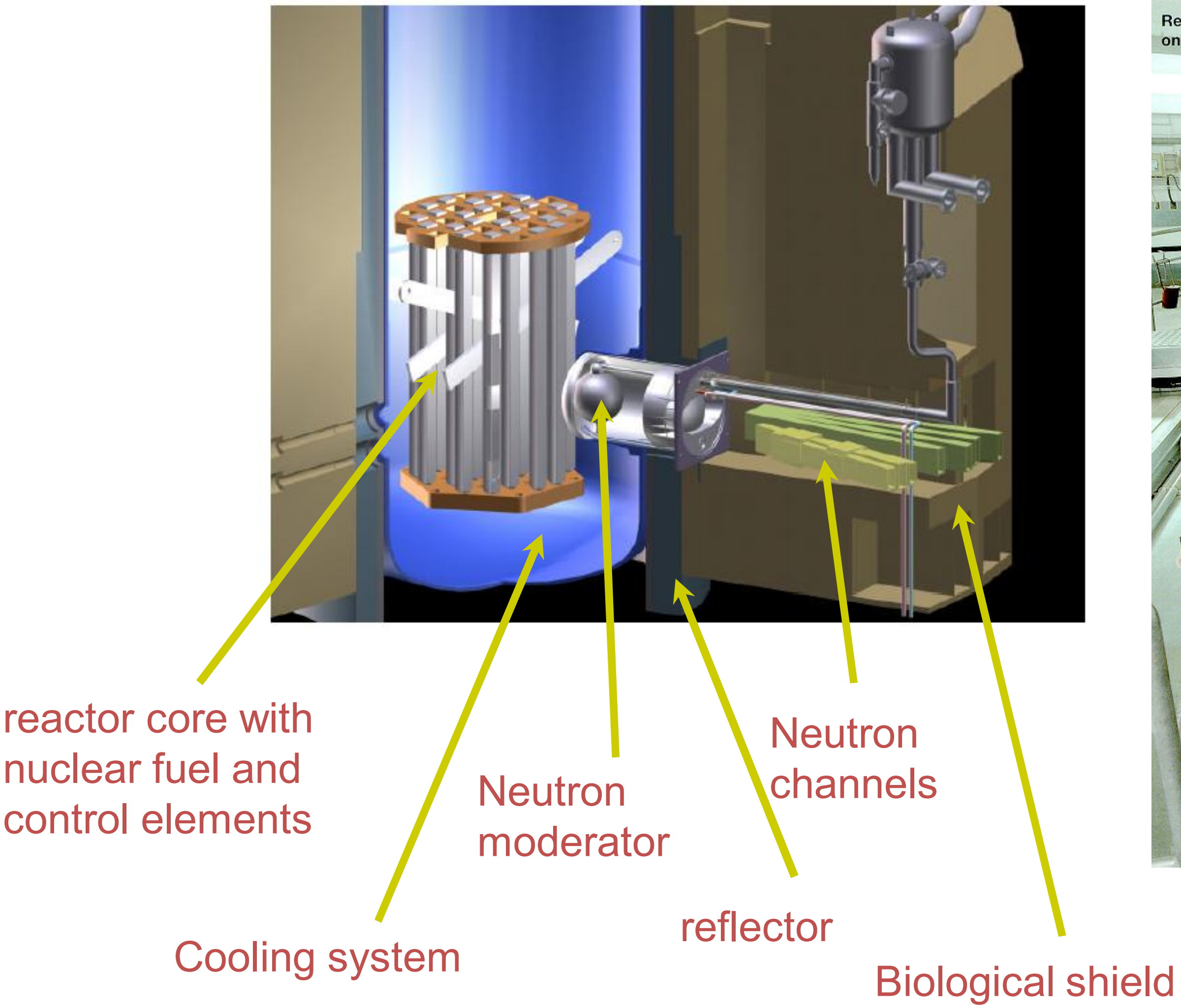
Production of neutrons



Each fission act produces in average ~2.5 neutrons with energy release about 200 MeV. In the case of chain (self sustained) reaction 1 neutron is necessary to ensure the next fission, 0.5 is lost because of absorption inside the neutron source and 1 neutron can be extracted for use in the experiment

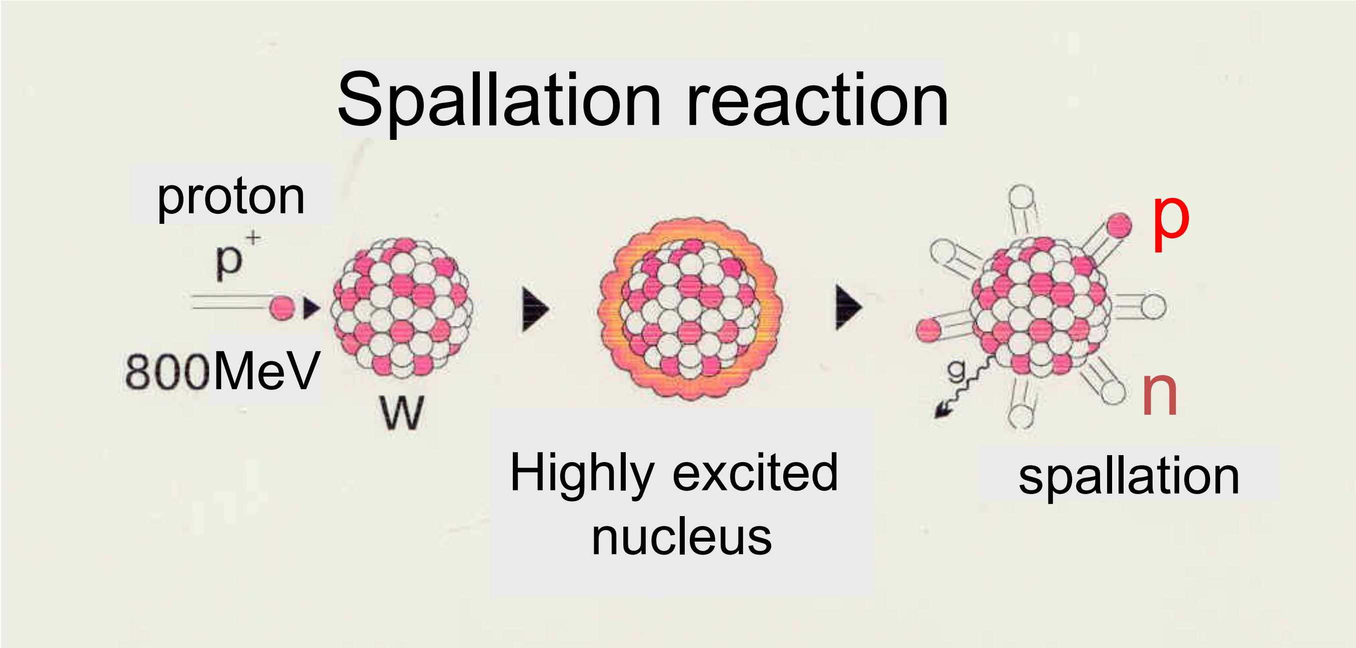
Production of neutrons

Steady state nuclear reactor



Research nuclear reactor.

Production of neutrons

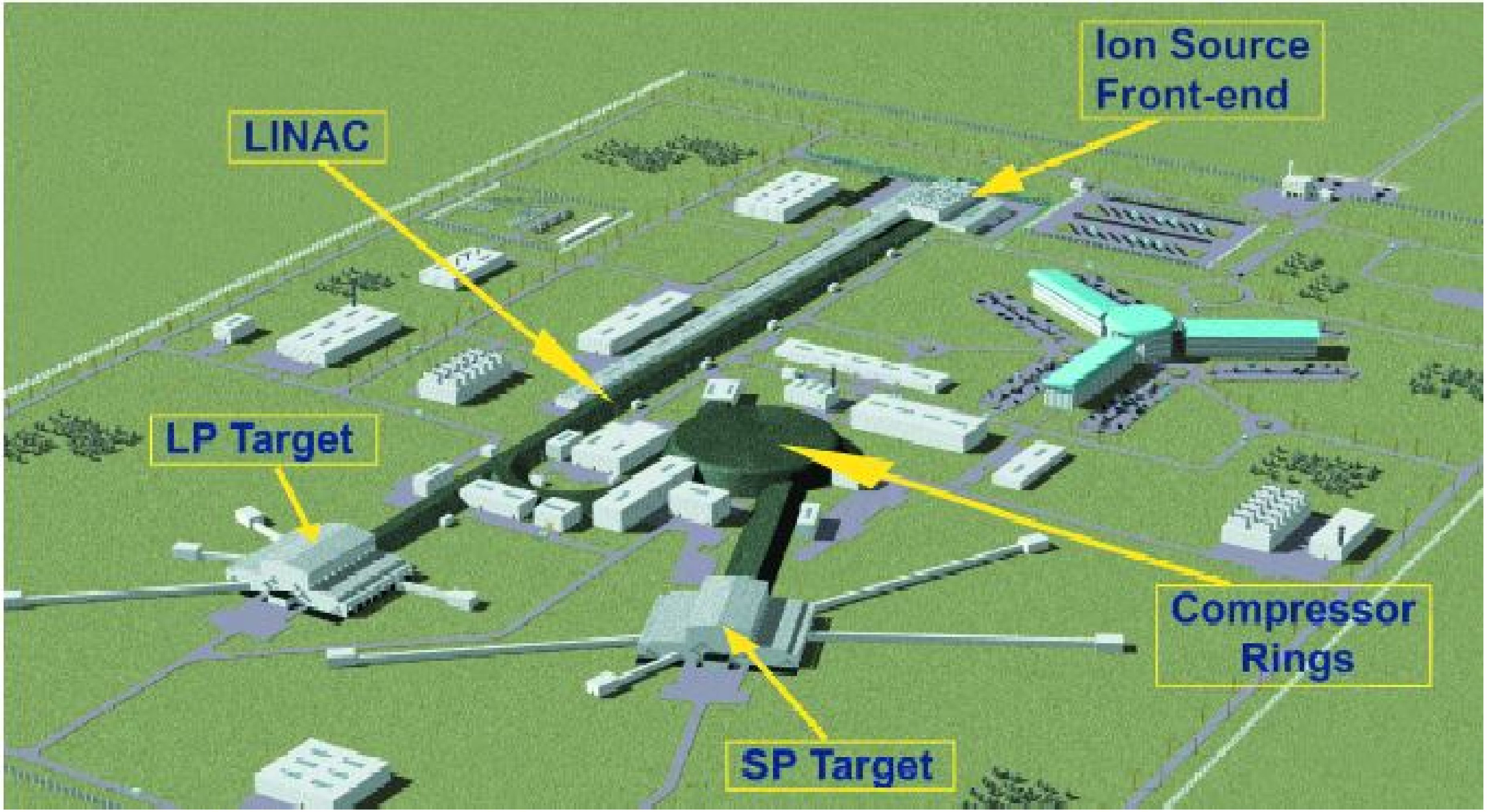


Spallation reaction gives up to 30 neutrons per 1 proton. There exists *empirical* expression for the estimation of neutron yield from the target when proton energy exceeds 120 MeV

$$N_n(E,A) = \begin{cases} 0.1 \times E_{GeV} \times (A+20) - \text{for non-fissile target} \\ 50 \times E_{GeV} - \text{for uranium-238} \end{cases}$$

Production of neutrons

Principal scheme of spallation neutron source

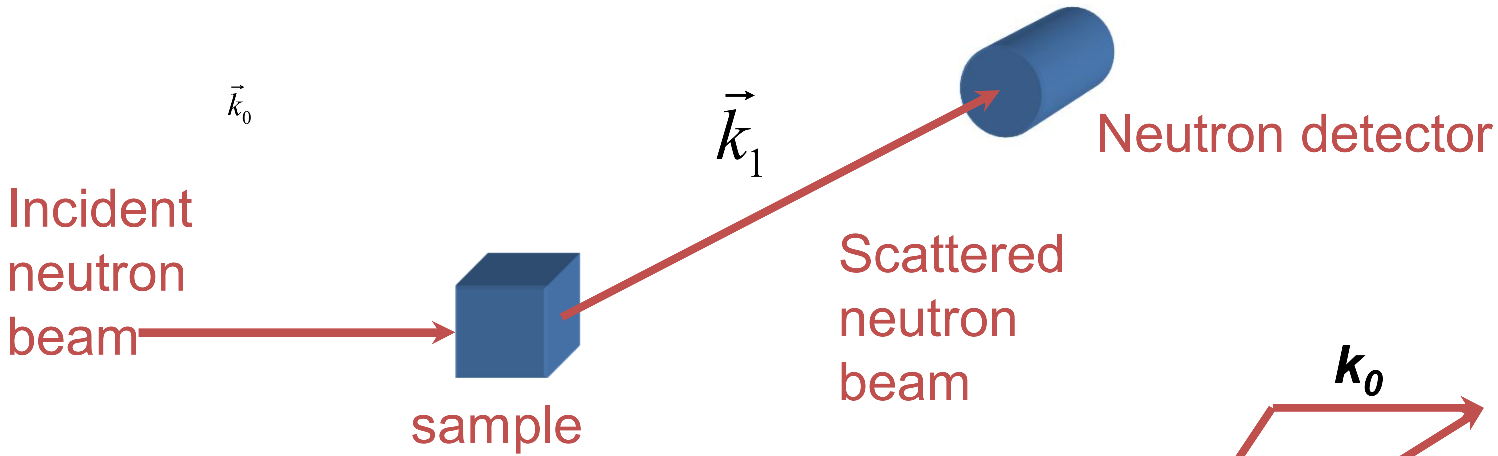


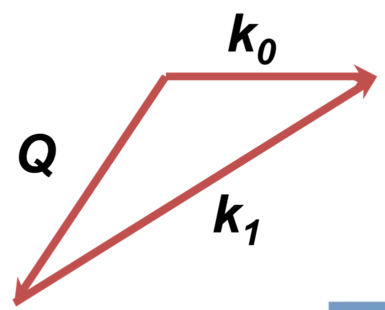
Components of neutron scattering instruments

What do we need to perform good neutron experiment?

- Intense neutron source with efficient moderator
- neutron shaping, guiding and velocity selection system
- interesting sample for the study
- system to analyse parameters of scattered neutron beam
- advanced neutron detector

Typical scheme of neutron scattering experiment



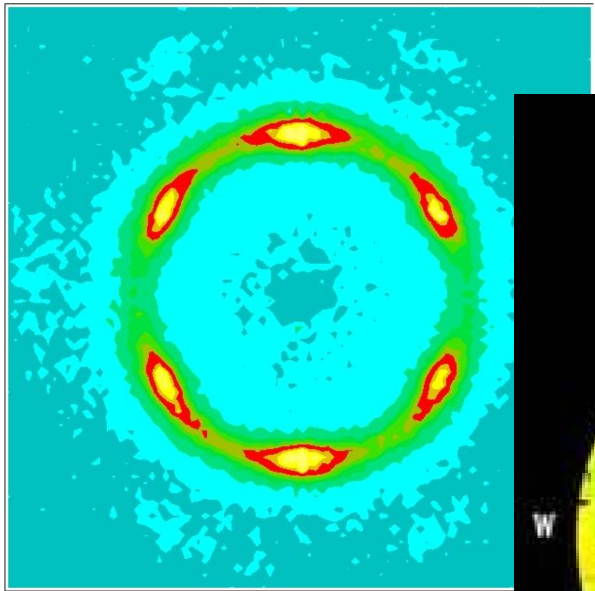


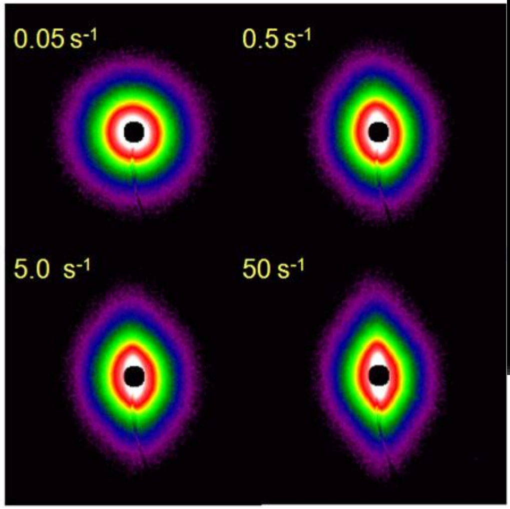
$k = m_n v/\hbar = 2\pi/\lambda$

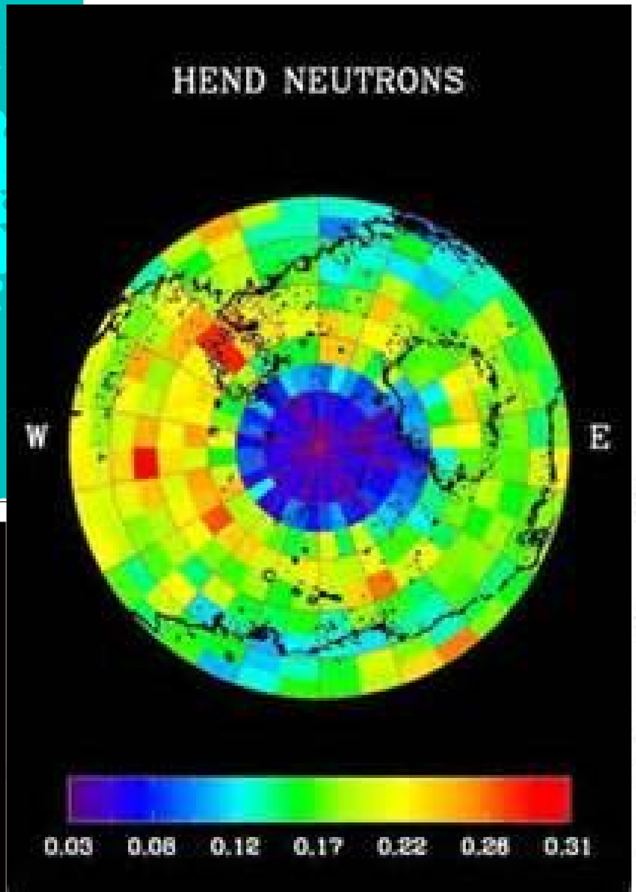
$$\vec{Q} = \vec{k}_0 - \vec{k}_1$$

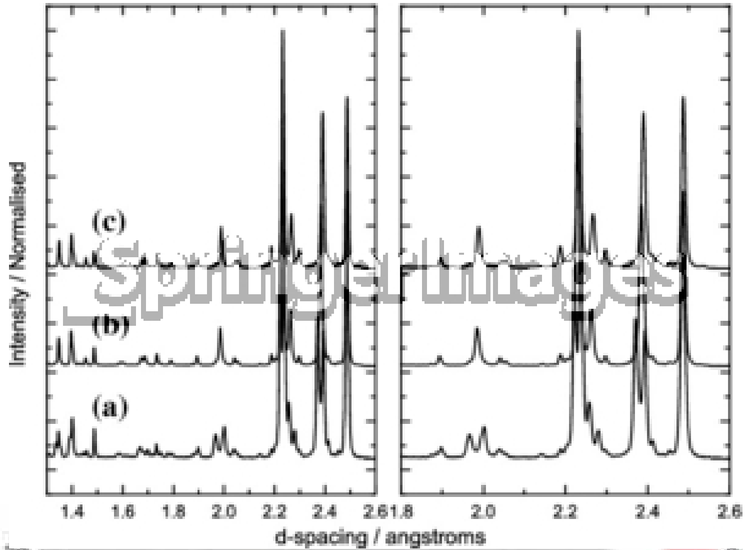
Examples of registered patterns on a detector

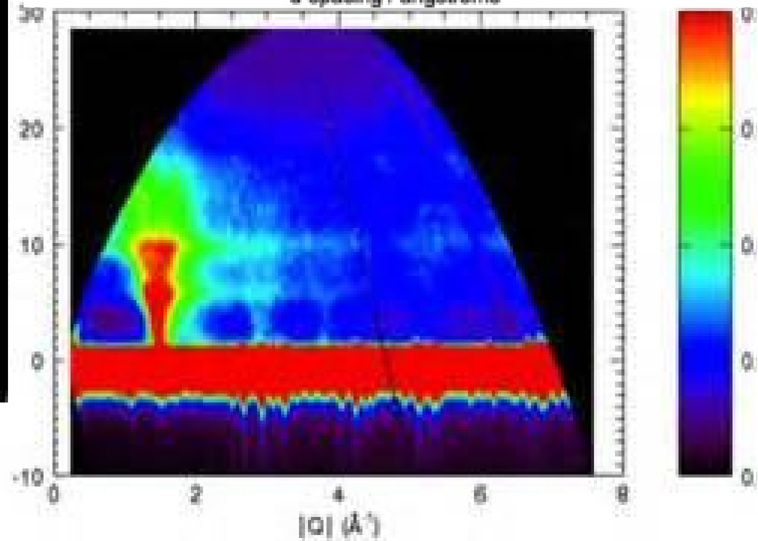
From the analysis of the signal on a detector, using advanced mathematical models one can extract information about characteristics of a sample under investigation











Cross-sections definitions

Let the sample is irradiated by flux Φ_{in} of neutrons per unit area per unit time. We define I_s and I_a as a number of neutrons scattered and absorbed by the sample per unit time, respectively. Then the total cross sections of scattering and absorption of neutrons by the sample are defined as:

$$I_s = \Phi_{in}\sigma_s$$

$$I_a = \Phi_{in}\,\sigma_a$$

Dimensionality of the total cross sections is [barn]:

$$1\text{barn} = 10^{-24}\text{cm}^2.$$

By definition the flux $\Phi_{in} = 1/S{\cdot}t = v_0/V$, where S – is the area irradiated by neutrons, t – time of irradiation, v_0 – velocity of neutrons, V – volume of the irradiated sample.

Nuclear neutron scattering

The interaction of neutron with nuclei is described by Fermi pseudopotential:

$$H = \frac{2\pi\hbar^2}{m_n} b\delta(\vec{r} - \vec{R})$$

Where m_n – neutron mass, b – scattering length, R – vector defining the position of a nucleus in space.

Let us first consider the scattering of a neutron on isolated nucleus under the following assumptions:

- neutron wavelength is much larger than the scattering length which is the radius of action of nuclear force (this is the limitation of applicability of Fermi pseudopotential)
- the scattering is purely elastic, e.g. the energy of neutron is conserved before and after the scattering
- the absorption of neutrons by the nucleus can be neglected

Nuclear neutron scattering

The nucleus is irradiated

by plane wave

$$\Psi_{in} = \frac{1}{\sqrt{V}} e^{i\vec{k}_0\vec{r}}$$

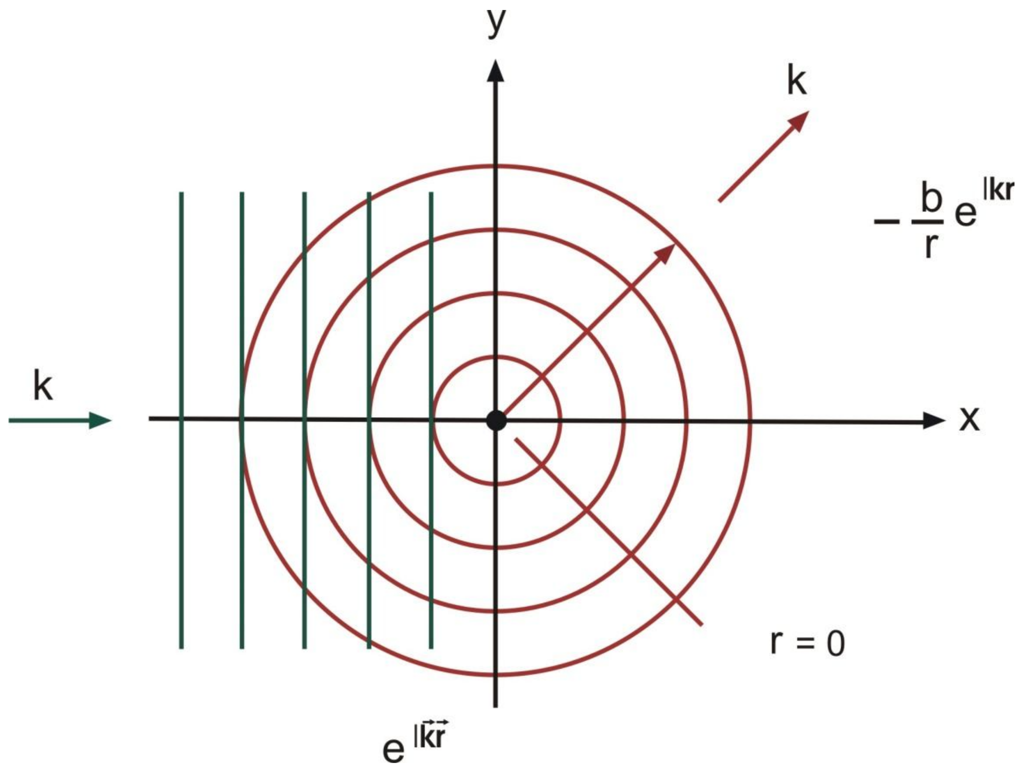
After the scattering

we have a spherical wave

$$\Psi_{out} = \frac{1}{\sqrt{V}}\left(-\frac{b}{r} e^{ik_0 r}\right)$$

Then the flux of scattered neutrons is

$$\Phi_{out} = \nu_0 \Psi^*_{out} \Psi_{out} = |b|^2 \frac{1}{r^2} \frac{\nu_0}{V}$$



Place the nucleus at coordinate origin

Nuclear neutron scattering

The number of neutrons passing through the element of spherical surface $S = r^2 d\Omega$ is equal

$$dI_{out} = \Phi_{out}(\vec{r})r^2 d\Omega = |b|^2 \frac{v_0}{V} d\Omega$$

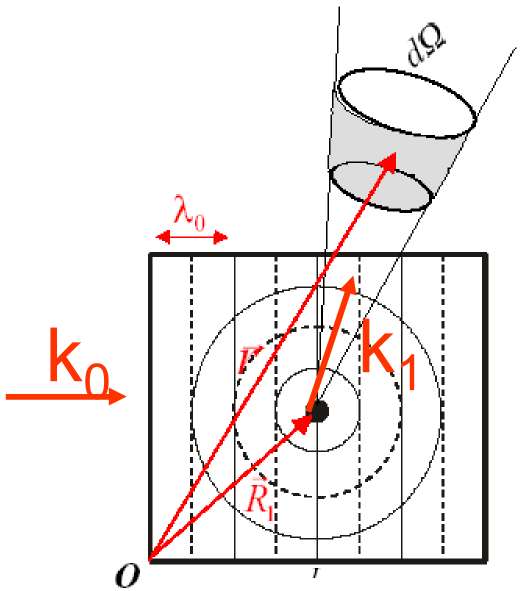
And differential scattering cross section (i.e. the probability that neutron is scattered in a direction defined by a vector ***r*** into an element of solid angle $d\Omega$) is equal

$$\frac{d\sigma}{d\Omega} = \frac{dI_{out}}{\Phi_{in} d\Omega} = |b|^2$$

And the total scattering cross section will be

$$\sigma = \int (d\sigma/d\Omega)\, d\Omega = 4\pi |b|^2$$ ISOTROPIC!!!

Nuclear neutron scattering



Let us now consider the scattering by a nucleus which position is defined by a vector $\vec{R}_i$. The wave function of incident neutrons will again be a plane wave:

$$\Psi_{in} = \frac{1}{\sqrt{V}} e^{i\vec{k}_0\vec{r}}$$

And for the scattered neutrons

$$\Psi_{out} = \frac{1}{\sqrt{V}} e^{i\vec{k}_0\vec{R}_i} \left[\frac{-b_i}{\left|\vec{r}-\vec{R}_i\right|} e^{ik_0\left|\vec{r}-\vec{R}_i\right|} \right]$$

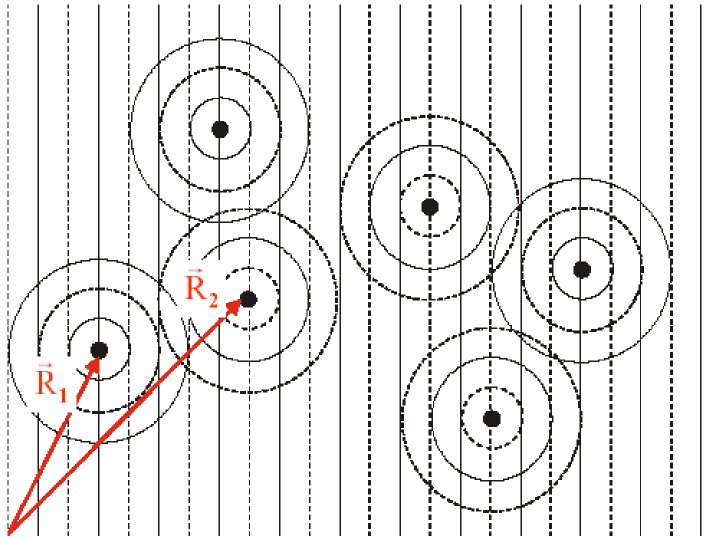
$$\left|\vec{r}-\vec{R}_i\right| = r - \frac{\vec{r}}{r}\vec{R}_i + O\left(\frac{1}{r}\right)$$

For r→∞ we have:

$$e^{ik_0\left|\vec{r}-\vec{R}_i\right|} = e^{ik_0 r} e^{-ik_0\frac{\vec{r}}{r}\vec{R}_i} = e^{ik_0 r} e^{-i\vec{k}_1\vec{R}_i}$$

$$\Psi_{out} = \frac{1}{\sqrt{V}} e^{-i\vec{k}_1\vec{R}_i} \left(\frac{-b_i}{r} e^{ik_0 r} \right)$$

Nuclear neutron scattering



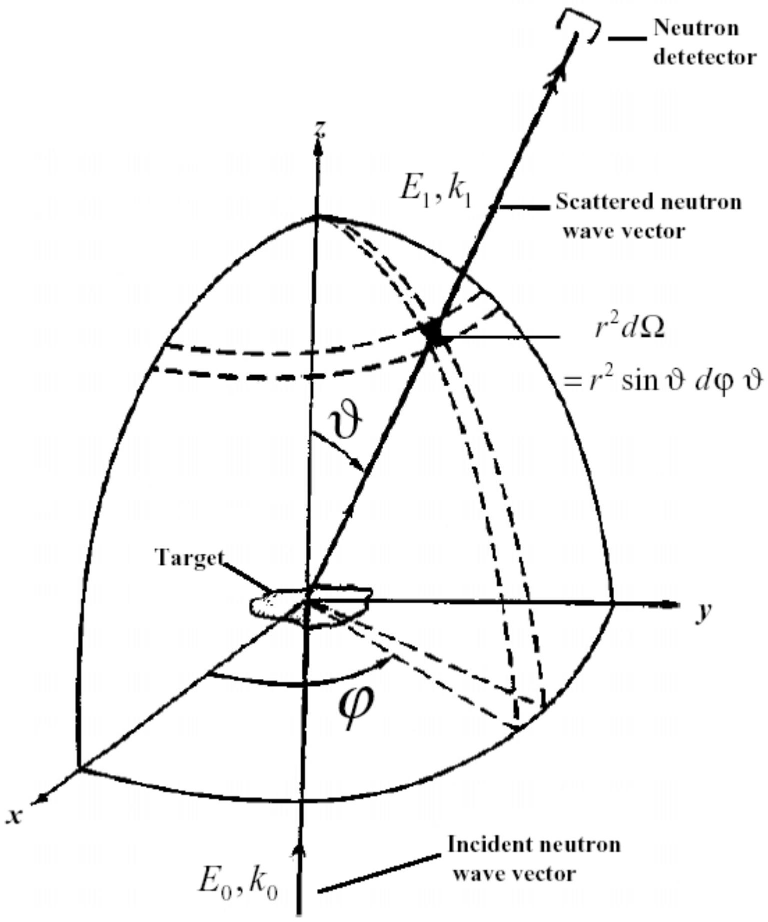
The resulting neutron flux after scattering on the nuclei **R_i** and **R_j** will be equal

$$\Phi_{out}^{i,j} = \frac{\nu_0}{V}\Psi_{out}^{i}{}^{*}\Psi_{out}^{j} = \frac{\nu_0}{V} b_i b_j e^{i\vec{k}_1\vec{R}_i} e^{-i\vec{k}_1\vec{R}_j}$$

Therefore, differential cross section for N nuclei:

$$\frac{d\sigma}{d\Omega} = \sum_{i,j}^{N} b_i b_j e^{i\vec{Q}(\vec{R}_i - \vec{R}_j)}, \text{ where } \vec{Q} = \vec{k}_1 - \vec{k}_0$$

Nuclear neutron scattering



Now, consider more common case, when the velocity of neutron is changing during the scattering process due the fact that atoms perform thermal vibrations and their coordinates in space become time dependent. This means that $v_1 \neq v_0$ and $\boldsymbol{R_i}=\boldsymbol{R_i(t)}$. Then the above formula can be written in a more common form giving the double differential cross section. This cross section defines the probability of neutron being scattered in a direction $\underline{\boldsymbol{r}}$ into an element of solid angle dΩ with the neutron energy change $E=E_1-E_0$ in an interval dE.

Nuclear neutron scattering

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{k_1}{k_0}\sum_i\sum_j\int_{-\infty}^{+\infty}\left\langle b_i b_j e^{i\vec{Q}\vec{R}_i(t)} e^{-i\vec{Q}\vec{R}_j(0)}\right\rangle e^{-i\omega t}dt$$

Angular brackets mean averaging over all values of nuclei coordinates in a space ***R_i****(t)* , isotope content and all possible spin states of nuclei. It is known, that the scattering length depends on a relative orientation of nucleus and neutron spins. For parallel spins denote the scattering length as b^+, and for anti parallel as b^-. Scattering length is also different for different isotopes of the chosen chemical element. Then one obtains:

$$\langle b_i b_j \rangle = \begin{cases} \langle b_i \rangle \langle b_j \rangle & \text{for } i \neq j \\ \langle |b_i|^2 \rangle & \text{for } i = j \end{cases}$$

Nuclear neutron scattering

Then $\langle b_i b_j \rangle = \overbrace{\langle b_i \rangle \langle b_j \rangle}^{\text{coherent term}} + \underbrace{\delta_{ij}\left(\langle |b_i|^2 \rangle - \langle b_i \rangle \langle b_j \rangle\right)}_{\text{incoherent term}}$

$$b_{coh}^2 = \langle b_i \rangle^2 \qquad b_{inc}^2 = \left\langle |b_i|^2 \right\rangle - |\langle b_i \rangle|^2$$

Consequently, neutron cross sections will consist of two terms – coherent and incoherent:

$$\sigma = \sigma_{coh} + \sigma_{inc}; \qquad \sigma_{coh} = 4\pi b_{coh}^2; \qquad \sigma_{inc} = 4\pi b_{inc}^2$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{coh} + \left(\frac{d\sigma}{d\Omega}\right)_{inc} = \underbrace{\left| \overbrace{\sum_i^N \langle b_i \rangle e^{i\vec{Q}\vec{R}_i}}^{\text{structure factor}} \right|^2}_{coh} + \underbrace{\left(\left\langle |b_i|^2 \right\rangle - |\langle b_i \rangle|^2\right)}_{inc}$$

Nuclear neutron scattering

$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{coh} + \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{inc}$$

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{coh} = \frac{k_1}{k_0}\sum_i\sum_j b_i^{coh} b_j^{coh} S(\vec{Q},\omega),\ \text{где}$$

$$S(\vec{Q},\omega) = \frac{1}{2\pi}\iint d\vec{r}dt\ e^{i(\vec{Q}\vec{r}-\omega t)} G_{п}(\vec{r},t)$$

$$G_{п}(\vec{r},t) = \sum_i\sum_j \int \left\langle \delta\left[\vec{r} - \vec{r}' + \vec{R}_j(0)\right] \cdot \delta\left[\vec{r}' - \vec{R}_i(t)\right] \right\rangle d\vec{r}'$$

$S(\vec{Q},\omega)$ - Is called the SCATTERING LAW

$G_{п}(\vec{r},t)$ - Is called PAIR CORRELATION FUNCTION,

Which is the probability, that if the arbitrarily chosen nucleus j at a time t=0 had a coordinate **R_j**(0), then at a moment t≠0 another atom i will have a coordinate **R_i**(t).

Nuclear neutron scattering

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{inc} = \frac{k_1}{k_0}\sum_i \left(b_i^{inc}\right)^2 S^{inc}(\vec{Q},\omega)$$

$$S^{inc}(\vec{Q},\omega) = \frac{1}{2\pi}\iint d\vec{r}dt\ e^{i(\vec{Q}\vec{r}-\omega t)} G_a(\vec{r},t)$$

$$G_a(\vec{r},t) = \sum_i \int \left\langle \delta\left[\overleftarrow{r} - \vec{r}'+\vec{R}_i(0)\right]\delta\left[\vec{r}'-\vec{R}_i(t)\right]\right\rangle$$

$G_a(\vec{r},t)$ - Is called an AUTOCORRELATION FUNCTION,

Which is the probability, that if at a time t=0 the arbitrary chosen atom i had a coordinate $\mathbf{\underline{R_i}}(0)$, then at a time $t \neq 0$ its coordinate will be $\mathbf{\underline{R_i}}(t)$.

Nuclear neutron scattering

Possible types of neutron scattering experiments and corresponding scientific applications

Type of scattering	$\vec{Q}$	ω	$\vec{r}$	t	Scattering law	Scientific applications
elastic	$\vec{Q}$	0	$\vec{r}$	$\int dt$	$S(\vec{Q},0)$	**Atomic and magnetic structures**
	$\vec{Q} \to 0$	0	$\vec{r} \to \infty$	$\int dt$	$S(\vec{Q},0)$	**Submolecular structures**
total	$\vec{Q}$	$\int d\omega$	$\vec{r}$	0	$S(\vec{Q})$	**Disordered structures**
inelastic	$\vec{Q}$	ω	$\vec{r}$	t	$S(\vec{Q},\omega)$	**Collective excitation**
	$\lvert\vec{Q}\rvert$	ω	$\vec{r}$	t	$S(\lvert\vec{Q}\rvert,\omega)$	**Atomic and molecular spectroscopy**
	$\int \vec{Q}$	ω	$r = 0$	t	$S(\omega)$	**Density of vibrational states**
quasi-elastic	$\vec{Q}$	$\omega \downarrow 0$	$\vec{r}$	$t \downarrow \infty$	$S(\vec{Q},\omega)$	**Diffusion of atoms and molecules**

Magnetic neutron scattering

The detailed evaluation of the expressions for cross sections of elastic and inelastic neutron scattering on different magnetic structures is rather complicated. Therefore, let's see only the final result for several most common cases.

General expression for double differential cross section (unpolarised neutrons)

Debye-Waller factor

Magnetic form-factor

Polarisation factor

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{k_1}{k_0}(\gamma r_0)^2 \left| \frac{g}{2} F(\vec{Q}) \right|^2 e^{-2W(\vec{Q})} \sum_{\alpha\beta} (\delta_{\alpha\beta} - \frac{Q_\alpha Q_\beta}{Q^2})$$

$$\times \int dt\, e^{-i\omega t} \sum_{ij} e^{i\vec{Q}(\vec{R}_i - \vec{R}_j)} \left\langle S^{\alpha}_{R_i}(0) S^{\beta}_{R_j}(t) \right\rangle$$

Spin correlation function

Magnetic neutron scattering

Magnetic form factor F(**Q**) is the Fourier transform of the magnetisation density in a crystal. It is important to note, that neutron magnetic form factor is defined by distribution of electrons with uncompensated spins only.

$r_0 = e^2/m_e c^2$ – electromagnetic radius of the electron

γ= -1.913 – neutron magnetic moment in Bohr magnetons

$$\delta_{ij} = \begin{cases} 0, \text{if } i \neq j \\ 1, \text{if } i = j \end{cases} - \text{Kroneker symbol}$$

Polarisation factor $(\delta_{\alpha\beta} - \frac{Q_\alpha Q_\beta}{Q^2})$ indicates that neutrons interact only with the components of atomic spin which are perpendicular to the scattering vector **Q**. This fact allows uniquely measure in an experiment the directions of atomic spins and polarisation of spin waves. r_0 value indicates that the magnetic neutron scattering cross section is of the order 10^{-24} cm^2, therefore comparable with nuclear scattering cross section.

Uses of neutron scattering in magnetism

Static properties (elastic scattering)

Spin arrangements in ordered magnetic structures

Static spin correlations in disordered or frustrated magnets

Magnetisation density (magnetic form factor)

Flux distributions in superconductors

Magnetism of surfaces (reflectometry)

etc

Dynamic properties (inelastic scattering)

Crystal field excitations

Inter-multiplet atomic excitations

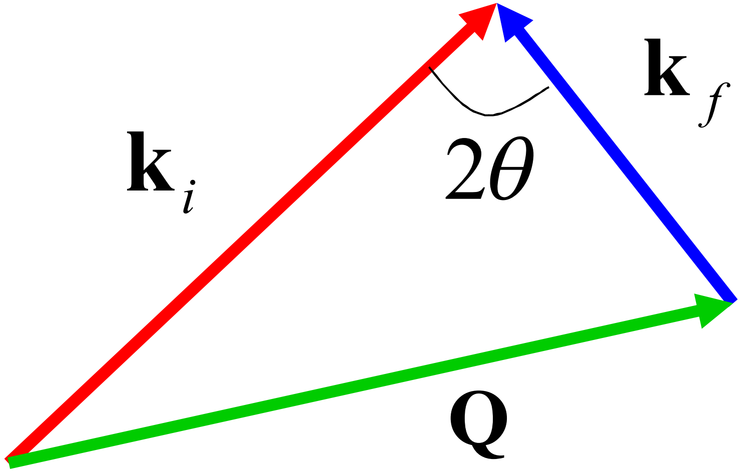
Spin waves in ordered magnetic structures

Spin fluctuations in strongly correlated or frustrated magnets

Magneto-phonon coupling

etc

Basic idea of the method



$$\mathbf{Q} = \mathbf{k}_i - \mathbf{k}_f$$

$$\hbar\omega = E_i - E_f$$

Nuclear scattering

$$\mathrm{S}(\mathbf{Q},\omega) = \frac{1}{2\pi\hbar}\int dt\, e^{-i\omega t}\,\frac{1}{N}\left\langle \rho_{\mathbf{Q}}(0)\rho_{-\mathbf{Q}}(t)\right\rangle$$

Magnetic scattering

$$\mathrm{S}^{\alpha\beta}(\mathbf{Q},\omega) = \frac{1}{2\pi\hbar}\int dt\, e^{-i\omega t}\,\frac{1}{N}\sum_{\mathbf{RR'}} e^{i\mathbf{Q}\cdot(\mathbf{R}-\mathbf{R'})} < S_{\mathbf{R}}^{\alpha}(0)\,\mathrm{S}_{\mathbf{R'}}^{\beta}(t) >$$

Modern challenges - novel fields of neutron scattering application

"There are no such things as applied sciences, only applications of science."

"A bottle of wine contains more philosophy than all the books in the world."

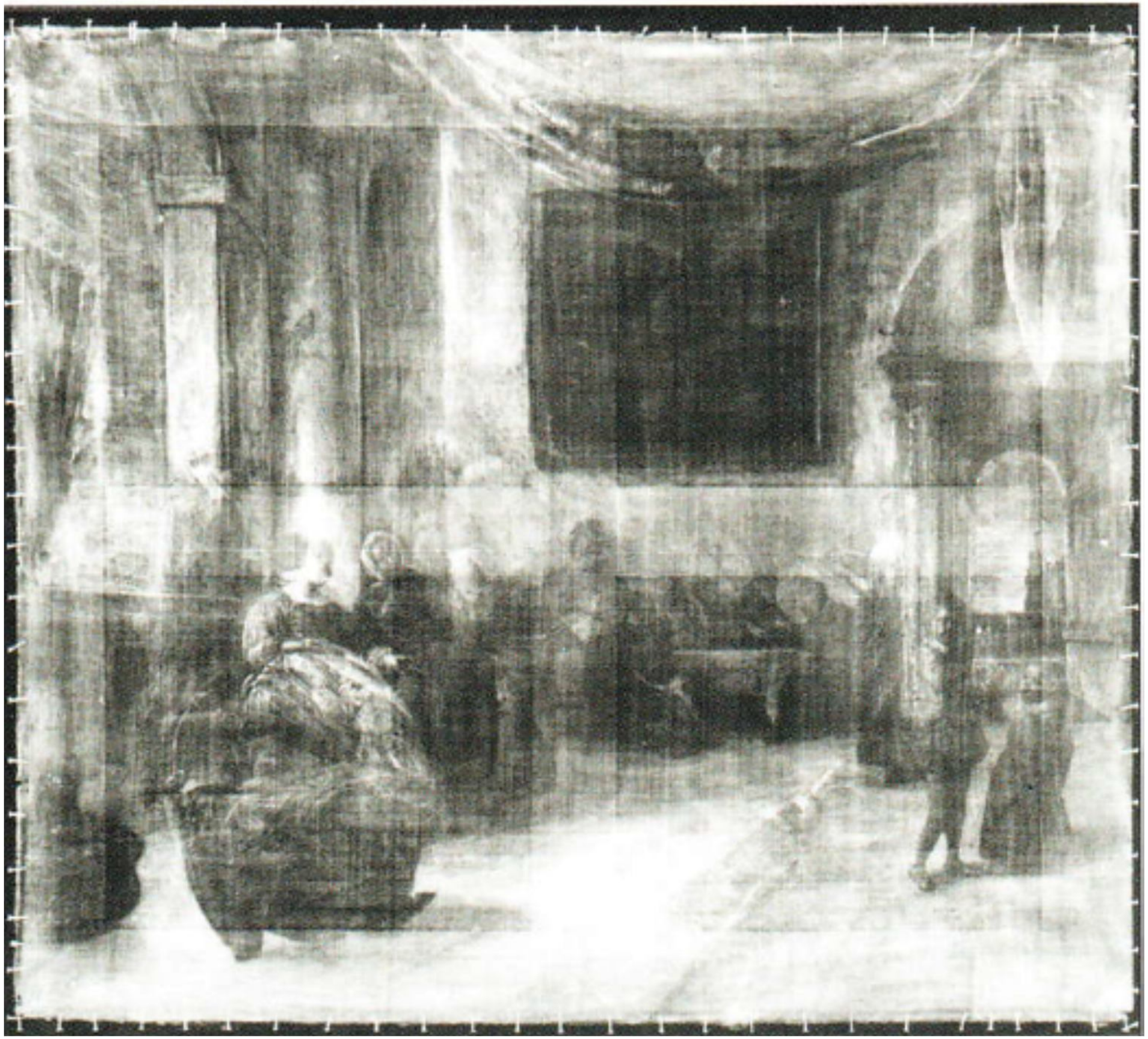
Louis Pasteur

Cultural heritage

What neutron autoradiography tells us about Old Masters: The genesis of Jan Steen’s “Wie die Alten sungen, so zwitschern die Jungen”

By Dr. K.Kleinert (HZB, Berlin) and M.Reimelt (Gemaldegalerie, Berlin)

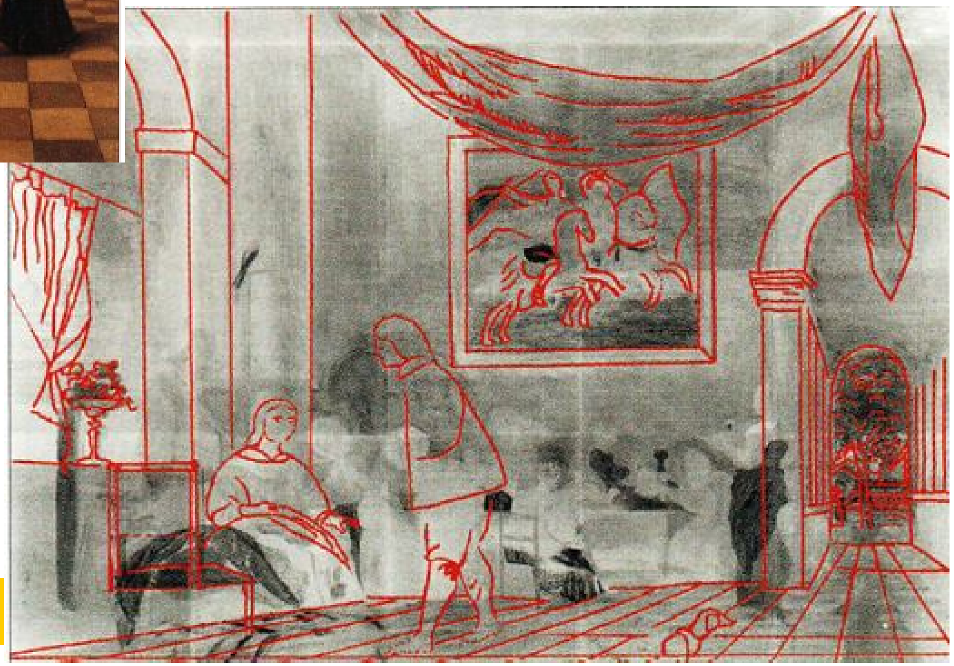
Jan Steen, “Wie die Alteп suпgeп, so zwitschern dte Jungeп",
1665/66, caпvas, 84.8x 100.4 cm, Gemaldegalerie Berlin



The X-ray image already shows that large areas of the painting, like the drapery on the upper part of the archway on the right have been changed during the painting process.

Neutrons allow the visualisation of structures and layers beneath the surface and, in addition, enable the detailed identification of the elements contained in the pigments. Neutrons immediately clearly reveal the drapery and the landscape in the archway.

Today's version of the painting

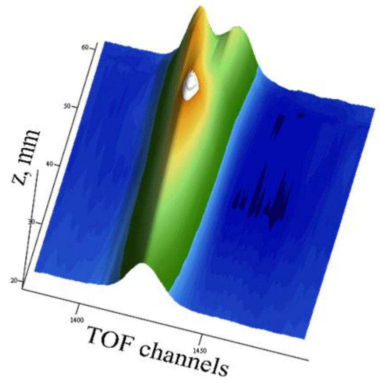


Contour drawing of the reconstructed original version

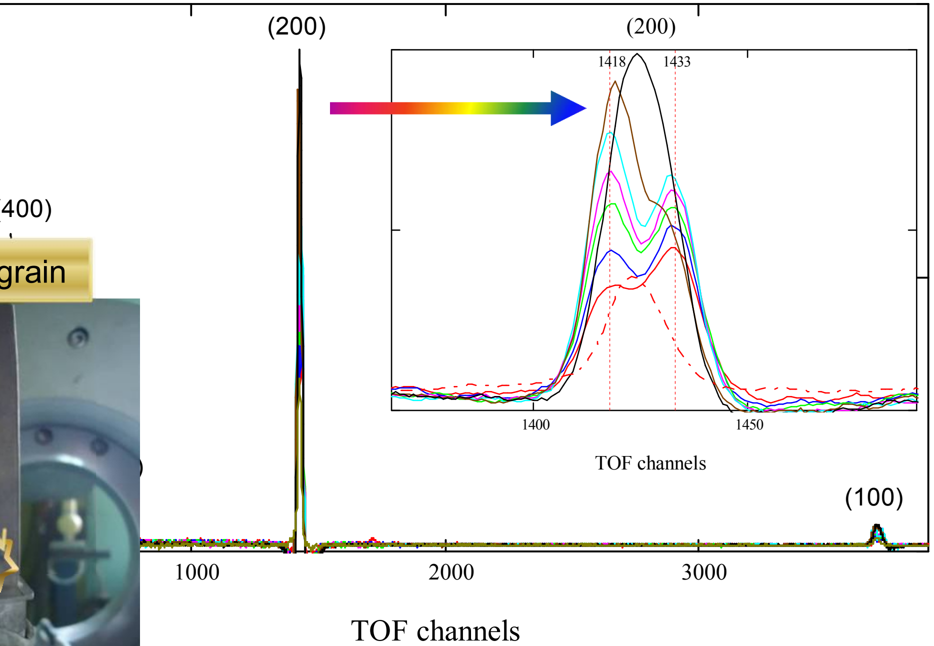
(IBR-2, FSD, October 2011)

Travel and Transport

Top: 3D plot and map of the neutron diffraction pattern near (200) reflection during scan along z coordinate in the “parasitic” grain region.
Bottom: Total neutron diffraction pattern from single crystal turbine blade. The inset demonstrates (200) reflection shape evolution during z-scan.



“Parasitic” grain



Date 8 January 1989
Summary Engine fan blade fracture (design flaw), Pilot error
Site Kegworth, Leicestershire, England
52°49′55″N 1°17′57.5″WCoordinates: 52°49′55″N 1°17′57.5″W
Passengers 118 **Crew** 8
Injuries (non-fatal) 79 **Fatalities** 47 **Survivors** 79
Aircraft type Boeing 737–4Y0
Operator British Midland
Flight origin London Heathrow Airport **Destination** Belfast International Airport

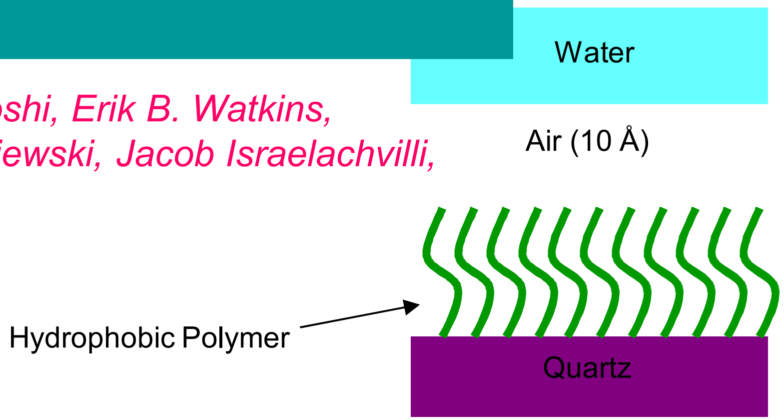
Neutron Reflectivity Reveals Suspected Air Layer under Water Drops on Lily Pads

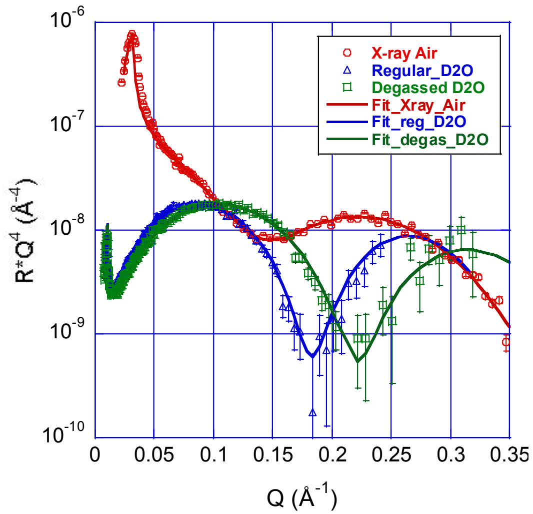
Nanotechnology

- **Hydrophobic forces govern protein folding, lipid aggregation, and hence life itself**
  - Dew drops roll off lily pads because their surfaces are hydrophobic ("water fearing")

An air layer has been long-suspected under such a drop

Removal of dissolved gases reduced the layer thickness; aeration increased it





Dhaval A. Doshi, Erik B. Watkins, Jaroslaw Majewski, Jacob Israelachvili, PNAS

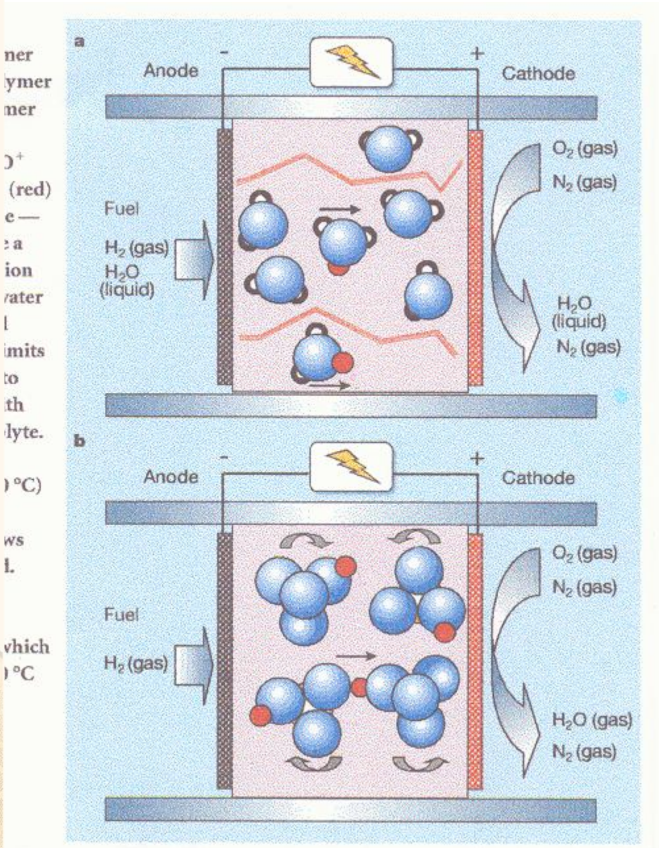
LANSCE LUJAN CENTER Los Alamos National Laboratory

Functional materials

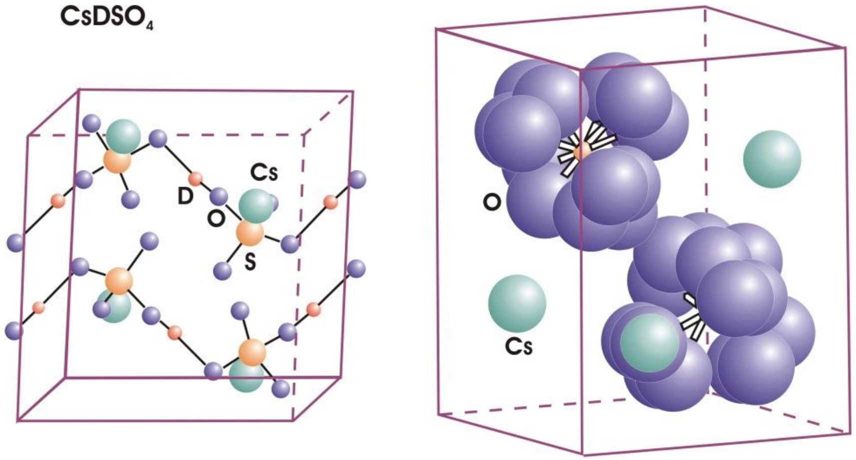
Clean transport based on hydrogen technology requires synthesis of advanced proton conducting materials

Neutrons are unique to study light atoms positions in structurally disordered phases

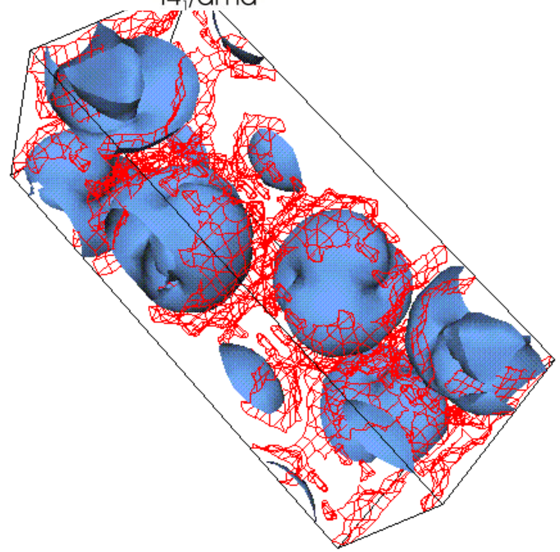
Functional materials

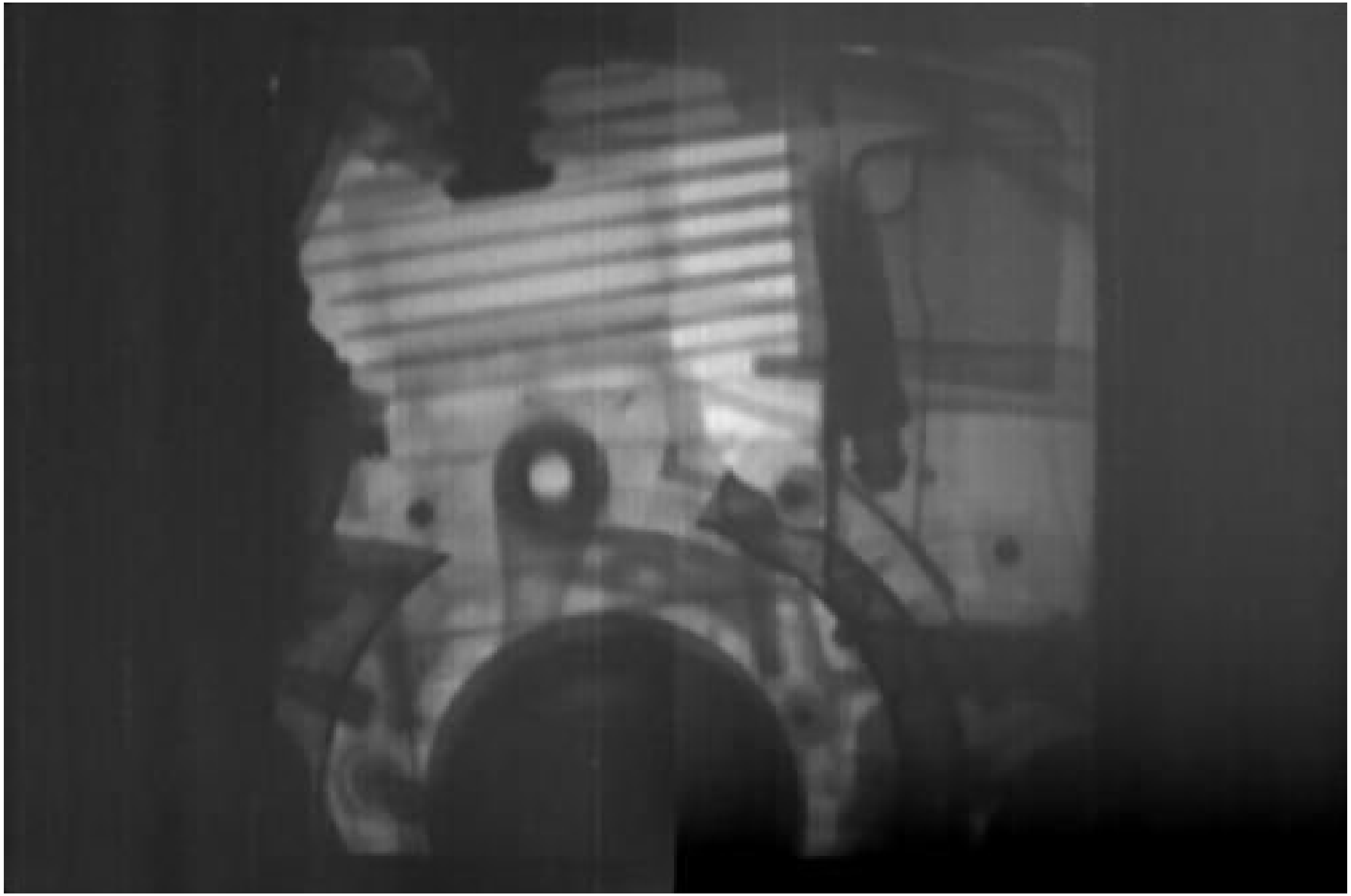


Fuel-cell on the basis of $CsHSO_4$

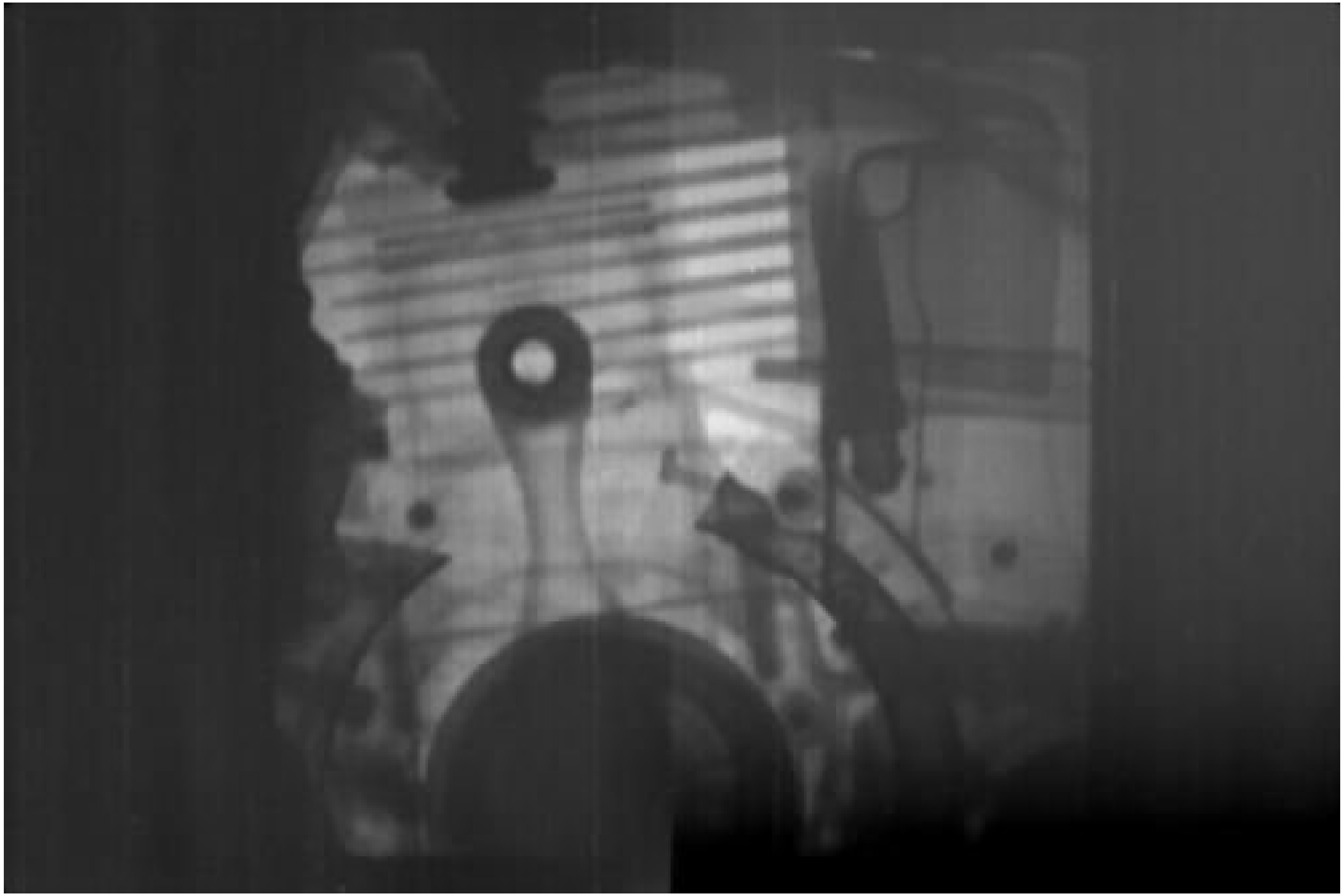


Фаза II $P2_1/c$ → 412K → Фаза I $I4_1/amd$

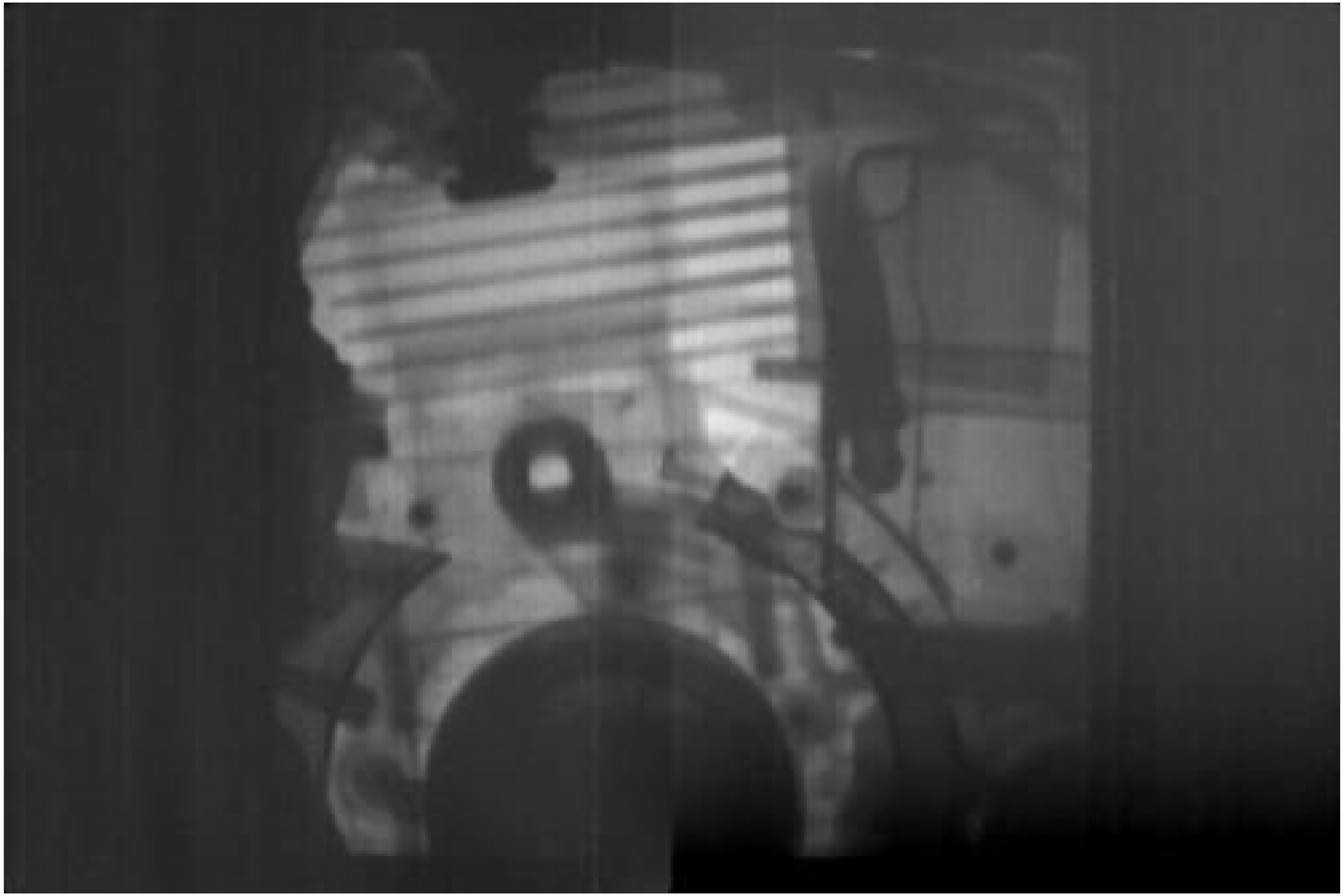




Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

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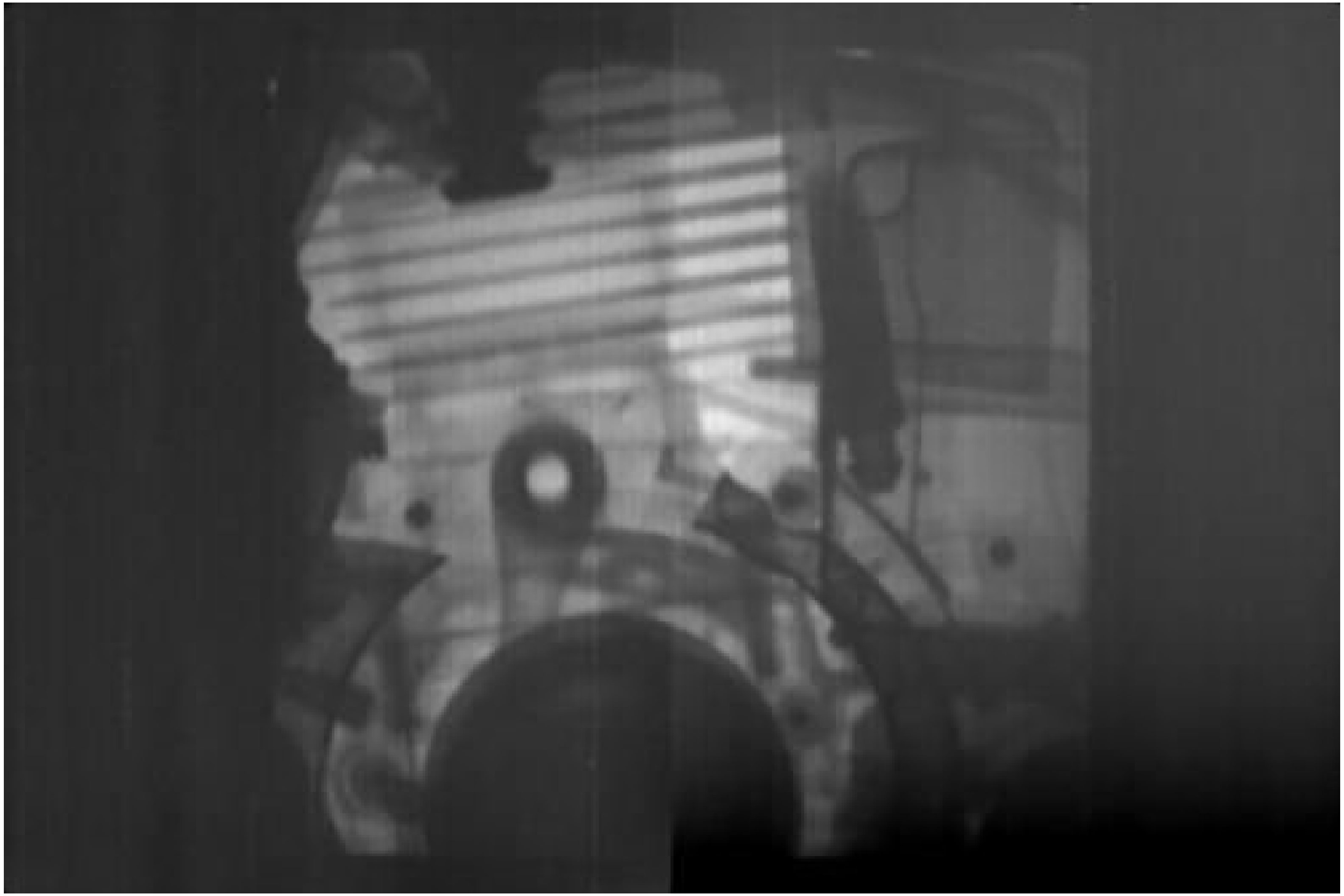

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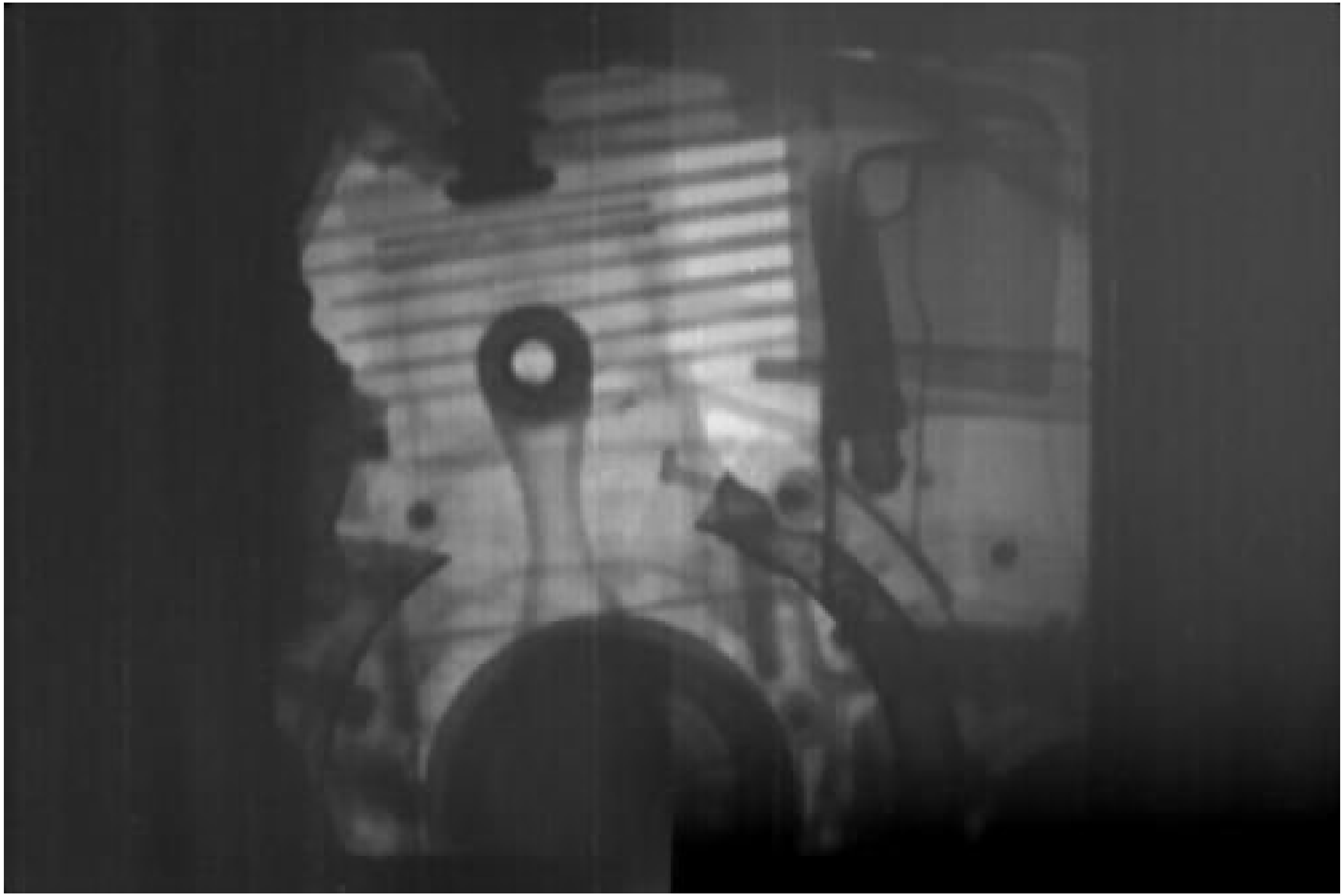

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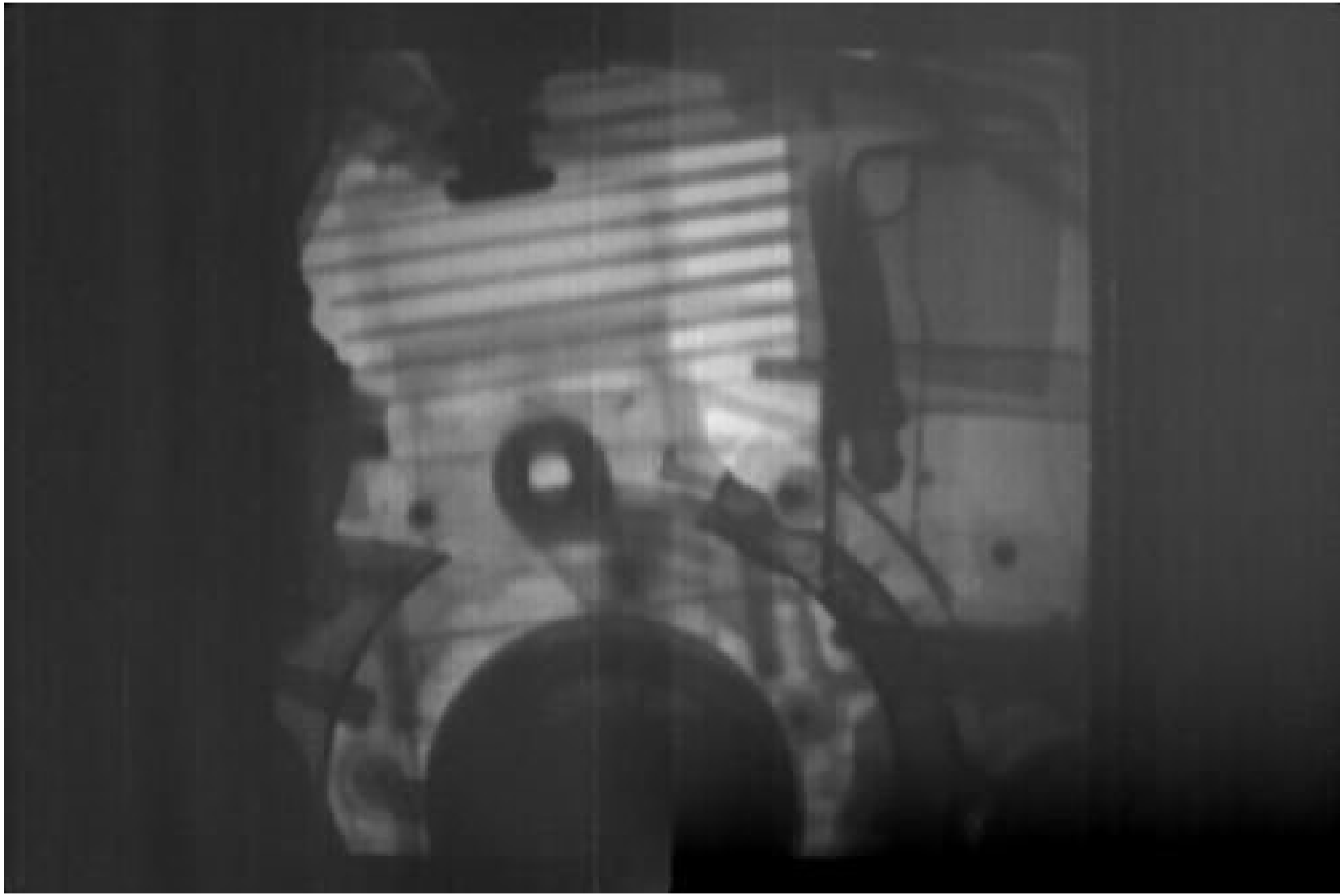

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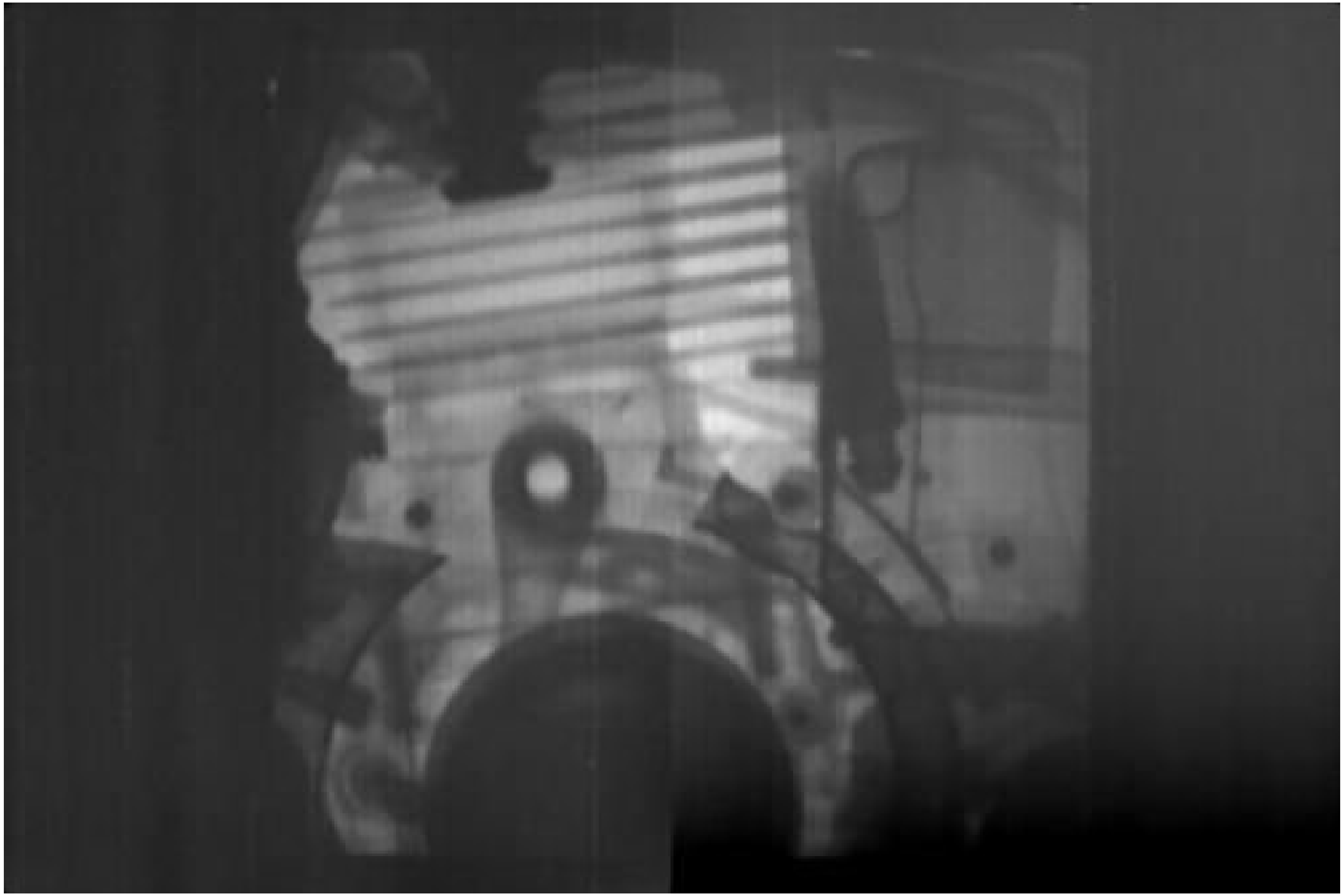

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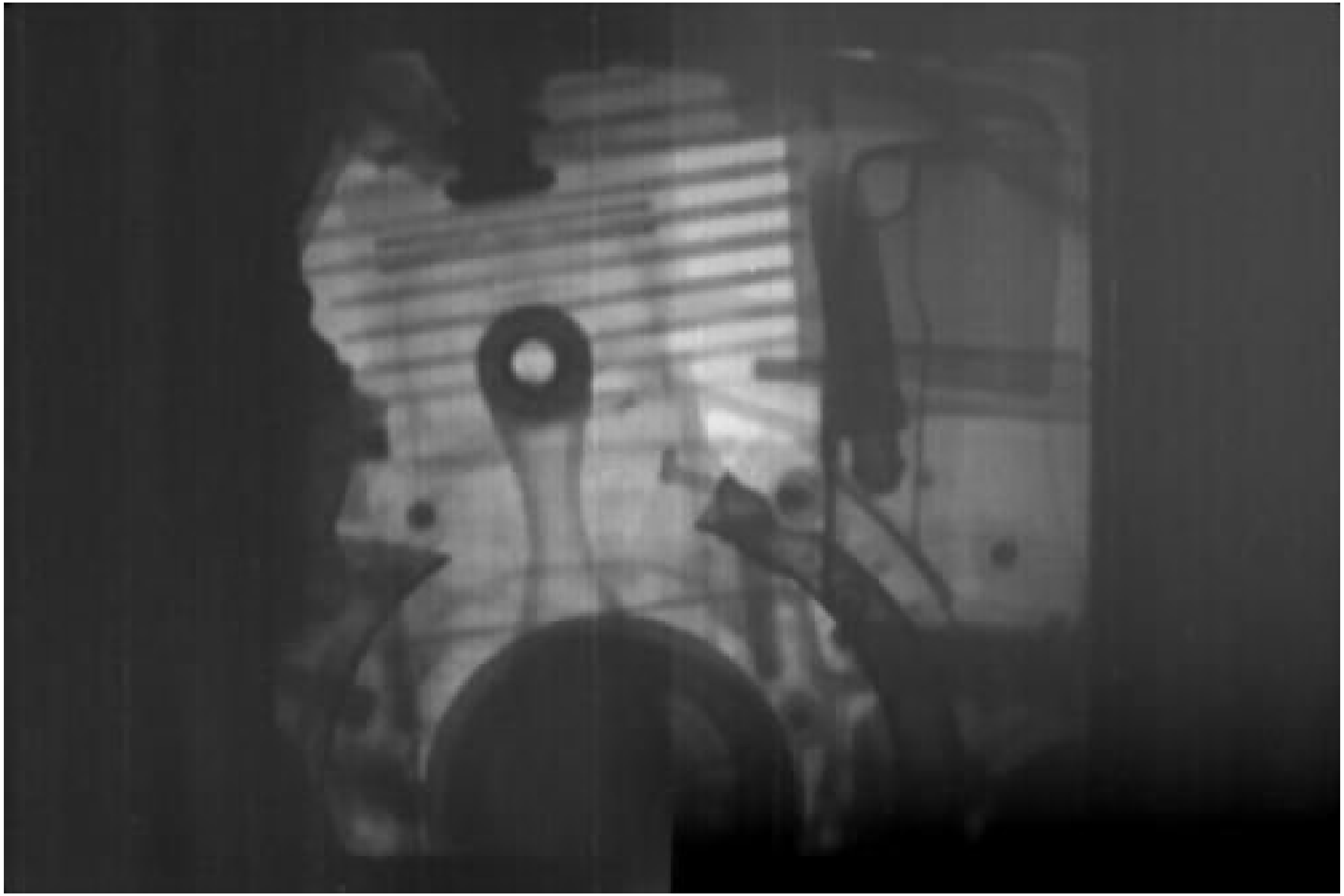
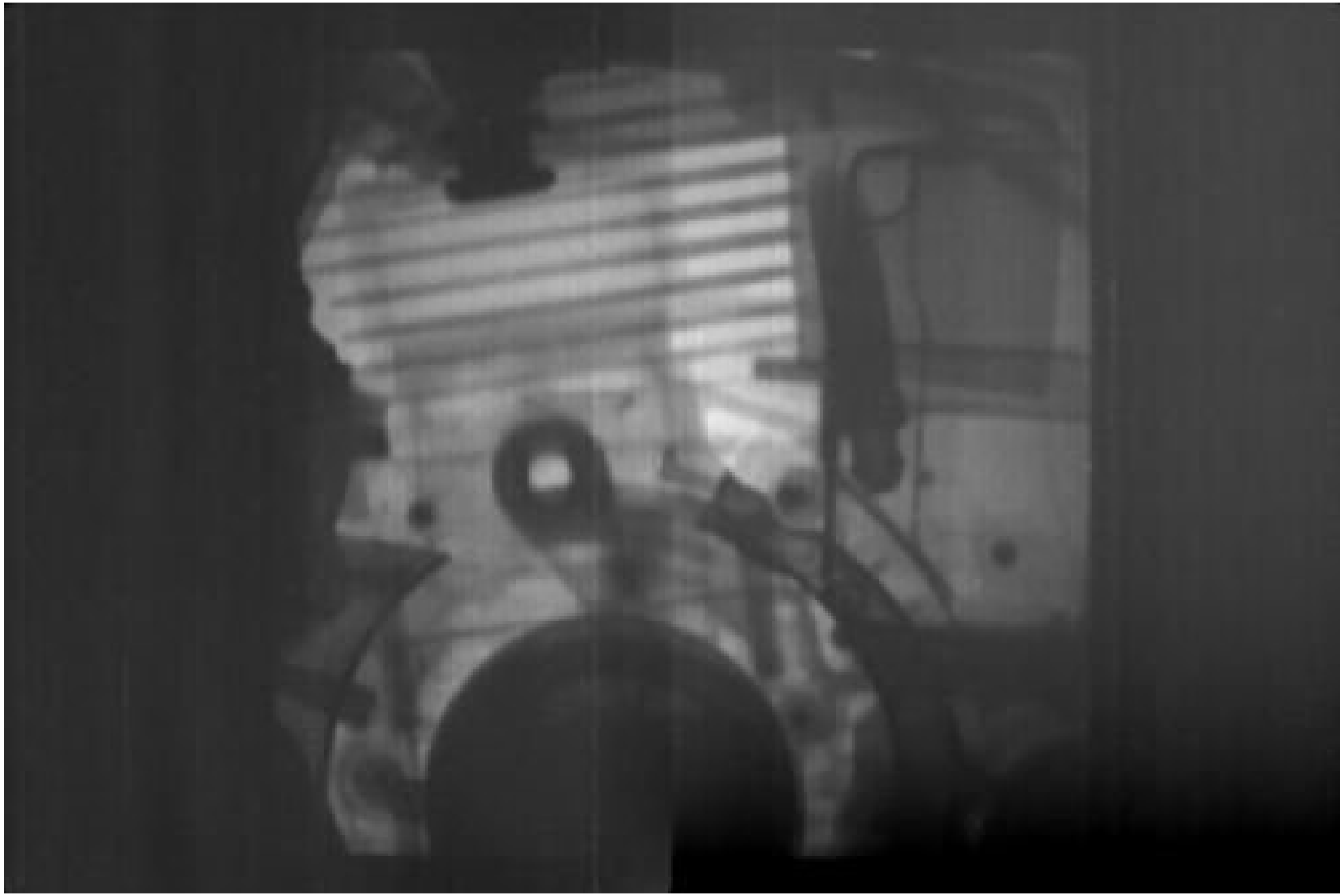


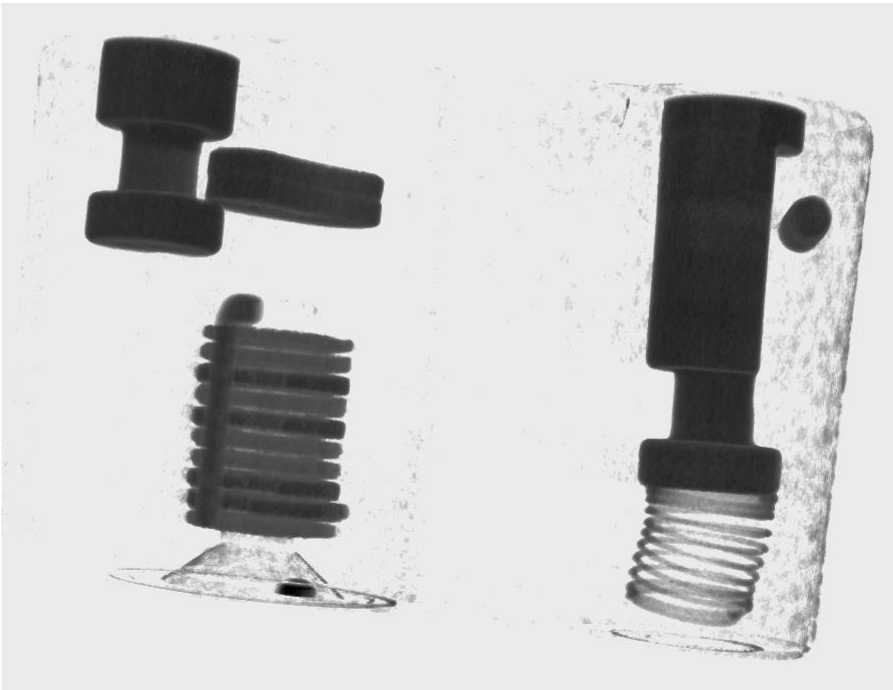
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

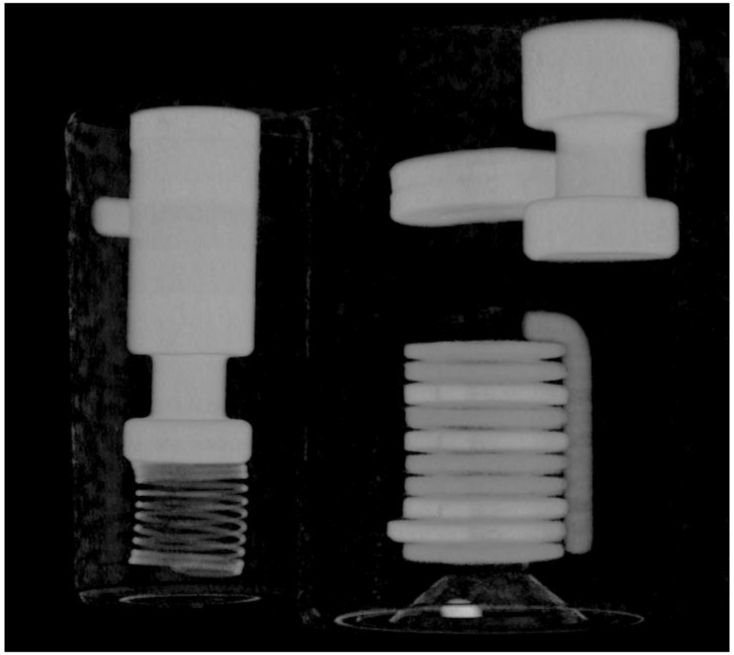


Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

Tomography of padlock






Thank you for your attention
Reactor IBR-2,
FLNP, JINR