# Neutronenstreuung : eine Einführung anhand aktueller Fragestellungen

M. Braden
WS 2007/08
Universität zu Köln

- von der Strukturbestimmung an Pulvern bis zur Analyse magnetischer Anregungen an Einkristallen

## 0. Einführung : Neutron : Geschichte Eigenschaften und Quellen

# Wilhelm Conrad Röntgen 1845-1923

Dr. W. C. Röntgen

EINE NEUE ART
VON
STRAHLEN.

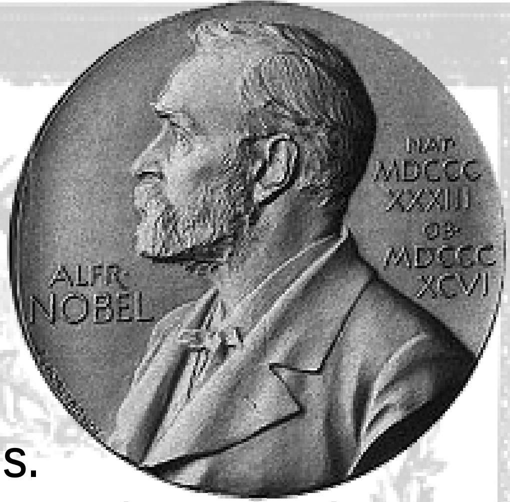
Von
Dr. W. RÖNTGEN,
Ö. O. PROFESSOR AN DER K. UNIVERSITÄT WÜRZBURG.

WÜRZBURG.
VERLAG UND DRUCK DER STAHEL'SCHEN K. HOF- UND UNIVERSITÄTS-
BUCH- UND KUNSTHANDLUNG.
Ende 1895.

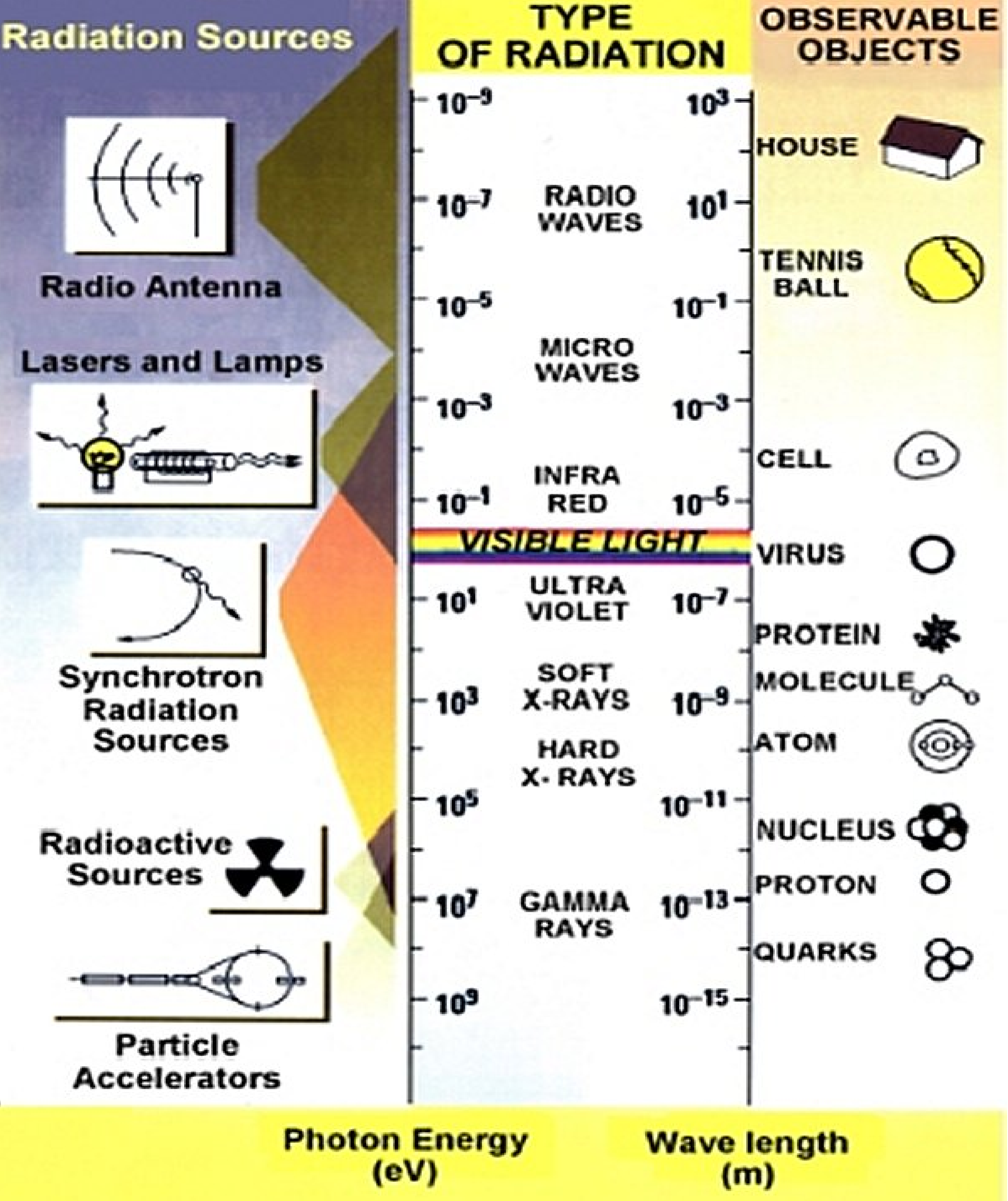
60 ₰.

1895: Discovery of X-Rays

# Nobel Prizes for Research with X-Rays



1901 W. C. Röntgen in Physics for the discovery of x-rays.
1914 M. von Laue in Physics for x-ray diffraction from crystals.
1915 W. H. Bragg and W. L. Bragg in Physics for crystal structure determination.
1917 C. G. Barkla in Physics for characteristic radiation of elements.
1924 K. M. G. Siegbahn in Physics for x-ray spectroscopy.
1927 A. H. Compton in Physics for scattering of x-rays by electrons.
1936 P. Debye in Chemistry for diffraction of x-rays and electrons in gases.
1962 M. Perutz and J. Kendrew in Chemistry for the structure of hemoglobin.
1962 J. Watson, M. Wilkins, and F. Crick in Medicine for the structure of DNA.
1979 A. McLeod Cormack and G. Newbold Hounsfield in Medicine for computed axial tomography.
1981 K. M. Siegbahn in Physics for high resolution electron spectroscopy.
1985 H. Hauptman and J. Karle in Chemistry for direct methods to determine x-ray structures.
1988 J. Deisenhofer, R. Huber, and H. Michel in Chemistry for the structures of proteins that are crucial to photosynthesis.



Wavelength

≈

Object Size

≈

Angstroms for Condensed Matter Research

$$\lambda[\text{Å}] = \frac{12.398}{E_{\text{ph}}[\text{keV}]}$$

# Nobelpreise Neutronen

## The Nobel Prize in Physics 1935

James Chadwick

"for the discovery of the neutron"

## The Nobel Prize in Physics 1994

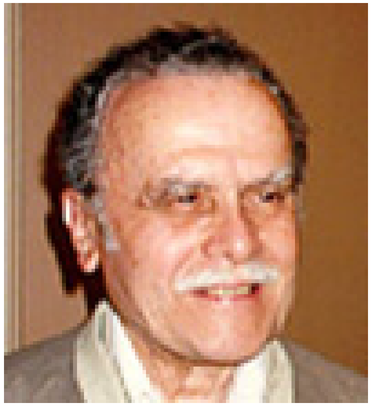
"In simple terms,
*Clifford G. Shull (1915-2001)*
has helped answer the question of **where atoms are**,

and

*Bertram N. Brockhouse*
(1918-2003)
the question of **what atoms do**",
(Nobel citation)

"for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter"

"for the development of the neutron diffraction technique"



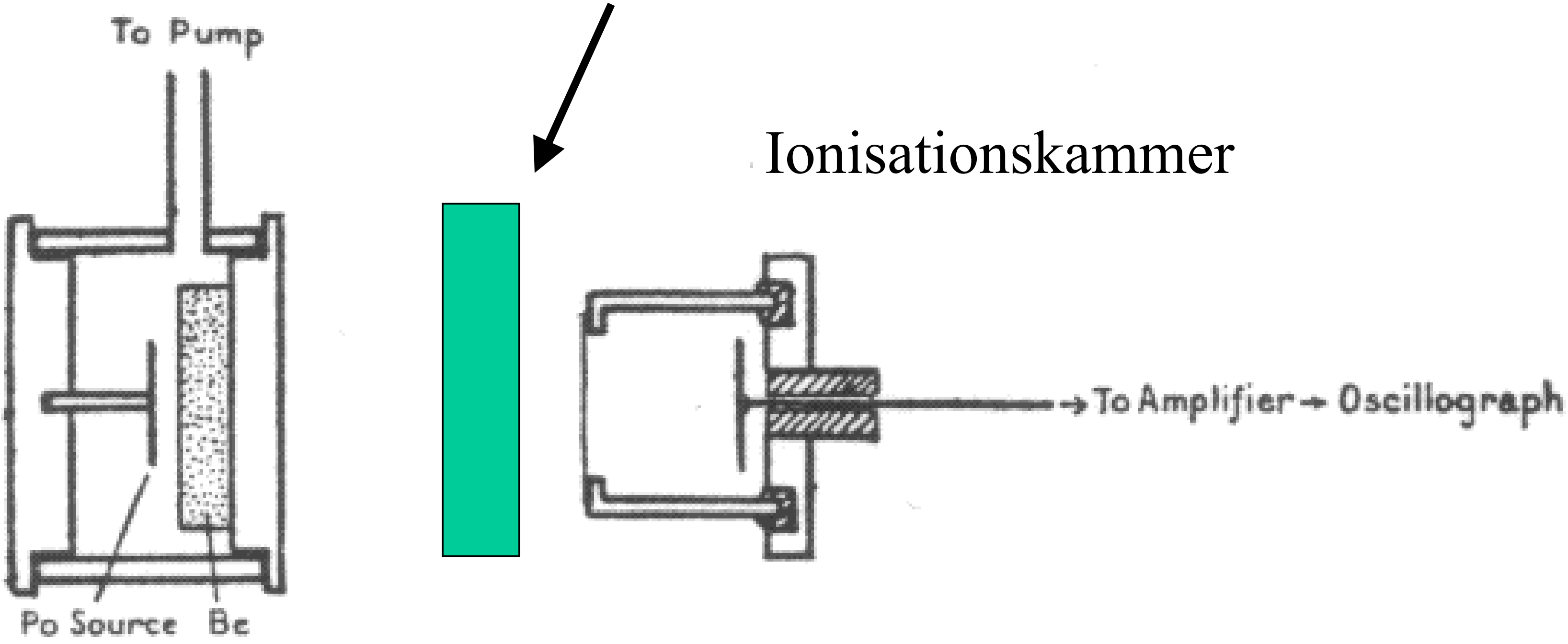
"for the development of neutron spectroscopy"

# 1932: Entdeckung von Chadwick

$^{212}\mathrm{Po} \rightarrow ^{208}\mathrm{Pb} + \alpha$

$\mathbf{^{9}Be + \alpha \rightarrow ^{12}C + n}$

verschiedene Absorber (Paraffin (H), He, Li)



Ionisationskammer

FIG. 1.

## Letters to the Editor

### Possible Existence of a Neutron

J. Chadwick.

Cavendish Laboratory,
Cambridge, Feb. 17.

① Bothe 1928 "durchdringende Strahlung"

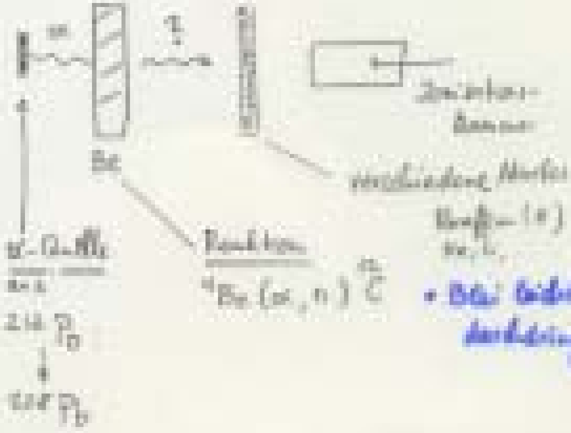
② Curie + Joliot 18.1.1932

durch "Compton-Effekt" werden Protonen aus wasserstoffhaltiger Probe gelöst

— falsche Erklärung! —

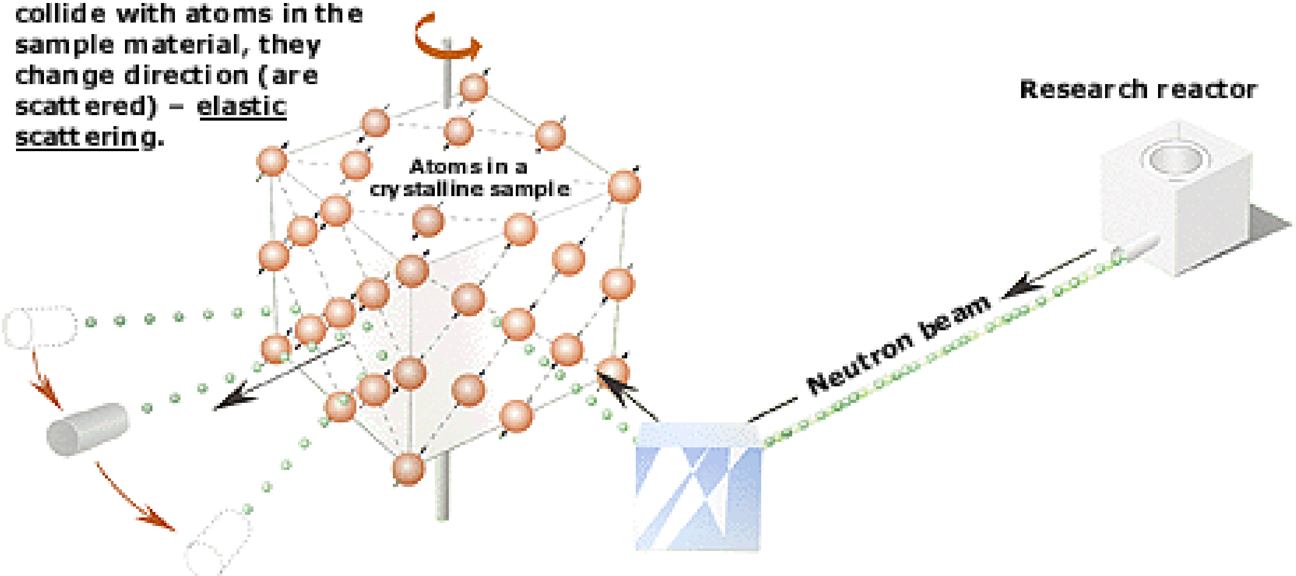
da Annahme: γ-Strahlung

③ Chadwick zwischen 18.1. und 17.2.32



* Blei Schicht durchdringend

# Neutrons show where atoms are



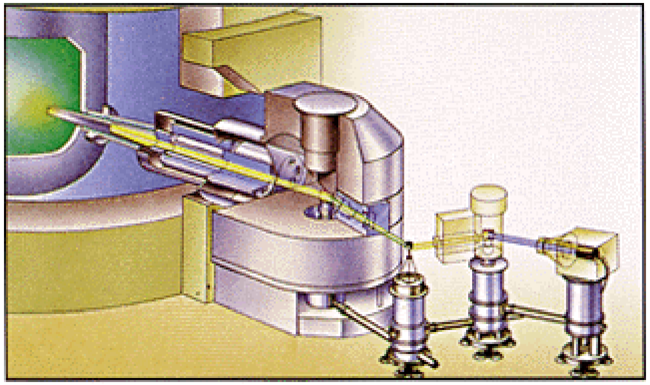
When the neutrons collide with atoms in the sample material, they change direction (are scattered) – <u>elastic scattering</u>.

Detectors record the directions of the neutrons and a diffraction pattern is obtained.

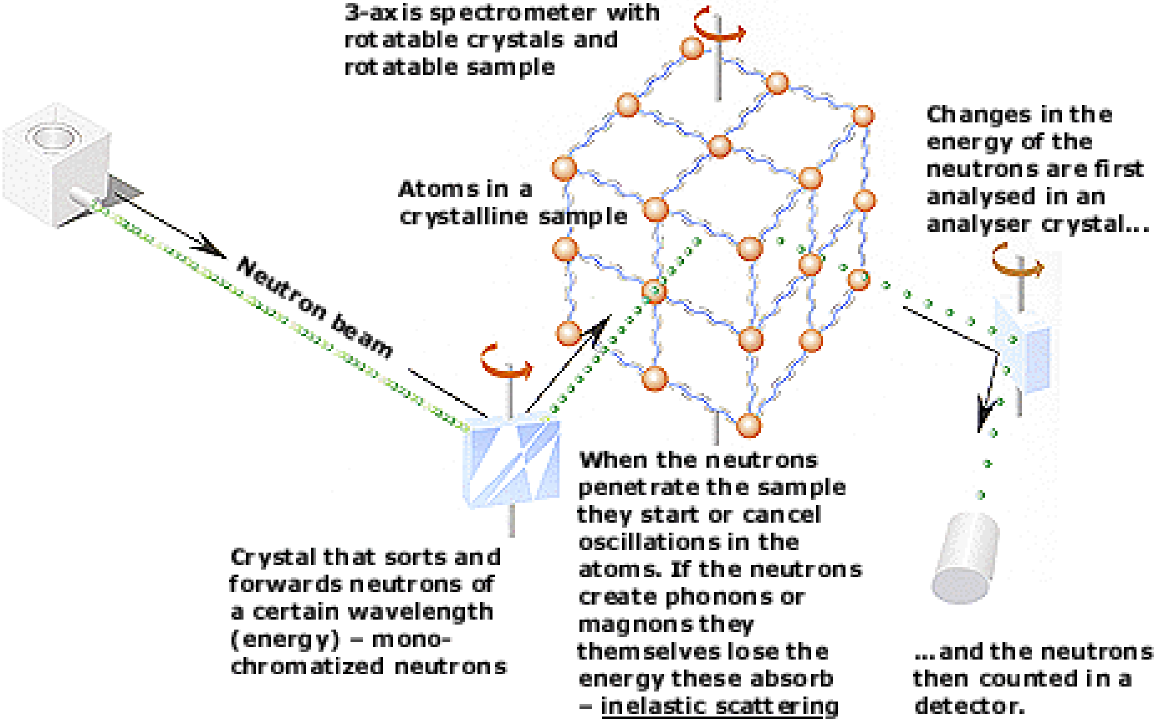
The pattern shows the positions of the atoms relative to one another.

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – monochromatized neutrons

# Neutrons show what atoms do



3-axis spectrometer



3-axis spectrometer with rotatable crystals and rotatable sample

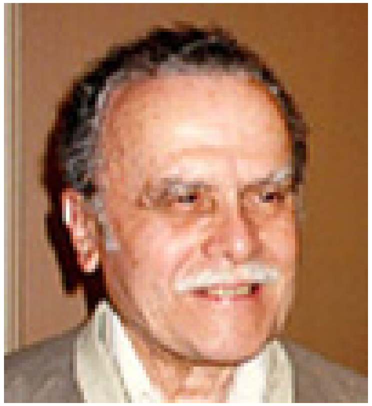
Atoms in a crystalline sample

Changes in the energy of the neutrons are first analysed in an analyser crystal...

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – mono-chromatized neutrons

When the neutrons penetrate the sample they start or cancel oscillations in the atoms. If the neutrons create phonons or magnons they themselves lose the energy these absorb – <u>inelastic scattering</u>

...and the neutrons then counted in a detector.



***1942*** – Nobel Laureate Enrico Fermi led the group that first demonstrated a controlled nuclear reaction (on December 2, 1942, shown below). On November 4, 1943, Fermi witnessed the initial operation of the Graphite Reactor in Oak Ridge.

## 1943 –

Designed using the results of the Chicago experiment, the Graphite Reactor produced small amounts of plutonium, setting the stage for large-scale plutonium production by reactors in Hanford, Washington. It was the world's first isotope-production reactor.

## 1943 –

Eugene Wigner, later an ORNL director who won a Nobel Prize for physics, predicted that radiation damage could be a problem for reactors. The behavior of irradiated materials was studied at ORNL, which became a leading materials research laboratory.

# Graphit-Reaktor in Oak-Ridge (Tennessee)

**1945** – Ion-exchange chromatography used at the Graphite Reactor enabled the discovery of promethium (element 61).

**1945** –The first neutron-scattering studies using a reactor were performed at the Graphite Reactor by Ernie Wollan (left) and Clifford Shull (right), who won a Nobel Prize for physics in 1994 for advancing the understanding of the positions of atoms and molecules in materials.

Wollan, Shull, Koehler the pioneers ! ! !

today **High Flux Isotope Reactor (HFIR) in 1966, ORNL**

PHYSICAL REVIEW VOLUME 100, NUMBER 2 OCTOBER 15, 1955

# Neutron Diffraction Study of the Magnetic Properties of the Series of Perovskite-Type Compounds $[(1-x)\mathrm{La}, x\mathrm{Ca}]\mathrm{MnO}_3$†

E. O. WOLLAN AND W. C. KOEHLER
*Oak Ridge National Laboratory, Oak Ridge, Tennessee*

(Received May 9, 1955)

A study has been made of the magnetic properties of the series of perovskite-type compounds $[(1-x)\mathrm{La}, x\mathrm{Ca}]\mathrm{MnO}_3$. The investigations have been made primarily by neutron diffraction methods, but x-ray diffraction measurements of lattice distortions and ferromagnetic saturation data are also included. This series of compounds exhibits ferromagnetic and antiferromagnetic properties which depend upon the relative trivalent and tetravalent manganese ion content. The samples are purely ferromagnetic over a relatively narrow range of composition ($x\sim 0.35$) and show simultaneous occurrence of ferromagnetic and antiferromagnetic phases in the ranges ($0<x<0.25$) and ($0.40<x<0.5$). Several types of antiferromagnetic structures at $x=0$ and $x>0.5$ have also been determined. The growth and mixing of the various phases have been followed over the whole composition range, the ferromagnetic and antiferromagnetic moment contributions to the coherent reflections have been determined, and Curie and Néel temperatures have been measured. The results have been organized into a scheme of structures and structure transitions which is in remarkable accord with Goodenough's predictions based on a theory of semicovalent exchange.

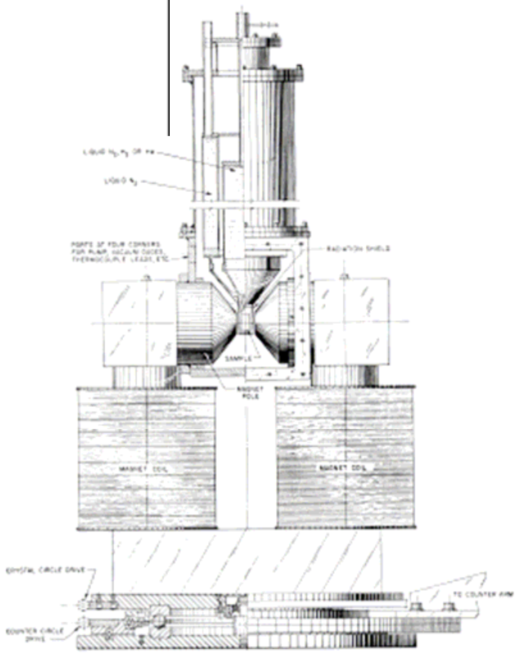


FIG. 1. Neutron spectrometer with cryostat and magnet.

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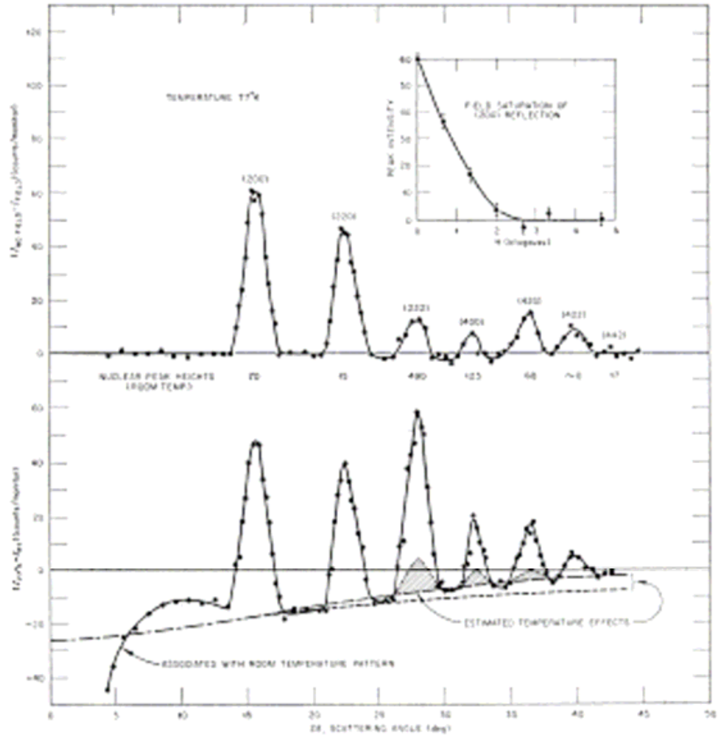


FIG. 9. Ferromagnetic patterns for [0.65 La—0.35 Ca]$\mathrm{MnO}_3$ No. 70. Upper curve gives magnetic field difference pattern for maximum field in inset curve. Lower curve gives comparative data from temperature difference patterns.

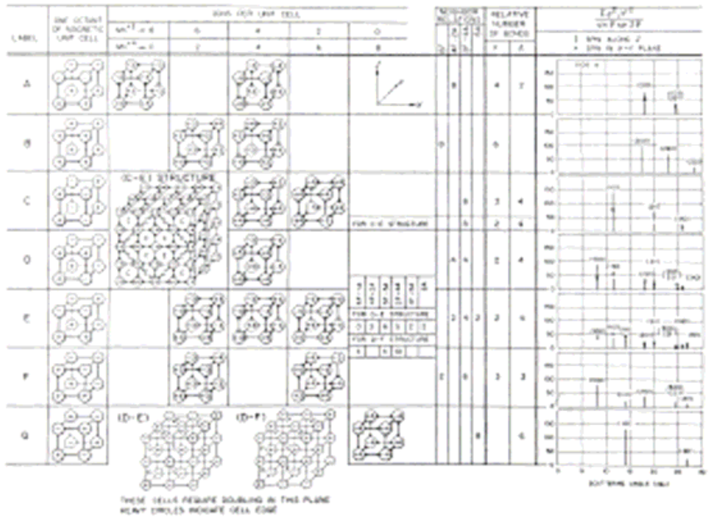


FIG. 18. Scheme of magnetic structures and related information. *A*, *B*, *C*, *G*, and (*C-E*) definitely observed and some evidence for *D* and *F*. Ion ordering schemes represent arrangements consistent with certain coupling criteria. Arrowheads are a schematic representation of Goodenough's semicovalent exchange coupling.

# Inelastische Neutronenstreuung : Bertram Brockhouse Chalk River Kanada (in den 50‘ern)

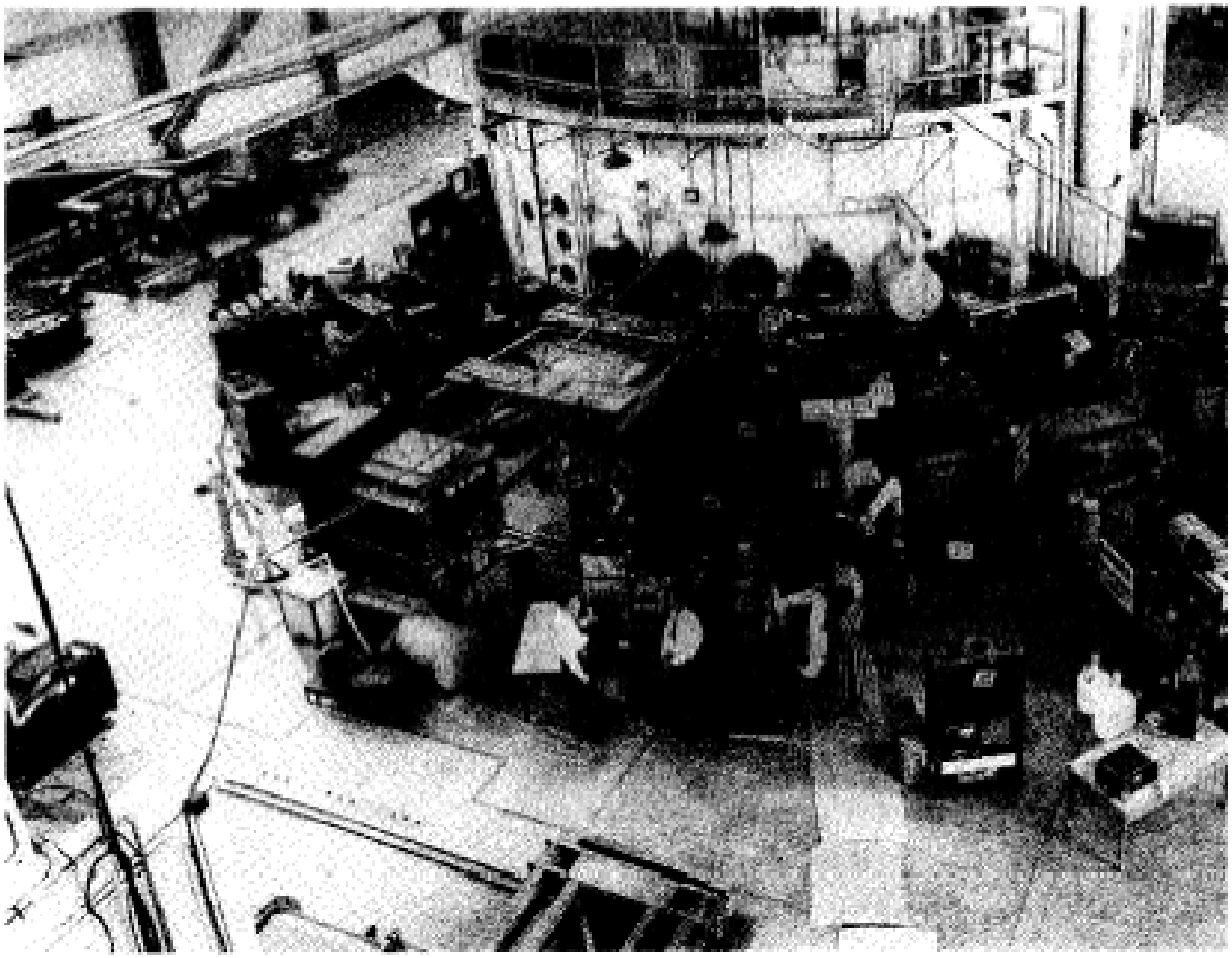


Fig. 1: The main floor of the NRX Reactor at the Chalk River Laboratory about 1950. The powder diffractometer constructed by Donald Hurst and associates is visible near the centre of the photograph. Most of the other equipment is concerned with nuclear physics or with the physics of the neutron itself. For reasons of space, each apparatus is located at the end of a long tube. (AECL photo)

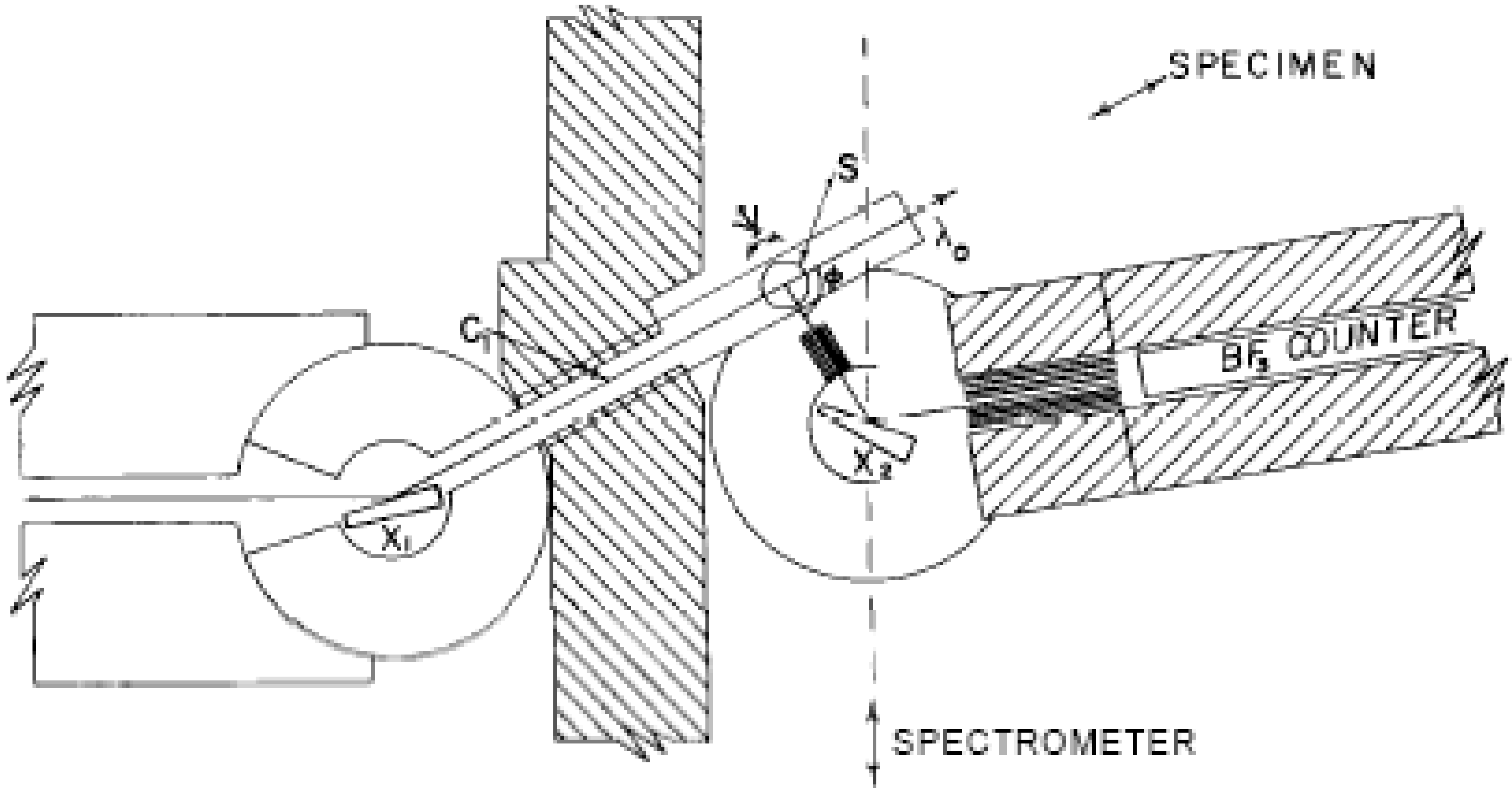
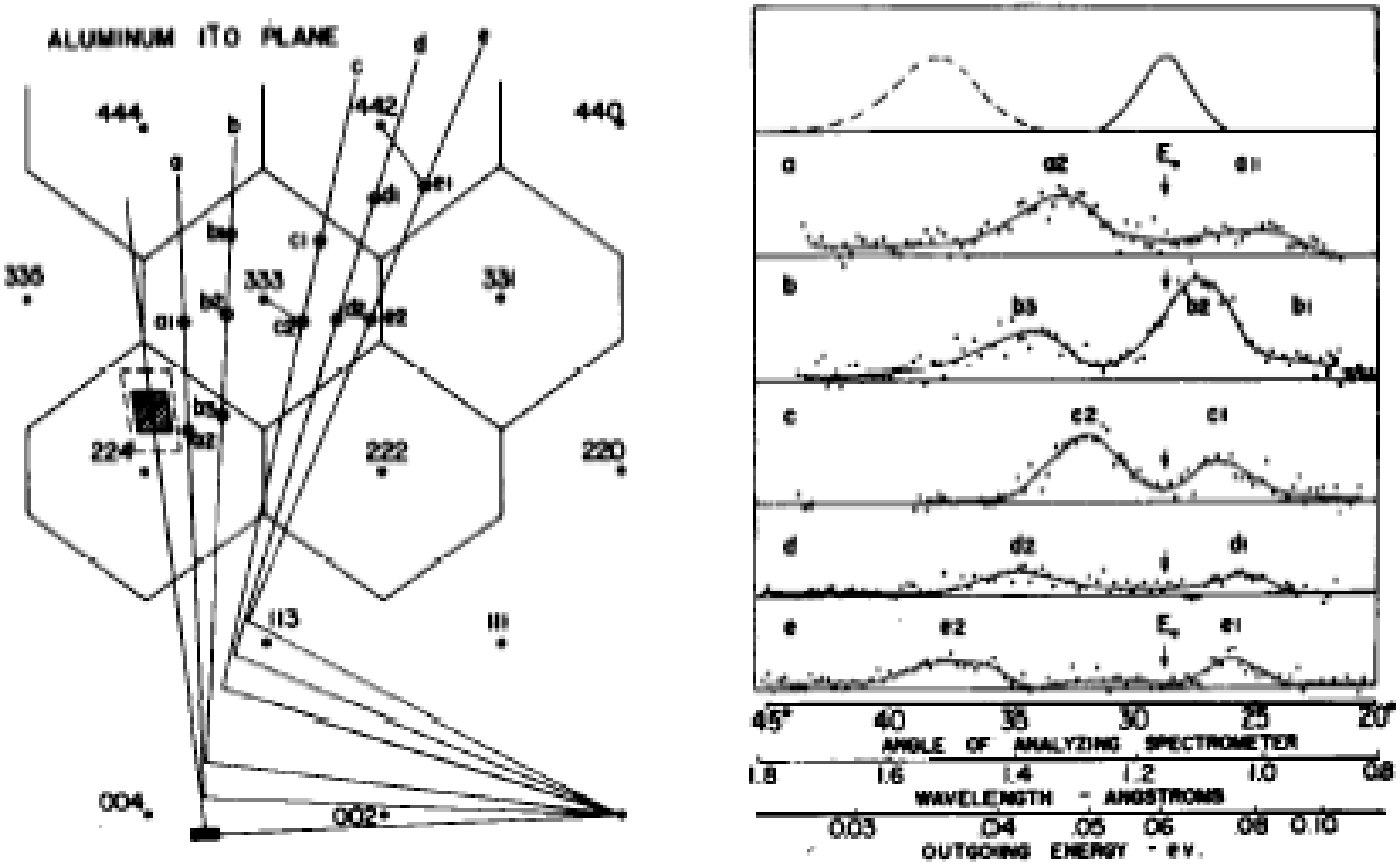
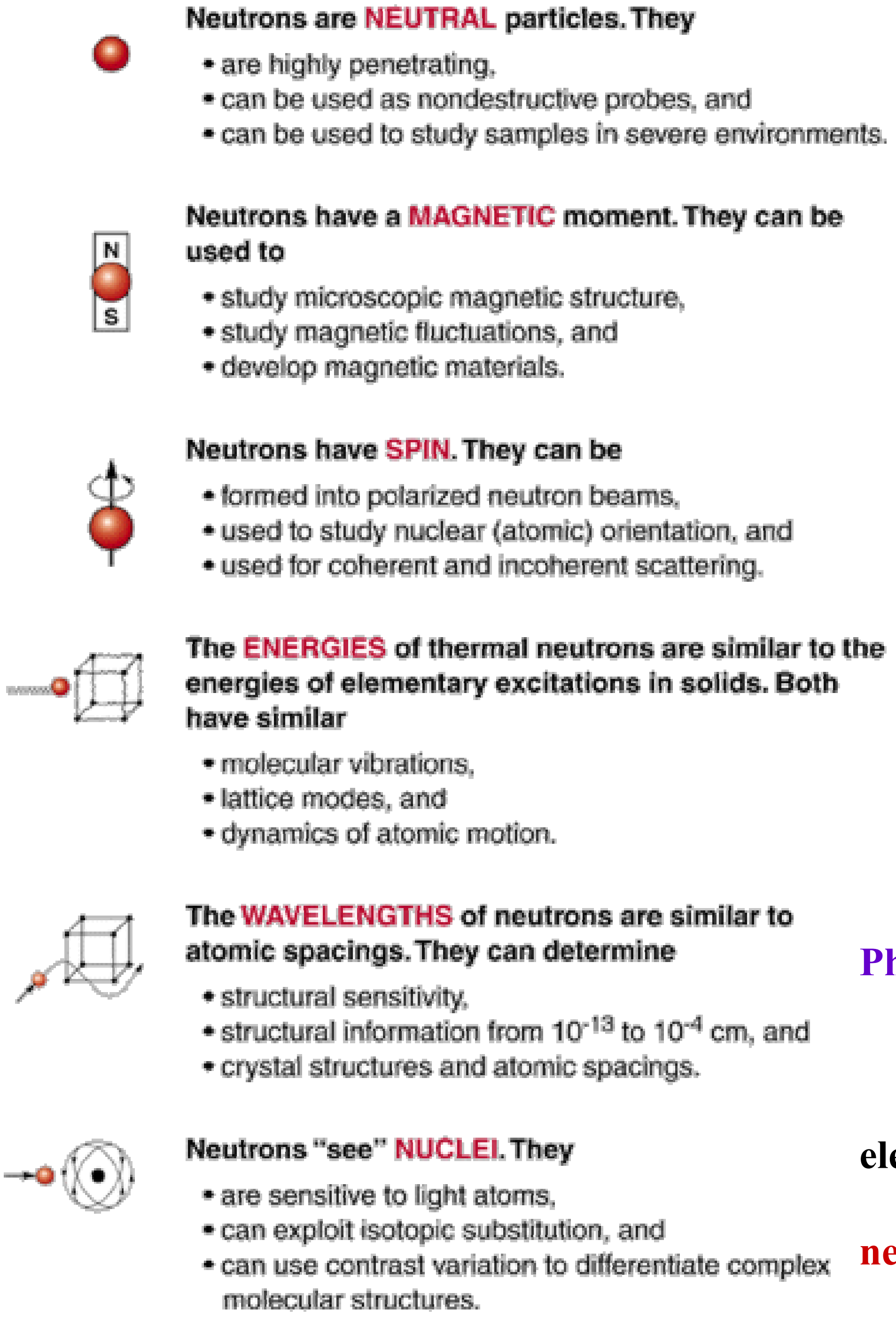


Fig. 3: The first crude version of the triple-axis crystal spectrometer [24 - 26]. Monoenergetic neutrons are selected by the large single crystal monochromator (XI) and impinge on the specimen (S), which is located on a table whose orientation (ψ) in the horizontal plane can he selected. This table can he moved along the direction of the incident beam as desired. The analyzing spectrometer, which employs crystal X2, is a diffractometer (of especially large aperture) which can he translated as a unit; the angle (φ) through which the examined neutrons are scattered is determined by triangulation.

Fig. 9: Photograph (1959) of the original triple-axis spectrometer at the NRU reactor at Chalk River. The bank of 52 rotary switches, preset to go through an energy scan of up to 26 points, can be seen in the upper- centre. One of the three variables involved would traverse linearly through the domain of settings desired, while the other two advance nonlinearly according to the settings of the appropriate switches. (AECL photo)


ALUMINUM 1T0 PLANE
444
442
440
335
333
331
224
222
220
113
111
004
002
a
b
c
d
e
a1
a2
b1
b2
b3
c1
c2
d1
d2
e1
e2
E₀
ANGLE OF ANALYZING SPECTROMETER
45°
40
35
30
25
20°
WAVELENGTH – ANGSTROMS
1.8
1.6
1.4
1.2
1.0
0.8
OUTGOING ENERGY – ev.
0.03
.04
.05
.06
.08
0.10

# Neutrons



Neutrons are **NEUTRAL** particles. They

- are highly penetrating,
- can be used as nondestructive probes, and
- can be used to study samples in severe environments.

Neutrons have a **MAGNETIC** moment. They can be used to

- study microscopic magnetic structure,
- study magnetic fluctuations, and
- develop magnetic materials.

Neutrons have **SPIN**. They can be

- formed into polarized neutron beams,
- used to study nuclear (atomic) orientation, and
- used for coherent and incoherent scattering.

The **ENERGIES** of thermal neutrons are similar to the energies of elementary excitations in solids. Both have similar

- molecular vibrations,
- lattice modes, and
- dynamics of atomic motion.

The **WAVELENGTHS** of neutrons are similar to atomic spacings. They can determine

- structural sensitivity,
- structural information from $10^{-13}$ to $10^{-4}$ cm, and
- crystal structures and atomic spacings.

Neutrons "see" **NUCLEI**. They

- are sensitive to light atoms,
- can exploit isotopic substitution, and
- can use contrast variation to differentiate complex molecular structures.

$M_n = 1.674928.10^{-27}$kg

$= 1.001\ M_{Proton}$

**$\tau =$ 885 s ($\beta$ decay)**

**$n \rightarrow p + e^{-} + \nu_e + 0.78$MeV**

**n: $E = h^2/2M_n\lambda^2 = 81.1\text{meV}/\lambda^2$**

**photon: $E = hf = hc/\lambda = 12398\text{eV}/\lambda$**

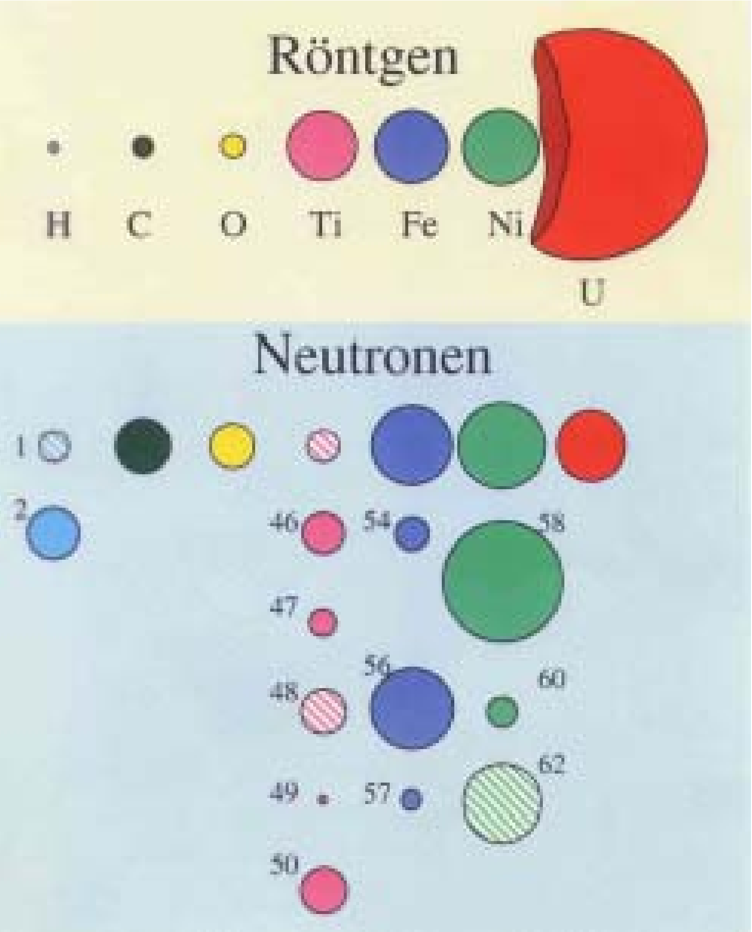
**$k = 2\pi/\lambda$ $p = h/\lambda$**

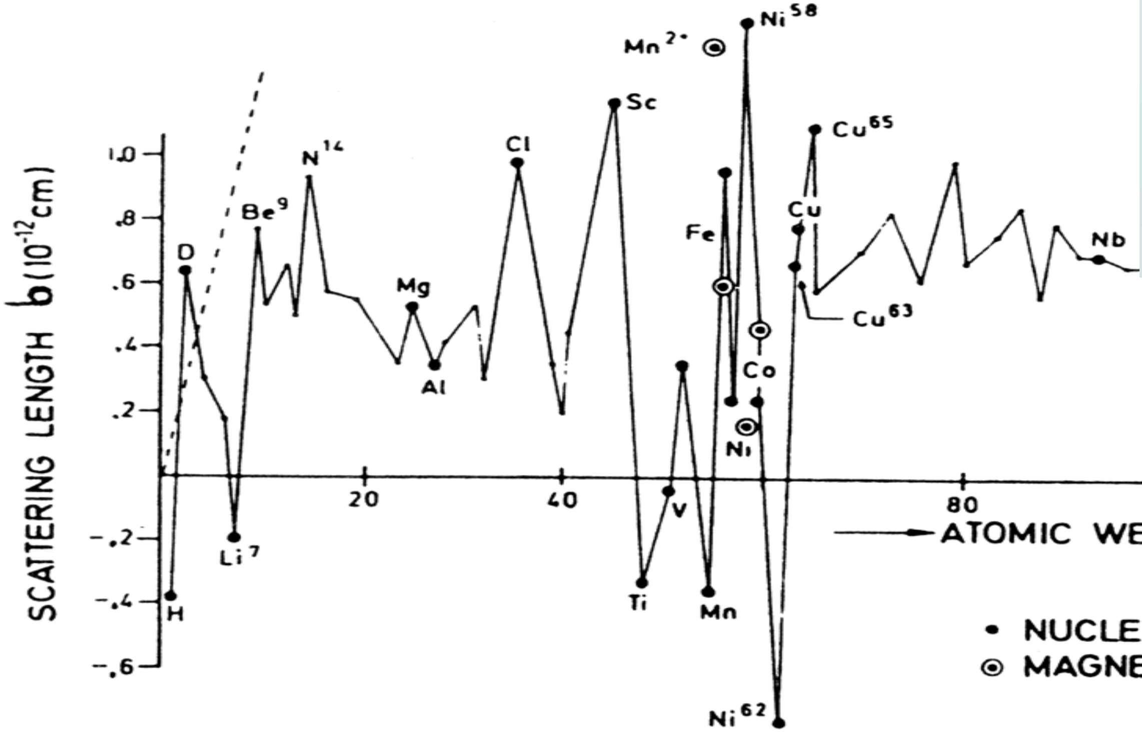
**units:**

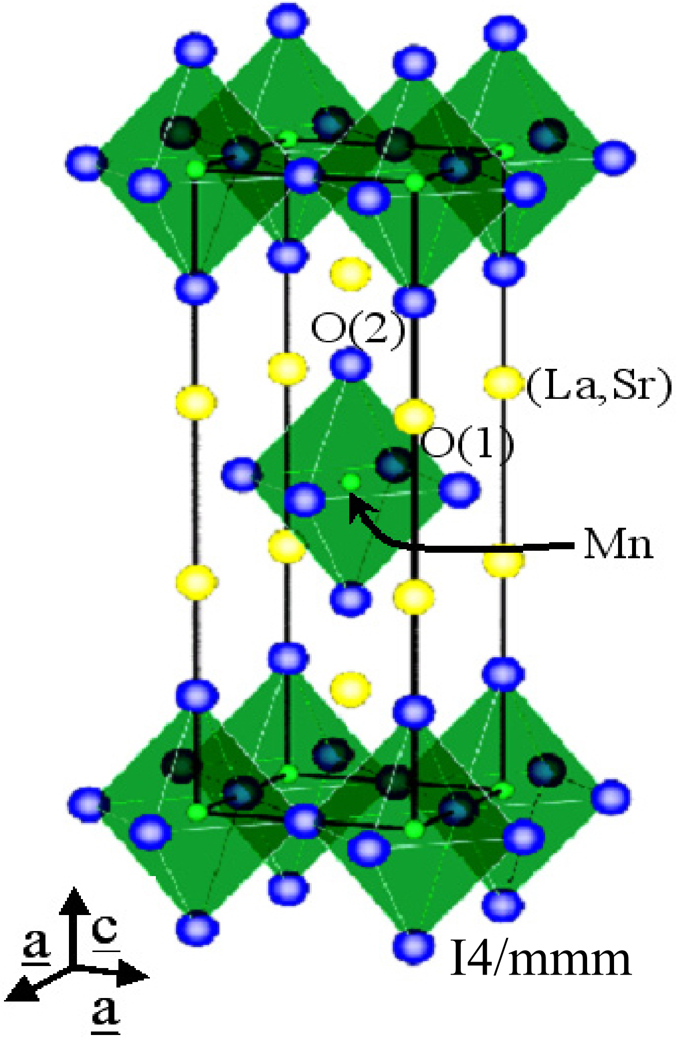
**1 meV=11.6 K=8.066/cm=0.241THz**

| | λ[Å] | k[1/Å] | v(m/s) | E | best ΔE/E |
|---|---|---|---|---|---|
| **Photon light** | **5000** | **$10^{-3}$** | **$3.10^8$** | **eV** | **$10^{-8}$** |
| **X-ray** | **1** | **1** | **$3.10^8$** | **keV** | **$10^{-6}$** |
| **electron** | **1** | **1** | **$6.10^7$** | **150eV** | **$10^{-5}$** |
| **neutron** | **1** | **1** | **400** | **meV** | **$10^{-6}$** |

- -Neutronen sind neutral (Q<$10^{-20}$e)
- -Wechselwirkung mit den Atomkernen
  - →lokal
  - →nicht direkt von Z abhängig
- ➔Bestimmung leichter **und** schwerer Atome !!!





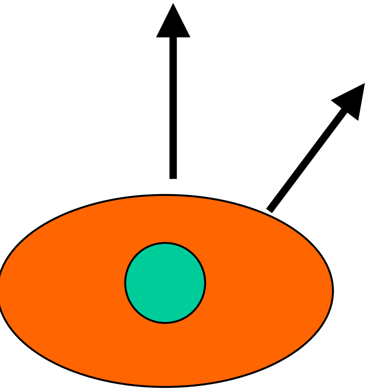


# Neutrons show where atoms are

-Sauerstoffpositionen in Oxiden mit Seltenen Erden oder La ➔ besser mit Neutronen !

# Analyse der Intensitäten

**Intensitäten der Reflexe**
**➔ komplette Strukturinformation**



$$F_G = \int_{\text{Zelle}} dV n(r) \exp(-iG \cdot r)$$ n(r)-Streudichte; Strukturfaktor

$$= \sum_j f_i \cdot \exp(-iG \cdot r_j)$$

$$f_i = \int dV \cdot n_j(\rho) \exp(-iG \cdot \rho)$$ Atomformfaktor

$$F_{(hkl)} = \sum_j f_j \exp\left[-i2\pi\left(x_j h + y_j k + z_j l\right)\right]$$

- weitere Verschmierung durch thermische Bewegung oder Unordnung

$$F_{(hkl)} = \sum_j f_j \exp\left[-i2\pi\left(x_j h + y_j k + z_j l\right)\right] * \exp\left(-\frac{1}{3}\langle u^2\rangle G^2\right)$$

-aber : man misst $F_{(hkl)}^2$ Verlust der Phaseninformation
bei Zentrosymmetrie nur Vorzeichen !!

# Magnetische Eigenschaften

Ladung=0
elektr. Dipolmoment=0

Spin: S = 1/2

magnetisches Dipolmoment:

$\mu = 9.6491783.10^{-27}$J/T
$= -1.913042\ \mu_N$

$\mu_N=\mu_B\ m_e/m_p=0.5446\ 10^{-3}\mu_B$

„Erklärung“:

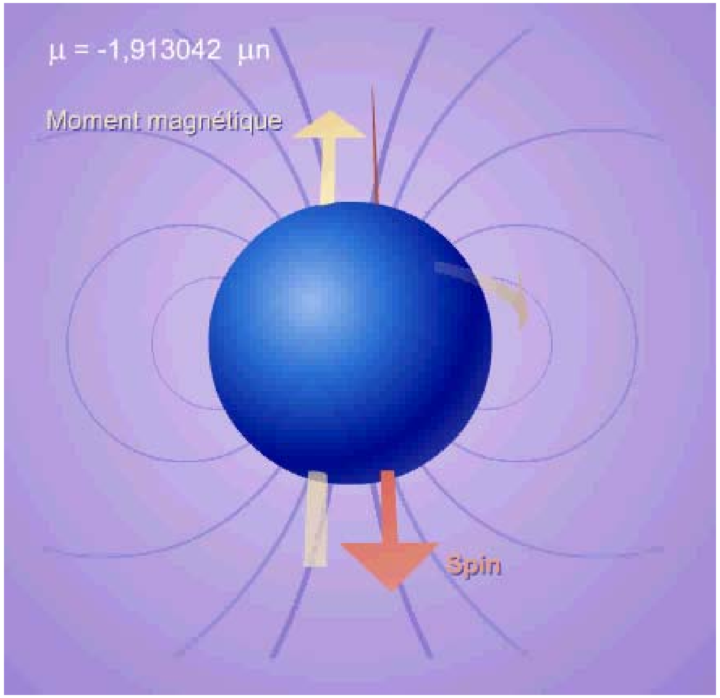
DIRAC $\mu_{Proton}=1\ \mu_N$ exp 2.8 $\mu_N$
$\mu_{Neutron}=0$ exp –1.9 $\mu_N$

MESON $p \leftrightarrow n + \pi^+$ $n \leftrightarrow p + \pi^-$
$\mu_{Neutron}\neq 0$: Neutron
ist 20% der Zeit $p+\pi^-$, wobei
$\pi^-$ Bahnmoment von 10 $\mu_N$
hat.

QUARK u d d

# Magnetic properties of the neutron

$$\vec{\mu}_n = -\gamma \mu_B \frac{m_e}{m} \vec{\sigma}$$



# Magnetische Wechselwirkung

$$V_m(\mathbf{r}) = -\vec{\mu}\cdot\mathbf{B}(\mathbf{r}) = -\frac{\mu_0}{4\pi} g\gamma \frac{m_e}{m} \mu_B^2 \vec{\sigma}\cdot\nabla\times\left(\frac{\mathbf{S}\times\hat{\mathbf{R}}}{R^2}\right)$$

**magnetische Streuung kann so stark wie Kernstreuung sein !**

**Spin-Dichte ist verteilt ➔ Streuung nimmt mit Q ab**

**sensitiv zu magnetischem Dipolmoment (Spin) senkrecht zu Q !**

# Anwendungen von magn.Einkristall-Beugung

- Moments are very small
- Transition temperatures lower than 1 K
- Incommensurate magnetic structures
- Magnetic transitions induced by H or P
- Magnetism of absorbing elements (Gd, Sm
- Mapping of the density of spin
- Molecular magnetism

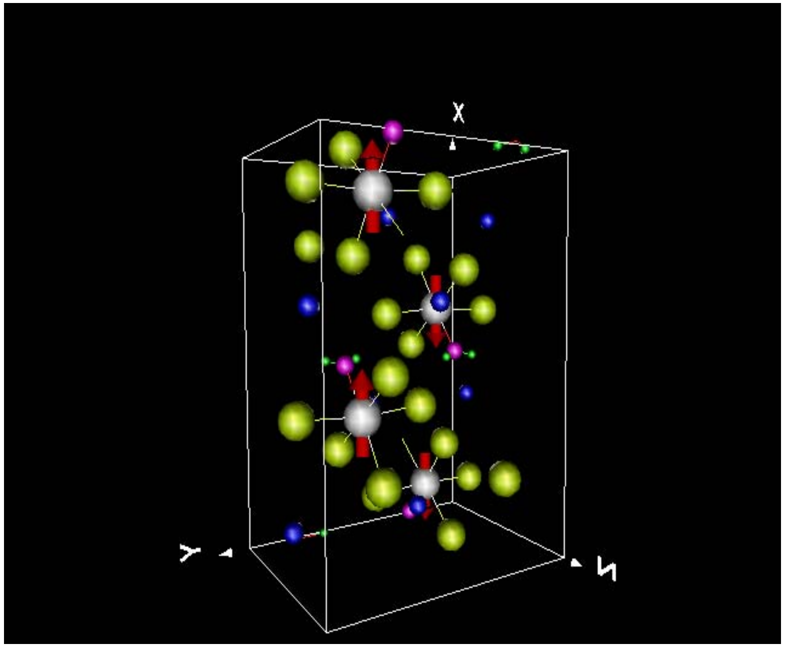
J.Campo et al. 2000

# Magnetic structure

## $A_2FeX_5 \cdot H_2O$ (A=K, Rb, X=Cl, Br)

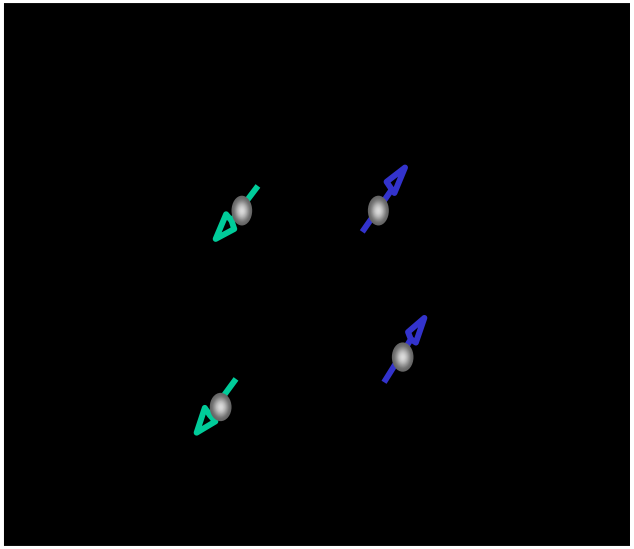
- Colinear AF with $T_N$ = 14.06 K

k = (0 0 0)



- Easy axis: *a*
- Ferromagnetic planes

⊥ *b*-axis AF coupled

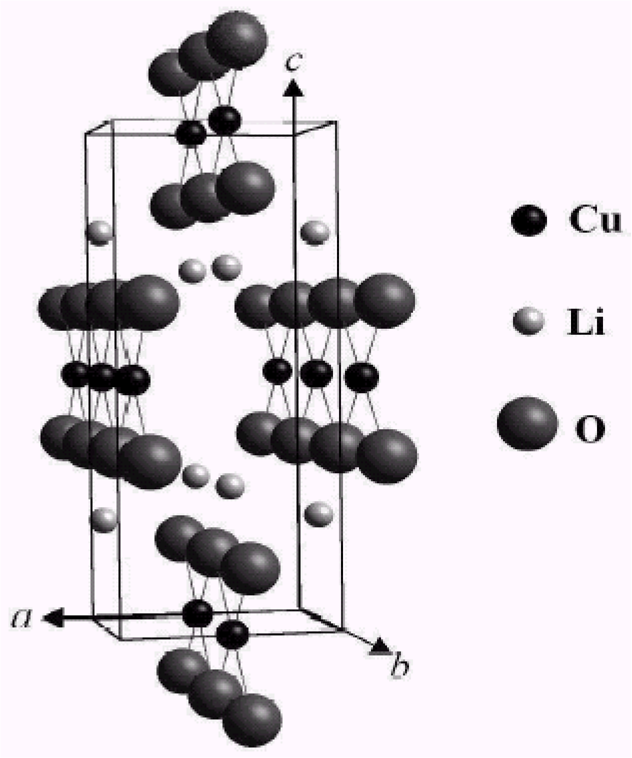


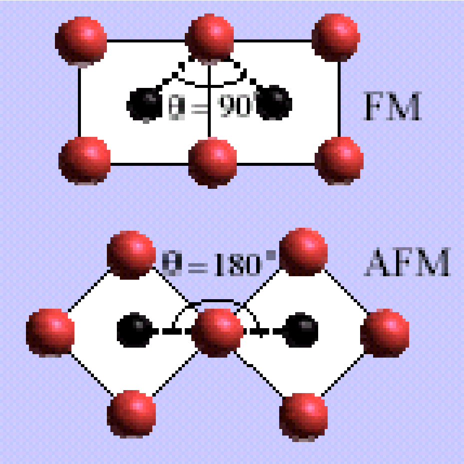
# Oxygen moment in $Li_2CuO_2$

E. Chung et al. 2003

**1D chains of S=1/2 Cu atoms**

**$CuO_4$ plaquettes (like in $CuGeO_3$, High-$T_C$ or chain-ladder system $La_{14-x}Ca_xCu_{24}O_{41}$ )**

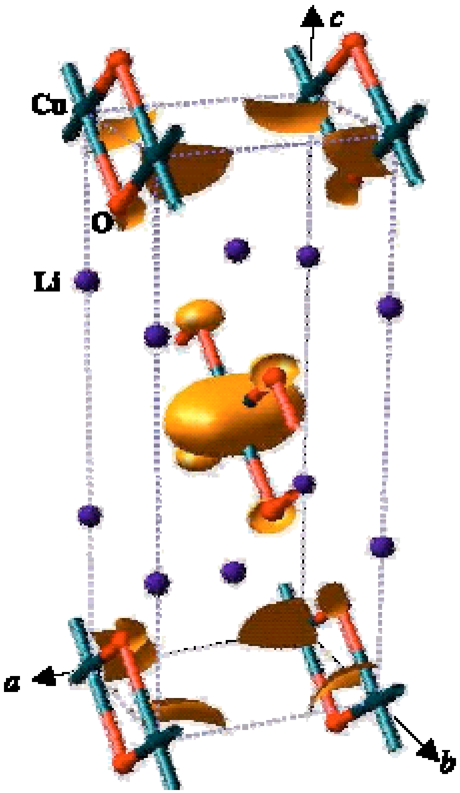




$Li_2CuO_2$ **crossover between AFM and FM ordering**

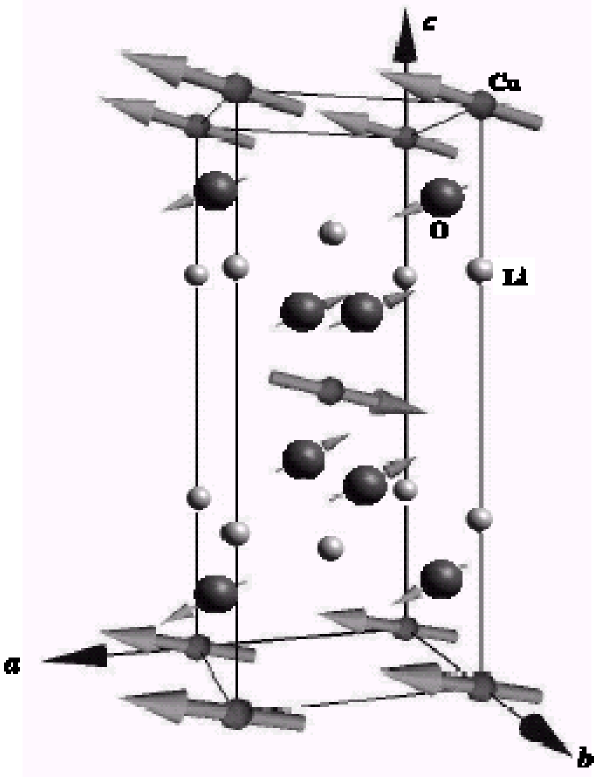
# Oxygen moment in $Li_2CuO_2$

## AF canted model



3-D spin density Patterson

Moments are canted in the a-c plane toward the c-axis. Canting of the Cu moments is almost fully compensated by counter-canting of the O moments



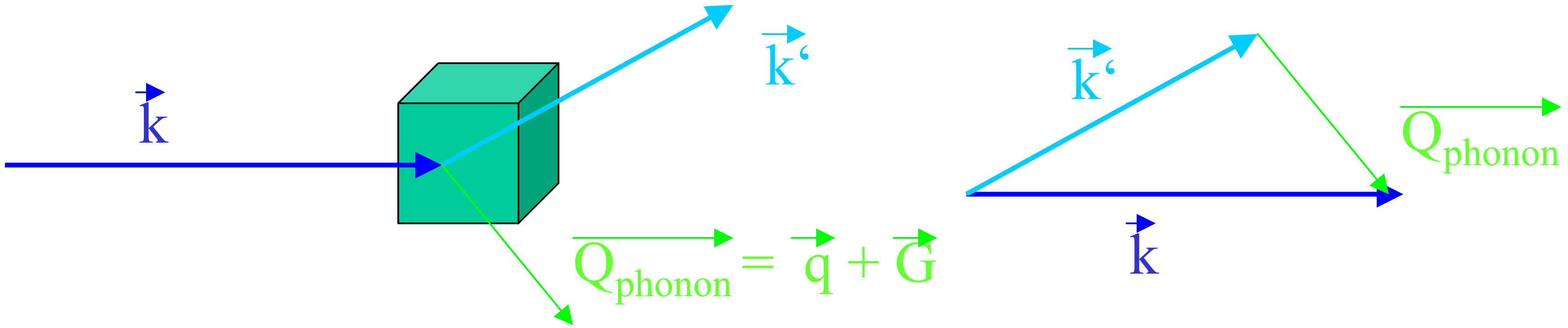
Cu moment: 0.91 $\mu_B$

O moment: 0. 12 $\mu_B$

# Inelastische Streuung

Neutrons show what atoms do

Streudreieck:



$$\mathbf{Impuls:}\quad \vec{Q} = \vec{k} - \vec{k}'$$

$$E = \frac{\hbar^2 \cdot k^2}{2 \cdot m}$$

$$\mathbf{Energie:}\ E = E' + E_{Phonon}$$

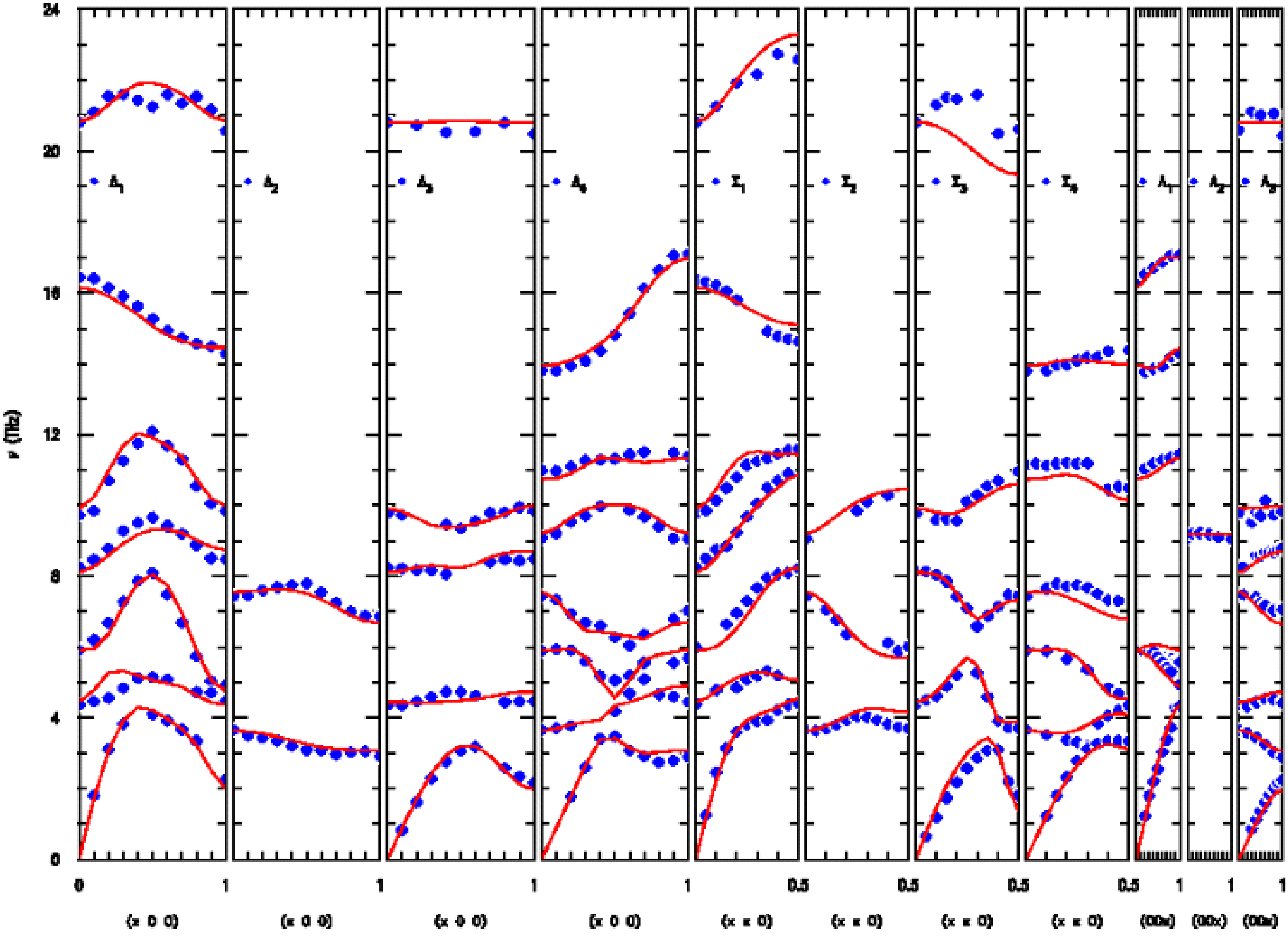
$$E_{Phonon} = \hbar \cdot \omega = \frac{\hbar^2}{2 \cdot m} \cdot (k^2 - k'^2)$$

**Spin: Gesamt-Spin vorher = nachher**

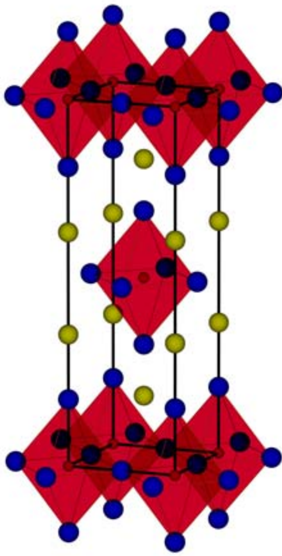
**Beispiel : Thermische Neutronen**

- **Energie : 5THz = 20.68meV = 240K = 167cm$^{-1}$**
- **Wellenlänge : 2.0Å Wellenvektor : 3.14 Å$^{-1}$**
- **Geschwindigkeit : 1988 m sec$^{-1}$**

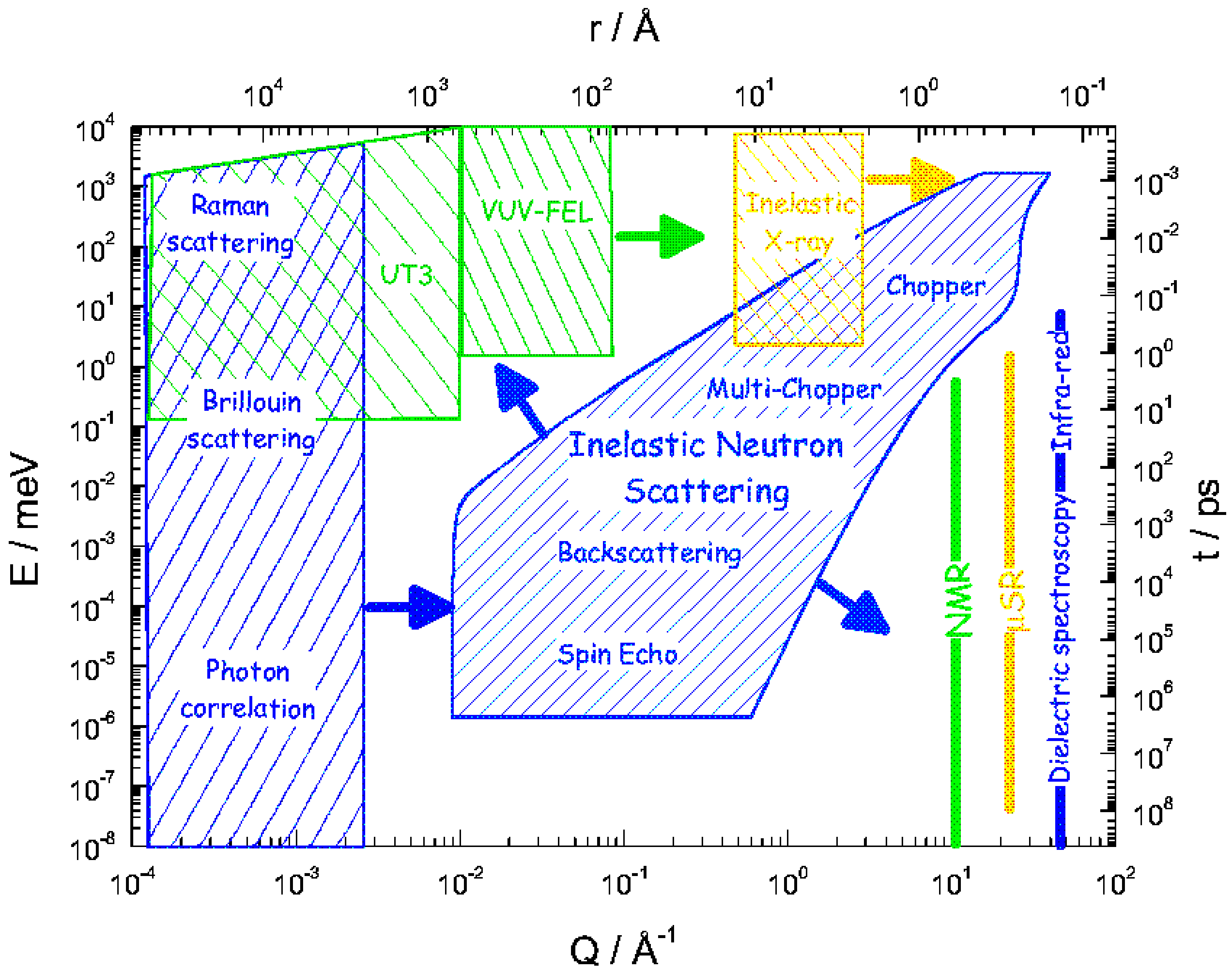
# Gitterdynamik in $Sr_2RuO_4$



**I4/mmm**
**7atoms**
**=>**
**21 branches**

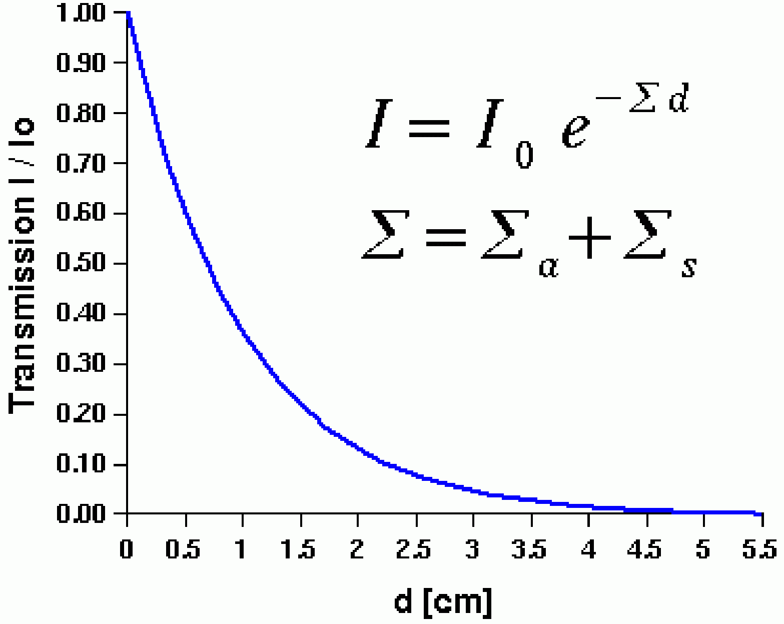


Braden et al., PRB 2007.


r / Å
10^4
10^3
10^2
10^1
10^0
10^-1
E / meV
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
t / ps
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Raman scattering
Brillouin scattering
Photon correlation
UT3
VUV-FEL
Inelastic X-ray
Chopper
Multi-Chopper
Inelastic Neutron Scattering
Backscattering
Spin Echo
NMR
μSR
Dielectric spectroscopy
Infra-red
Q / Å^-1
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2

# Wechselwirkung mit Materie

## Exponential Attenuation Law



$$I = I_0\, e^{-\Sigma d}$$

$$\Sigma = \Sigma_\alpha + \Sigma_s$$

Macroscopic Cross Section Σ

$$\Sigma = N\sigma \quad [cm^{-1}]$$

$$N = \frac{\rho}{A} N_A \quad [cm^{-3}]$$

$N \; := \text{number density} \, [cm^{-3}]$

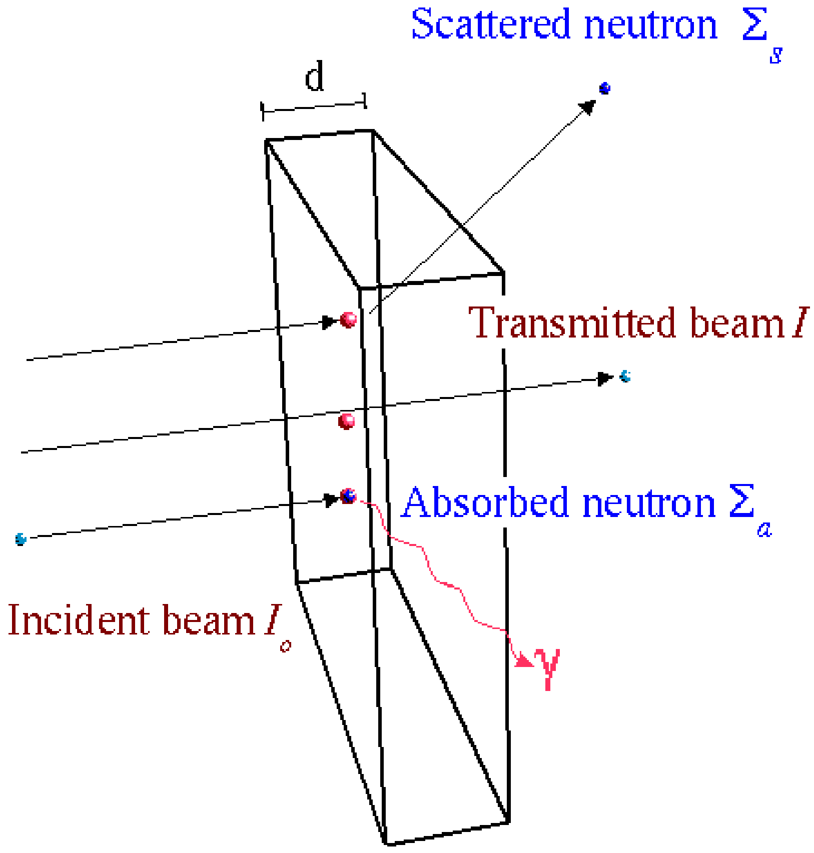
$\rho \; := \text{material density} \, [g\, cm^{-3}]$

$A \; := \text{atomic weight} \, [g\, mol^{-1}]$

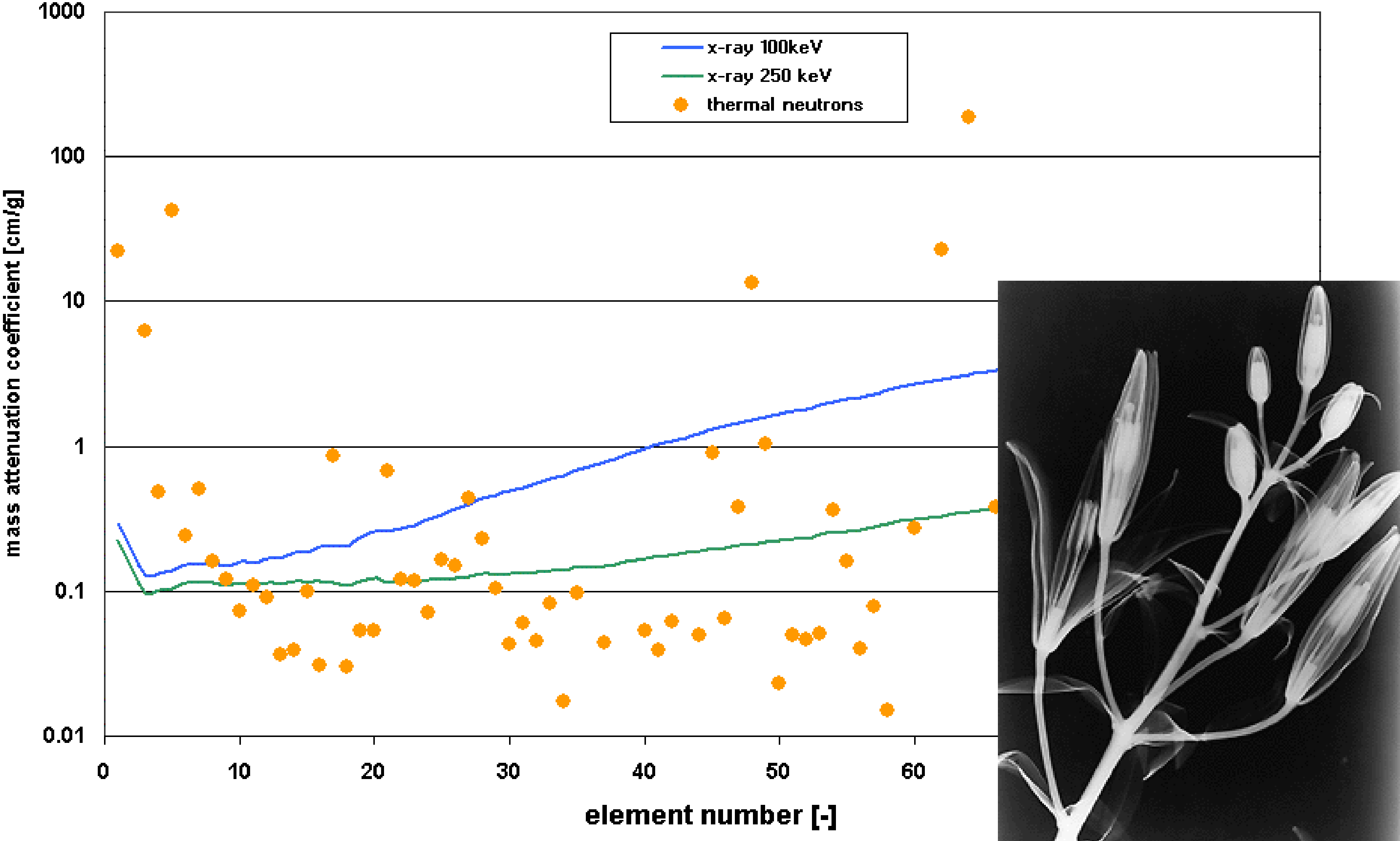
$N_A := \text{Avogadro number } 6.022\,10^{23} \, [mol^{-1}]$

## Narrow Beam Attenuation

$$I = I_o e^{-\Sigma d}$$

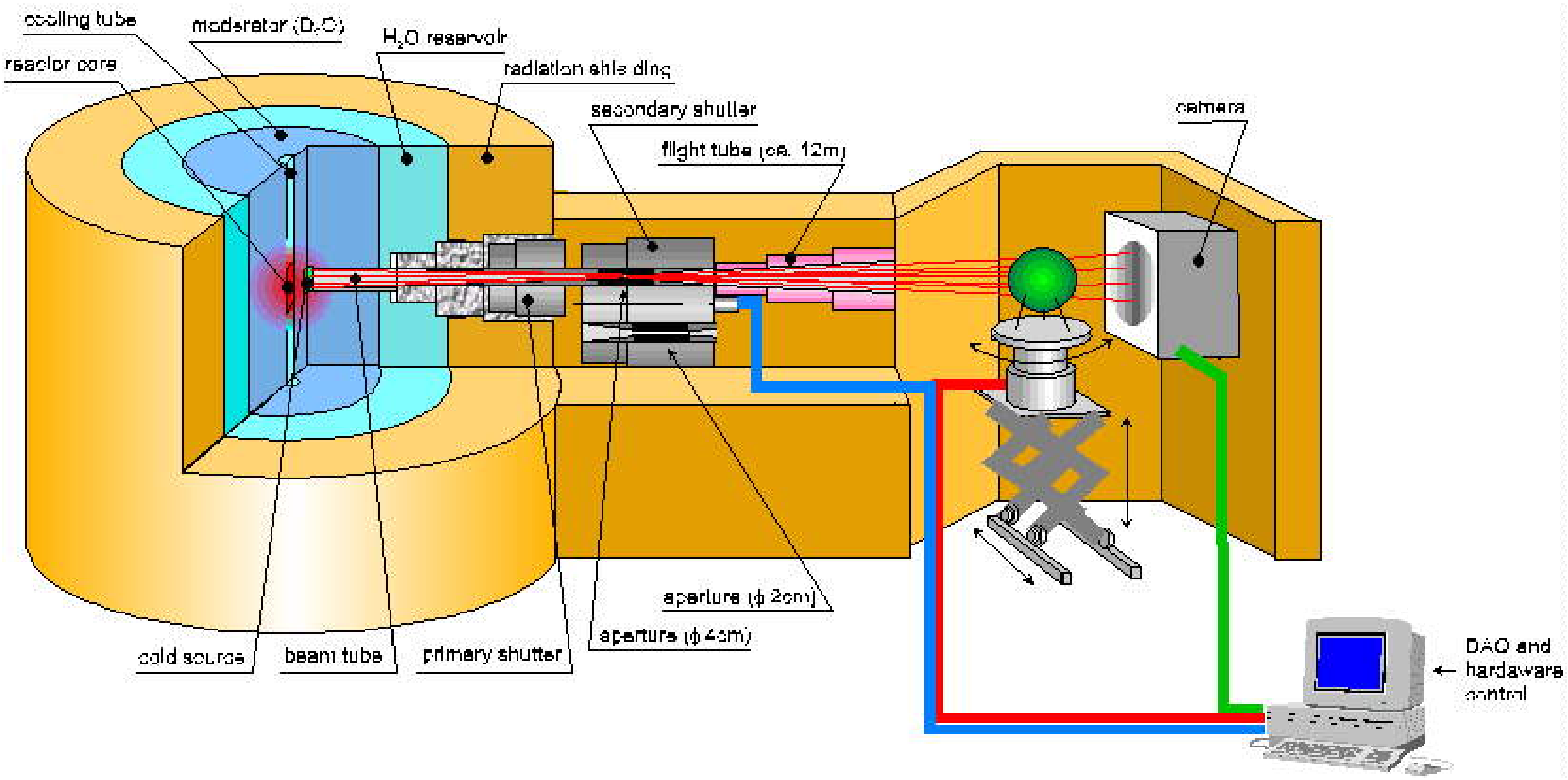


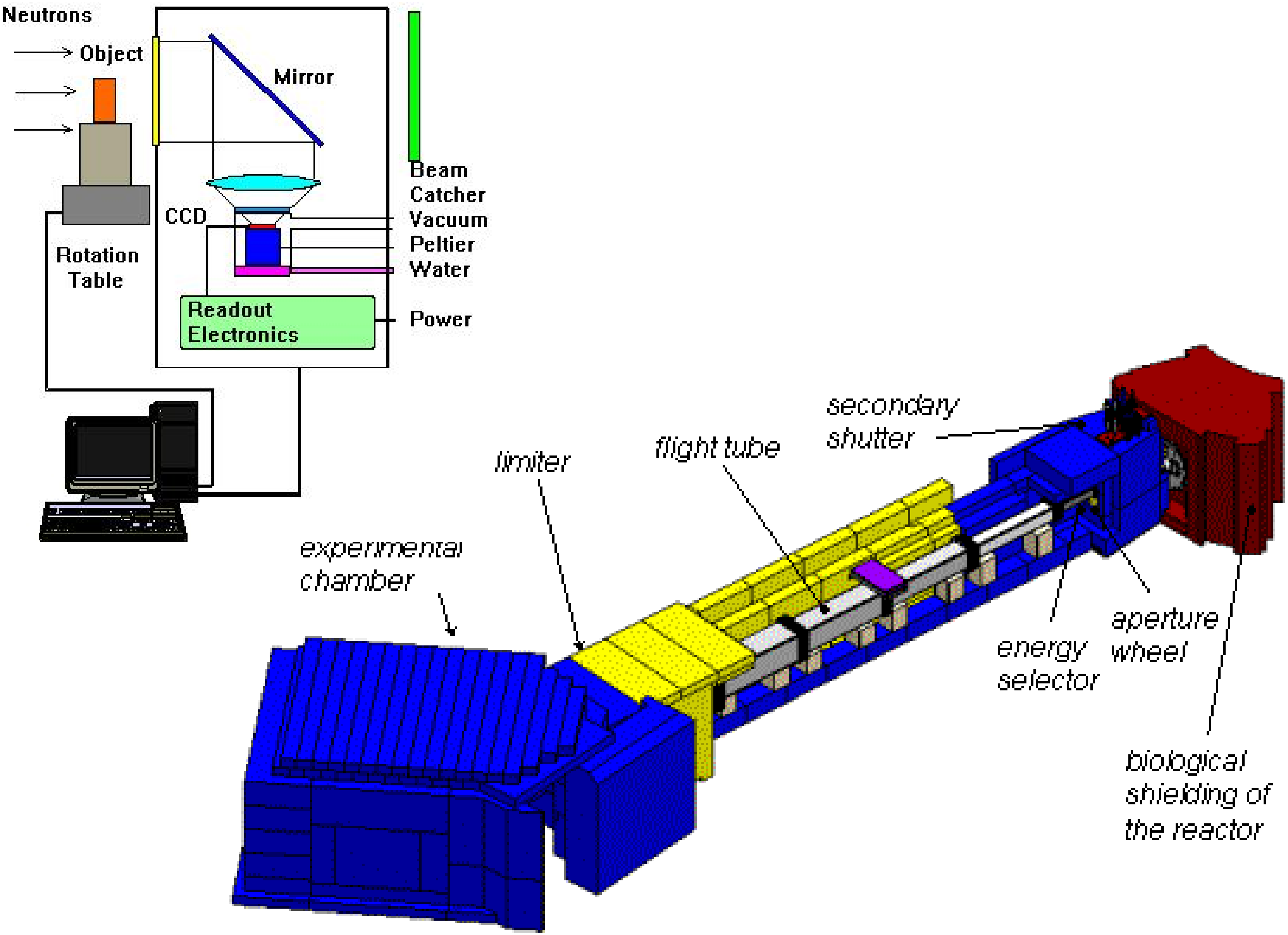
# Schwächungskoeffizienten Σ



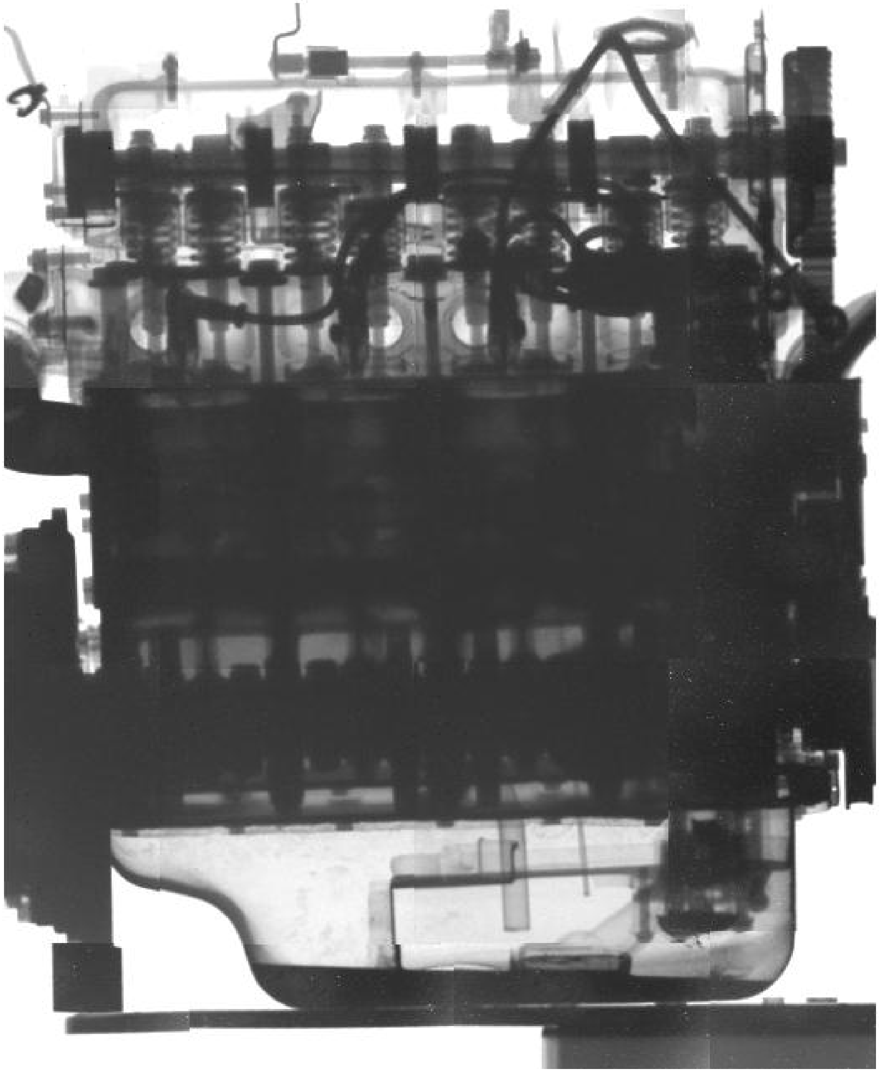
# *Antares*

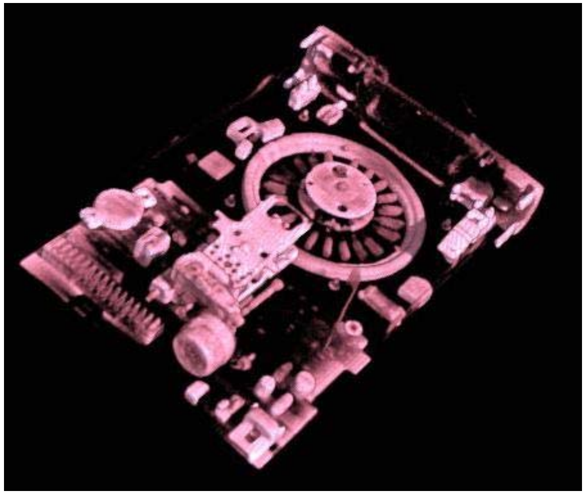
## Advanced Neutron Tomography And Radiography Experimental System



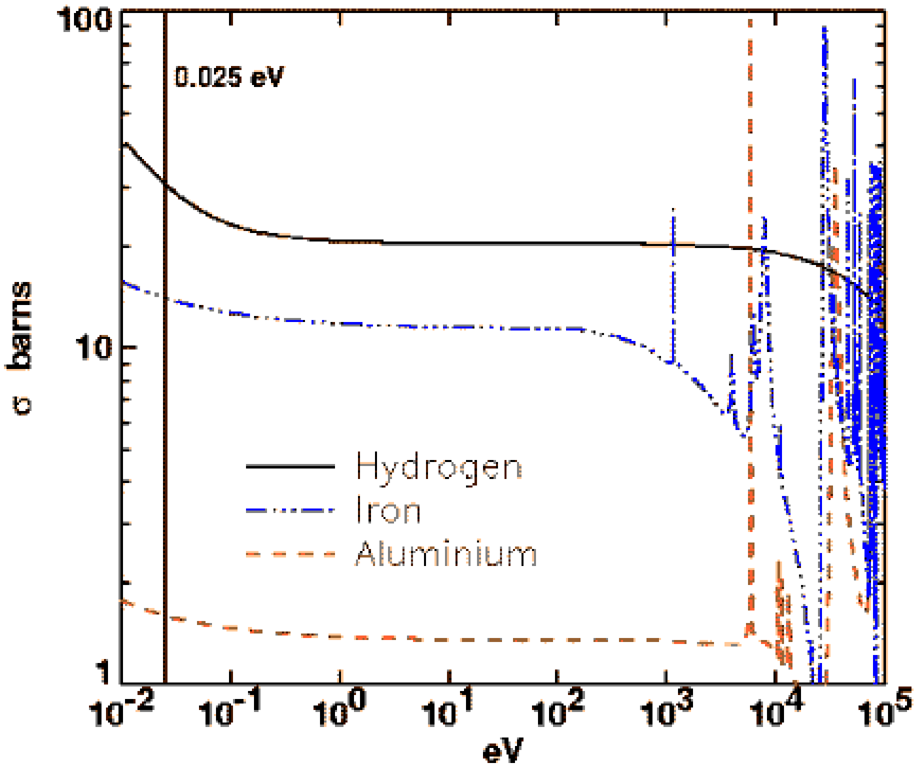

Neutrons
Object
Mirror
Beam
Catcher
CCD
Vacuum
Peltier
Water
Rotation
Table
Readout
Electronics
Power
secondary
shutter
flight tube
limiter
experimental
chamber
aperture
wheel
energy
selector
biological
shielding of
the reactor

23.10.2007





# Neutron Cross Sections (Energy – Dependence)



***Thermal Neutron Cross Sections at 0.025eV***

| *Material* | ρ | σ | Σ |
|---|---|---|---|
| *Water* | 1 | 103 | 3.45 |
| *Iron* | 7.9 | 14 | 1.18 |
| *Aluminium* | 2.7 | 1.7 | 0.1 |

# Was sind die Charakteristika von Neutronen ?

1) Masse vergleichbar zu Kern-Massen ➔ elastische und inelastische Streuung
2) Wellenlänge 1-5Å im Bereich der Gitterabstände
3) nukleare und lokale Wechselwirkung : keine Z-Abhängigkeit
➔ $V(r) = b*\delta(r)$
4) Energie im Bereich 1-100meV vergleichbar zu der von Phononen
(x-ray : Cu-K hat $8*10^6$meV ➔ Energieauflösung besser als $10^{-7}$ )
5) das Neutron hat einen Spin ½

- **Kontrast : leichte schwere Atome**
- **Magnetismus**
- **Experimente bei grossem Streuvektor möglich**
- **Messungen in der ganzen Brillouin-Zone (inelastisch)**

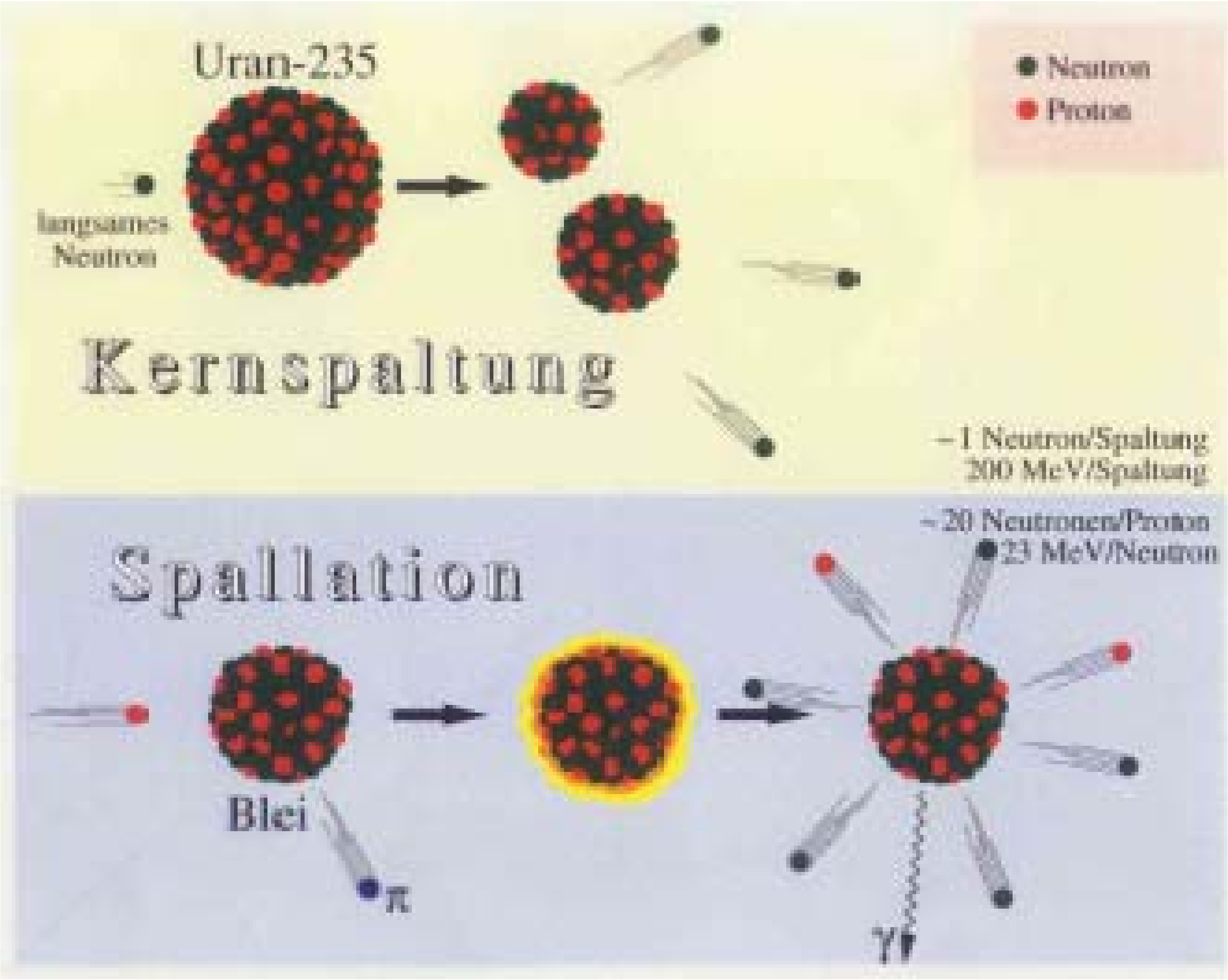
**Beispiel : Thermische Neutronen**

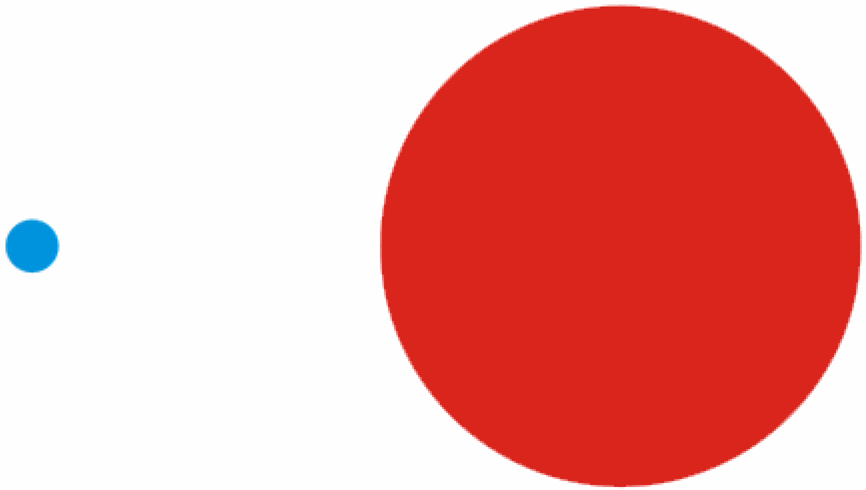
**Energie : 5THz = 20.68meV = 240K = 167cm$^{-1}$**
**Wellenlänge : 2.0Å Wellenvektor : 3.14 Å$^{-1}$**
**Geschwindigkeit : 1988 m sec$^{-1}$**

**ABER : Quellen sind teuer und schlecht !!!**

Liste ist nicht vollständig ! ! !

# Neutronen-Quellen

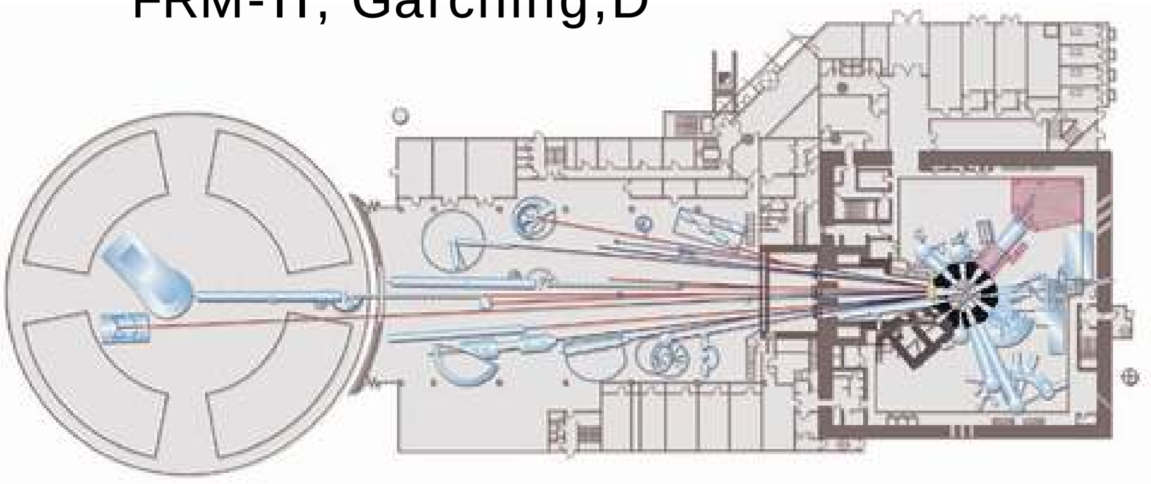


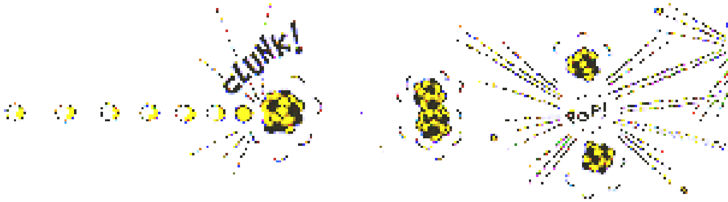


# Reaktor-Neutronenquellen

FRM-II, Garching,D

ILL, Grenoble,F



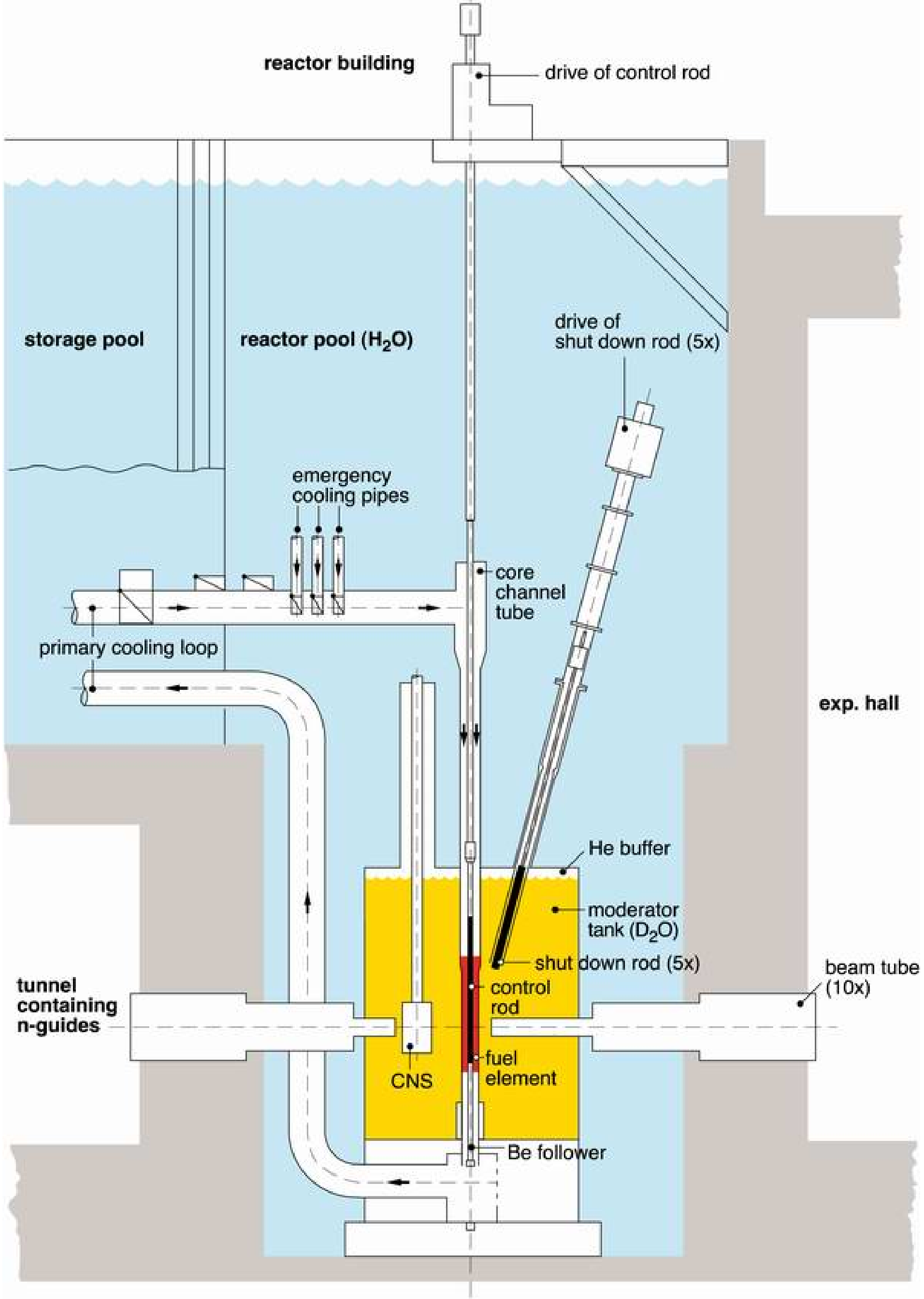


$U^{235}+n \rightarrow Mo^{95}+La^{139}+2n$

235x7.6 95x8.6 138x8.4MeV

i.e. 200MeV freiwerdende Energie

Davon 6MeV kin Energie der n



**FRM-II** - thermal power: 20MW
ILL: 56MW

unperturbed thermal
neutron flux: $8x10^{14}cm^{-2}s^{-1}$

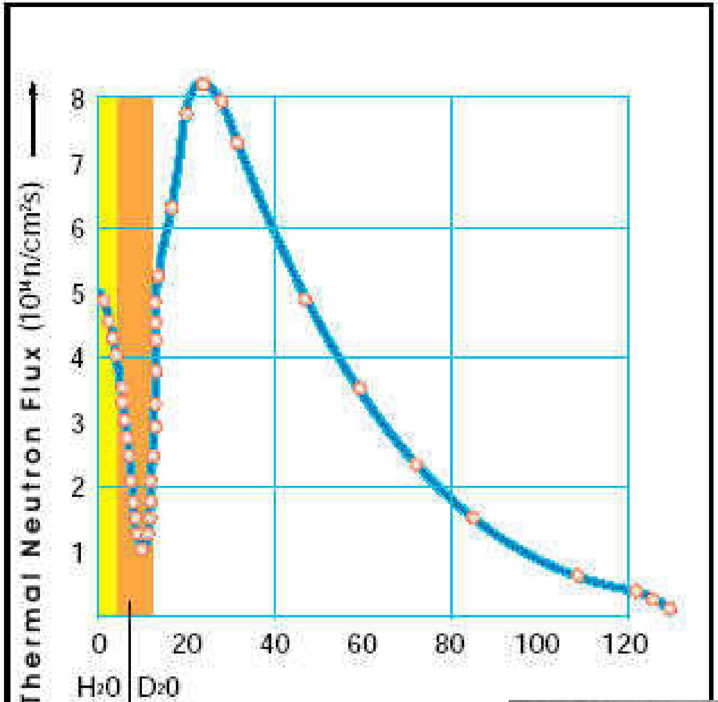
core cooled with light water $H_20$

moderator tank: heavy water $D_20$
diameter of approx. 2,5m

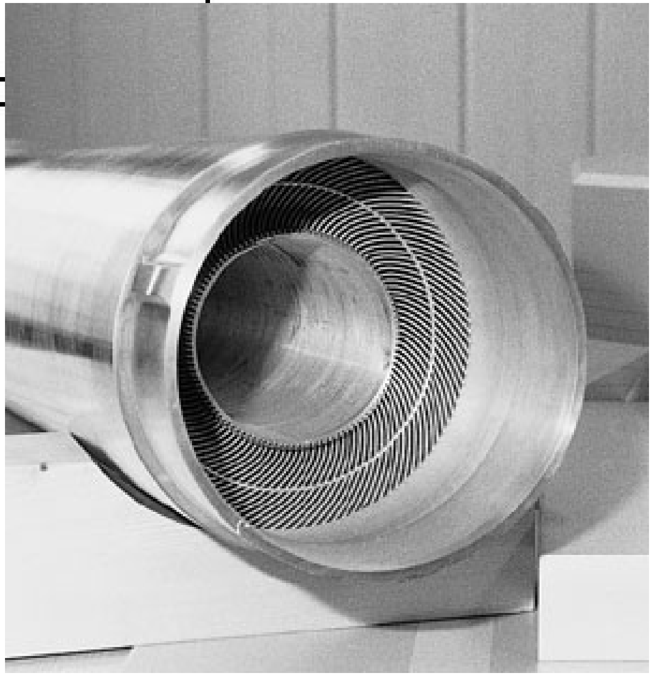
***FRM-II's reactor core:***

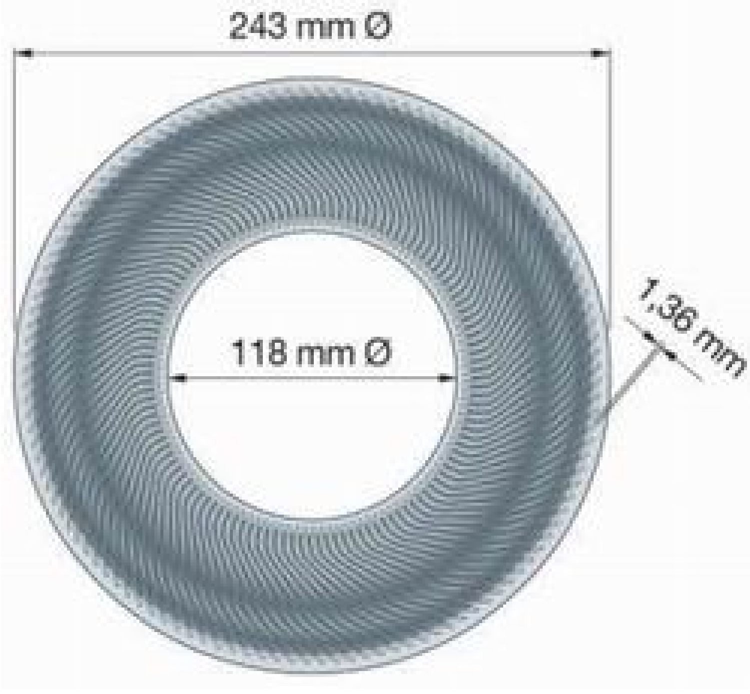
*a single, cylindrical fuel element 700mm height.*

*113 involuted, curved fuel plates*
*three layers: fuel $U_3Si_2$ +*
*aluminium powder*
*in an aluminium matrix.*
*5 elements will be required per year.*

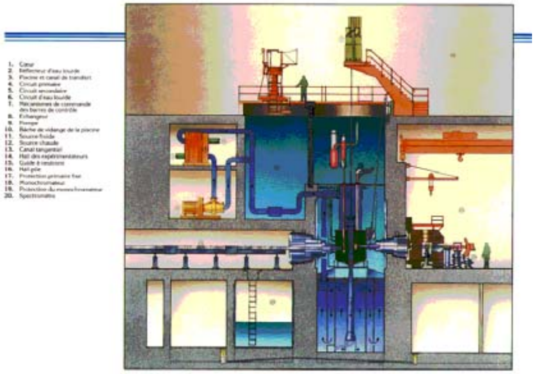


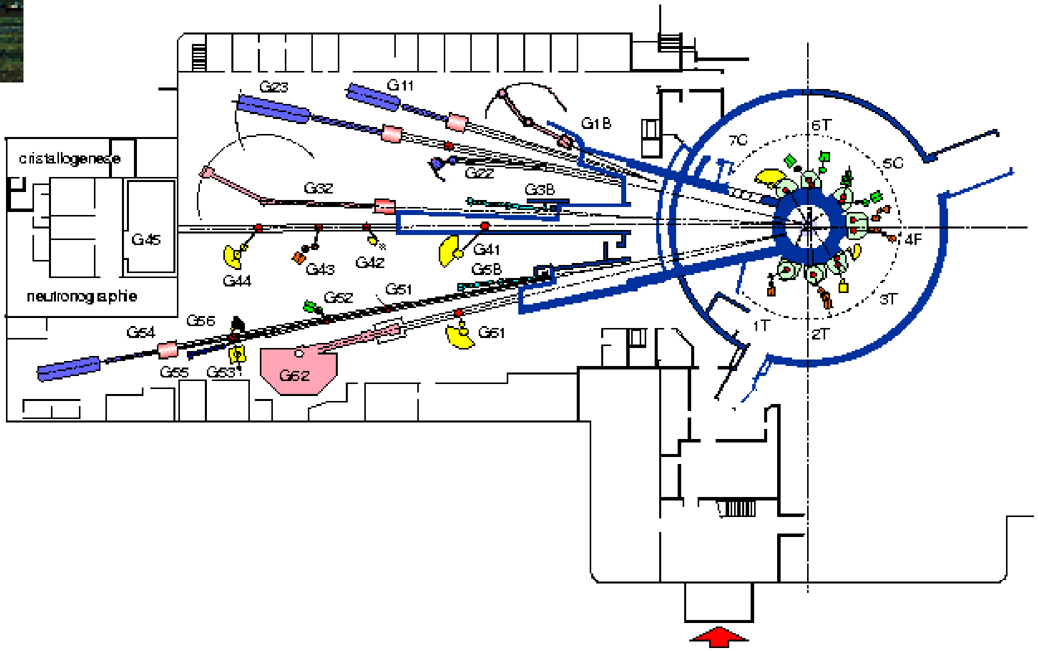
***Thermal*** *neutron flux density as function of the radius (FRM-II)*





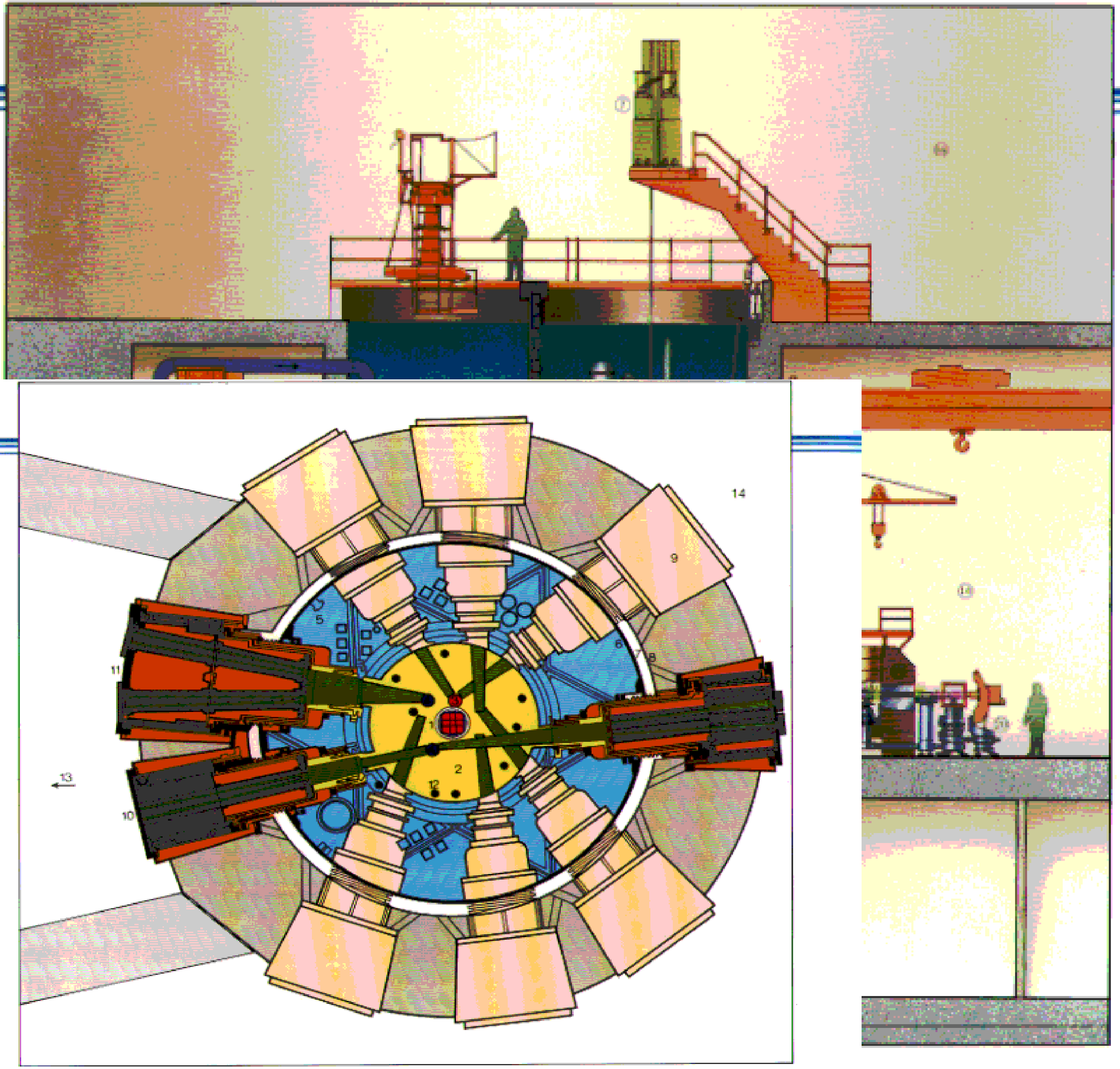
# Laboratoire Leon Brillouin (Saclay, Paris)





1. Cœur
2. Réflecteur d'eau lourde
3. Piscine et canal de transfert
4. Circuit primaire
5. Circuit secondaire
6. Circuit d'eau lourde
7. Mécanismes de commande des barres de contrôle
8. Echangeur
9. Pompe
10. Bâche de vidange de la piscine
11. Source fr
12. Source c
13. Canal tar
14. Hall des
15. Guide à
16. Hall-pile
17. Protectio
18. Monochr
19. Protectio
20. Spectrom

1. Cœur
2. Réflecteur d'eau lourde
3. Source chaude
4. Source froide
5. Piscine
6. Cuvelage de la piscine
7. Vide annulaire
8. Doublante piscine
9. Canal standard
10. Canal simple
11. Canal double
12. Canal vertical
13. Hall des guides à neutrons
14. Hall des expérimentateurs



**Facility:** LLB

**Type:** Reactor

**Flux:** $3.0 \times 10^{14}$ n/cm2/sec

**Operational days/year:** 250 no longer now 114 till 180

**Total number of instruments:** 28

**Number of instruments available to users:** 24

**Type of instruments available to external users:**

6 powder/liquid diffractometers

2 single crystal diffractometers

1 Strain diffractometer

1 Texture diffractometer

3 SANS

3 reflectometers

5 3-axis spectrometers

1 TOF (MET)

1 spin echo

1 polarised neutron instrument

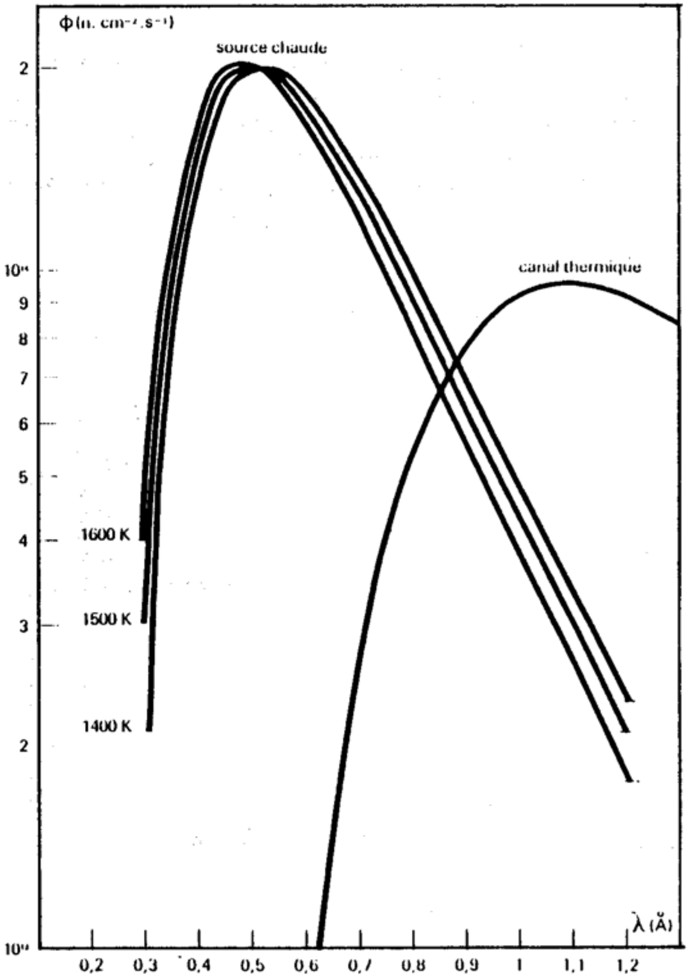
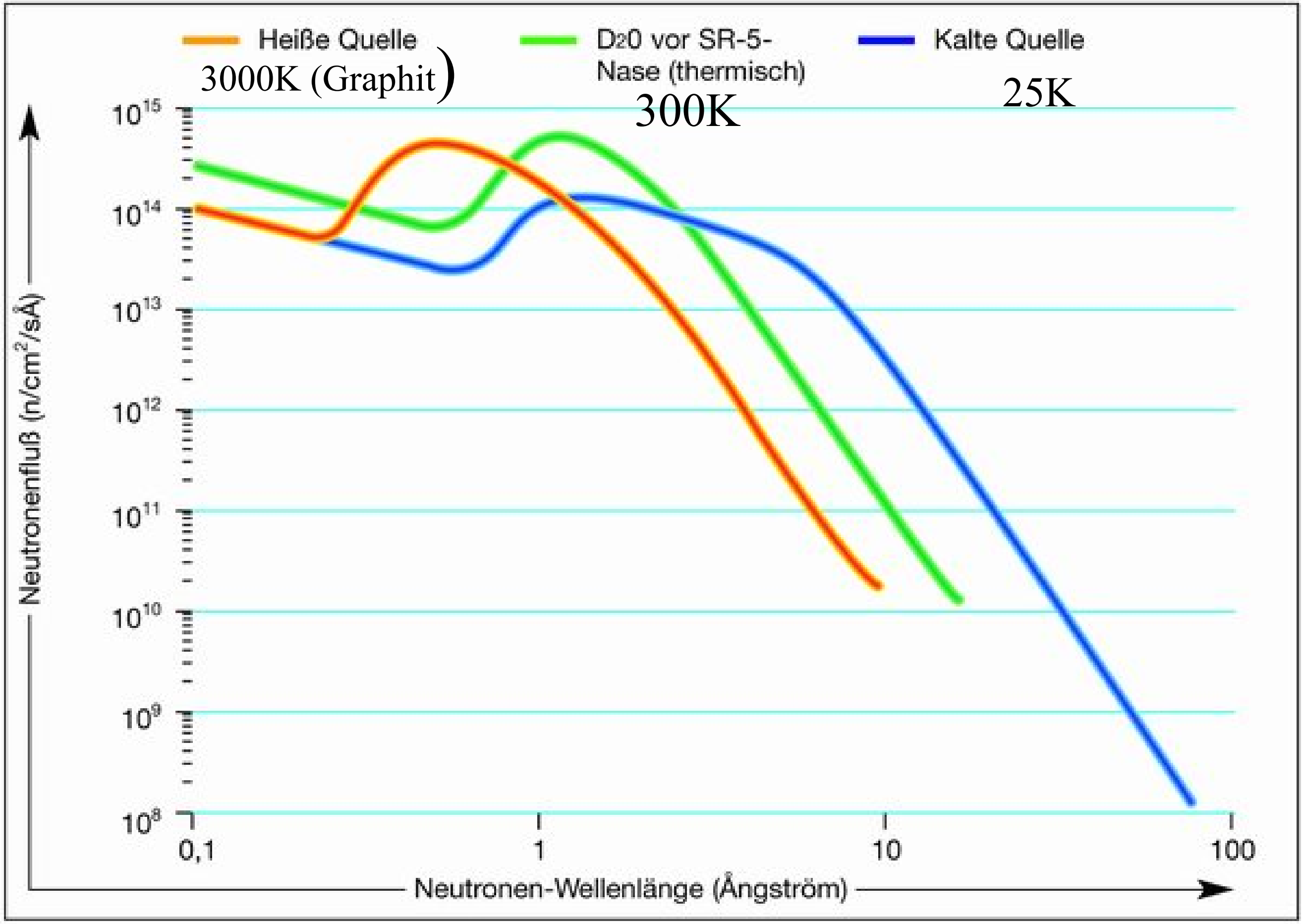


***Figure 3 : Source chaude***
***Distribution du flux en fonction de la longueur d'onde pour trois températures de sources chaudes.***

# **Moderatoren** ($D_2O$)

MeV→meV durch elastische Streuung an leichten Elementen
verlieren die Neutronen Energie und es ergibt sich im Idealfall eine Maxwell Verteilung der n-Geschwindigkeit entsprechend der Moderator Temperatur

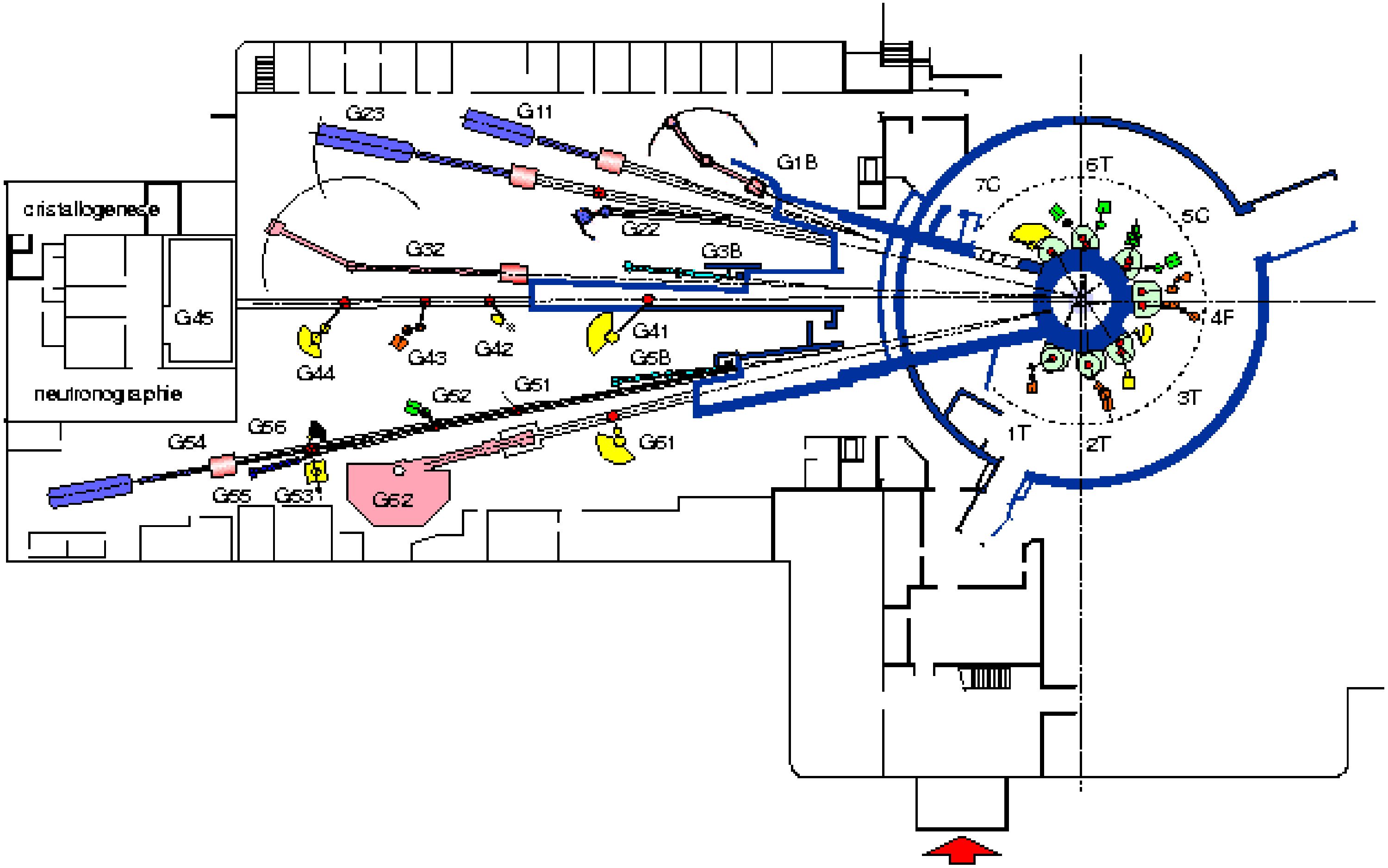


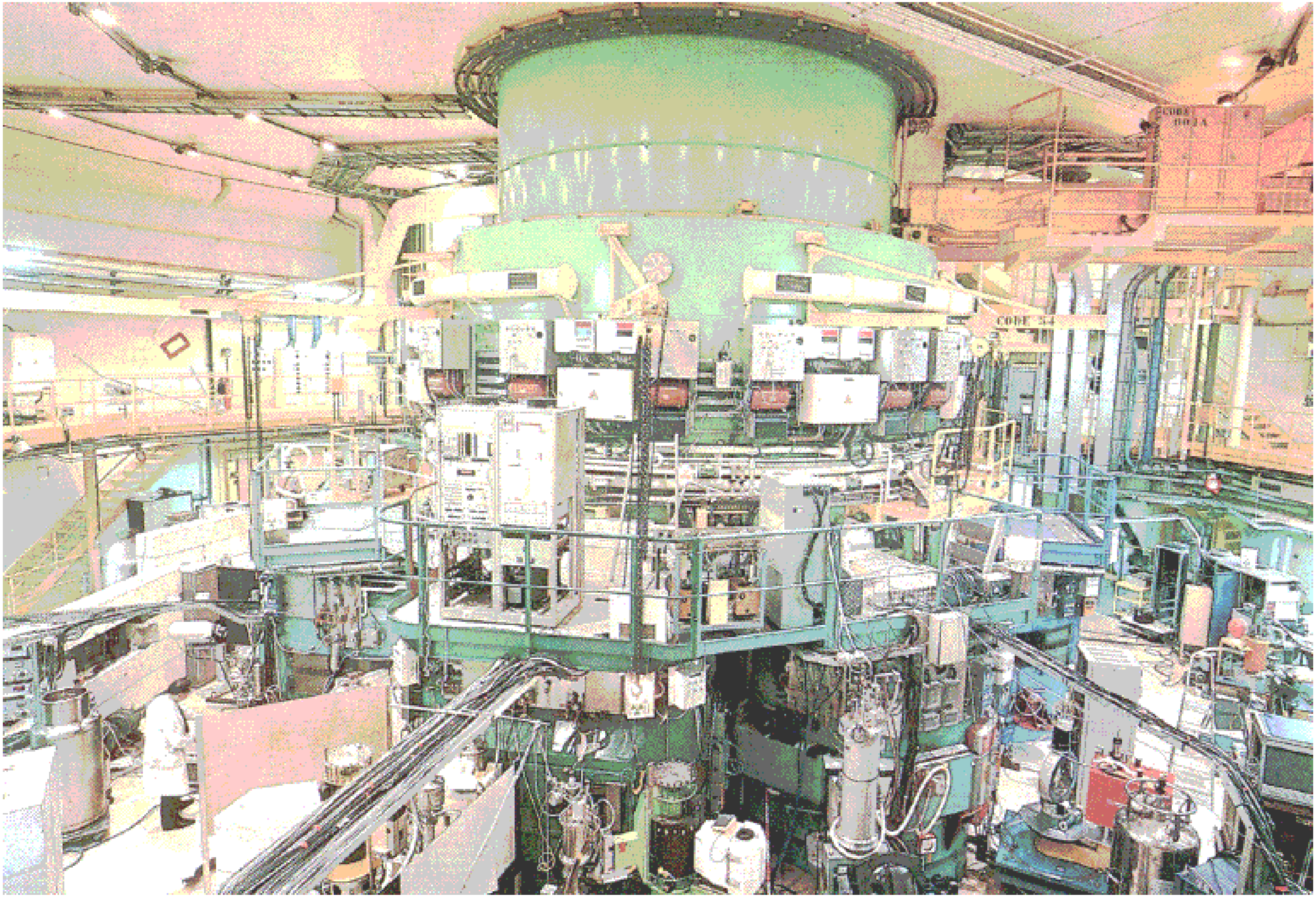
Berechnung für FRM-II, Garching

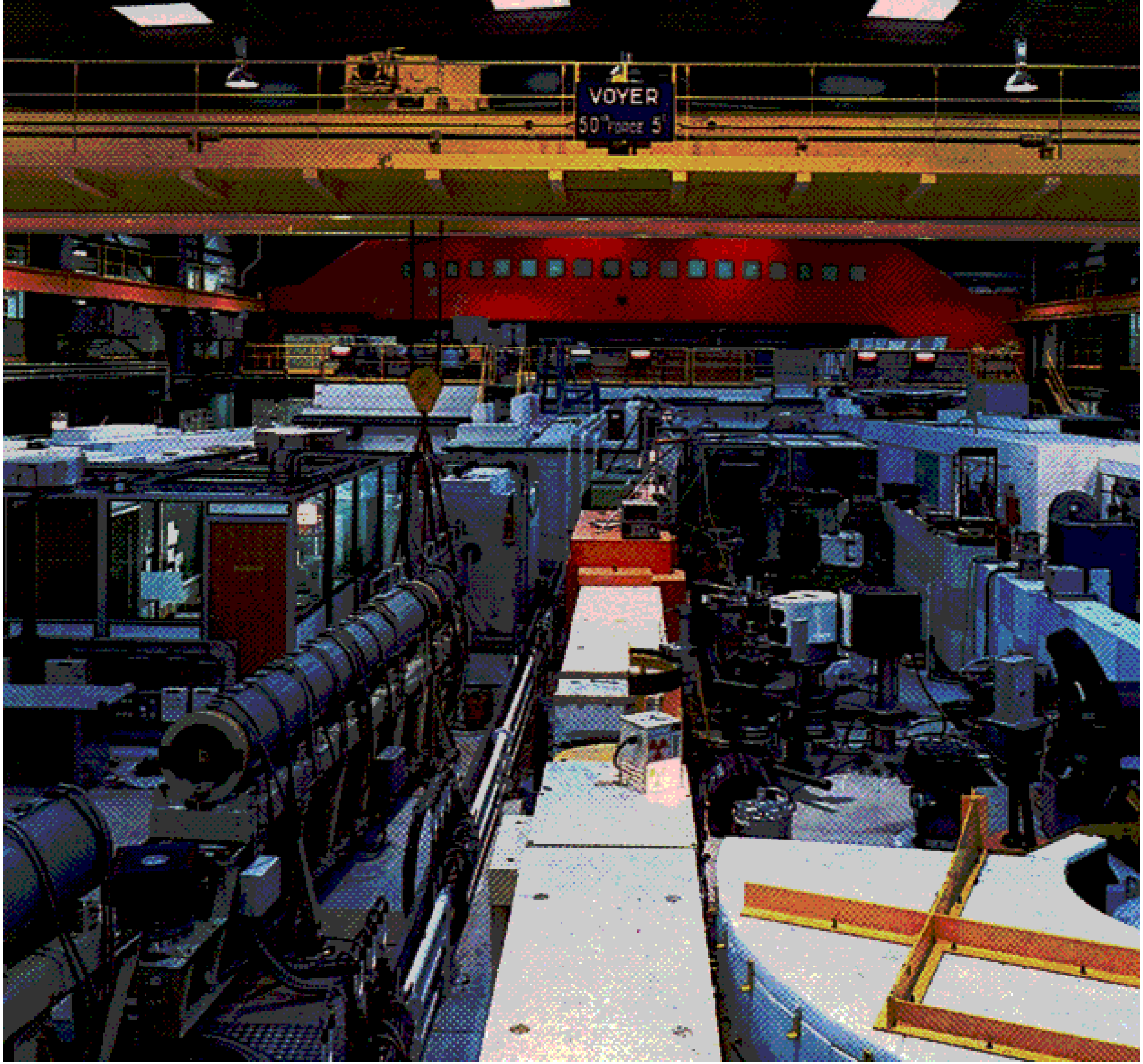
Betrachtung eines elastischen Stoßes eines Neutrons mit einem Kern der Massenzahl A ergibt:

Am besten wäre Wasserstoff
Problem
- Absorption -
- daher Deuterium !

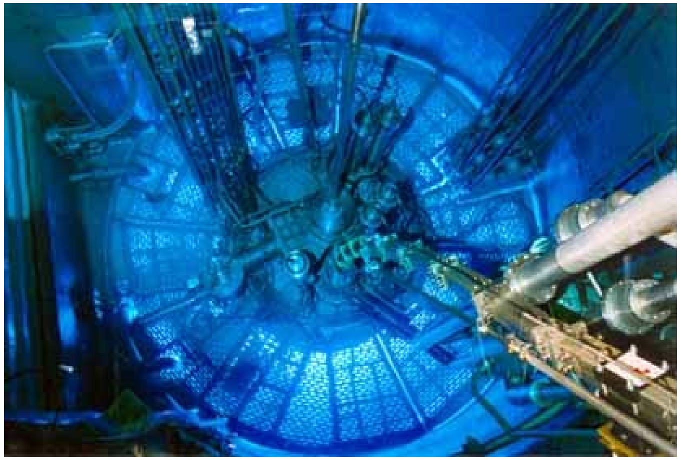
# Genereller Aufbau der Spektrometer um den Reaktor






VOYER
50t FORCE 5t

# Institut Laue Langevin (Grenoble)



**Facility:** ILL

**Type:** 58MW High Flux Reactor

**Flux:** 1.5 x$10^{15}$ n/cm2/sec

**Operational days/year:** 225

**Total number of instruments:**

Approximately 43 including test

**Number of instruments available to users:** 36

**Type of instruments available to external users:**

5 powder/liquid diffractometers

7 single crystal diffractometers

2 SANS*

3 reflectometers*

5 polarised neutron instruments*

2 Nuclear Physics

6 3-axis spectrometers

2 backscattering spectrometers

3 TOF (MET)

2 spin echo

2 Fundamental Physics

*some double counting

**NB:** 7 of the above instruments are operated and supported by external groups

# BENSC (Berlin)

**Facility:** BER II, BENSC

**Type:** Swimming pool reactor

**Flux:** $2x10^{14}$ n/cm2/sec

**Operational days/year:** 250

**Total number of instruments:** 24

**Number of instruments available to external users:** >17

**Type of instruments available to external users:**

2 powder/liquid diffractometers

3 3-axis spectrometers

4 single crystal diffractometers

1 quasielastic spectrometer

1 membrane diffraction

2 TOF (MET)

2 SANS

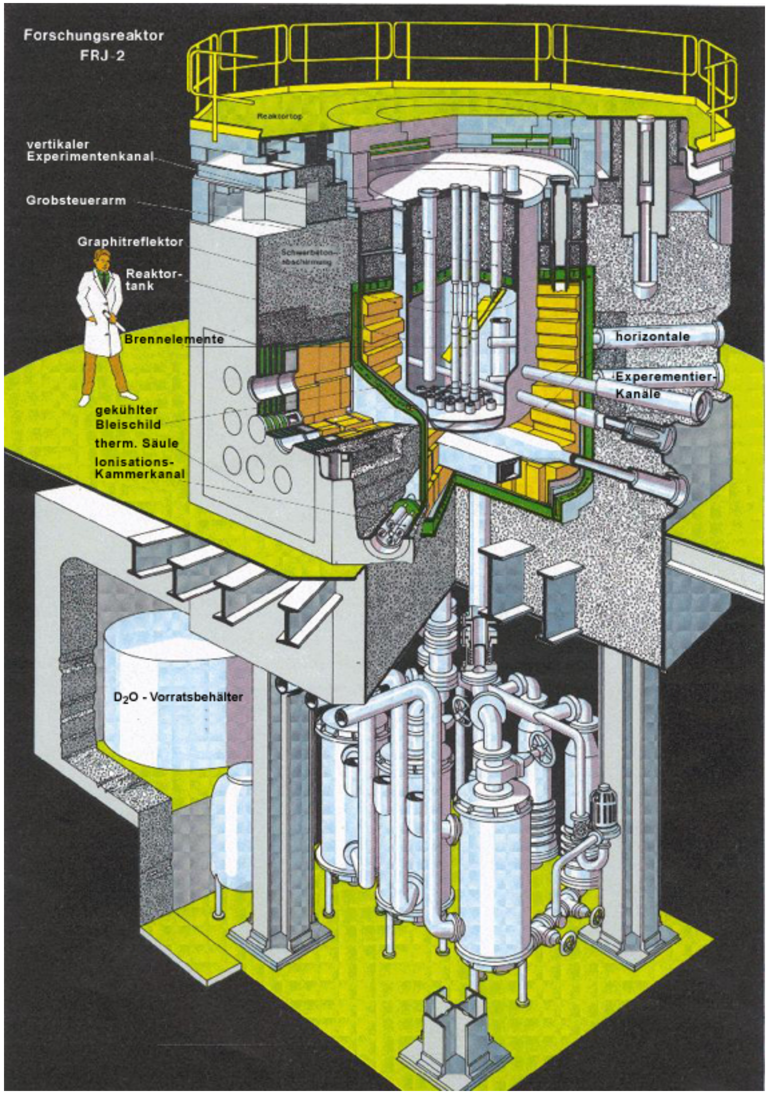
1 spin echo 1 reflectometer

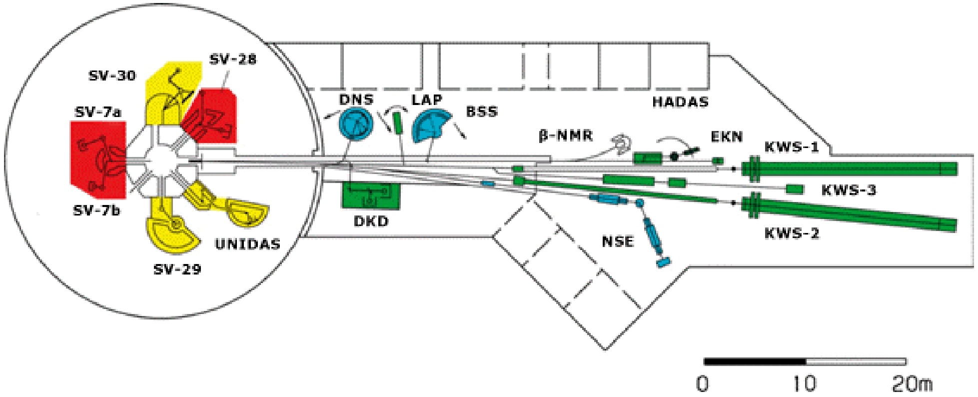
1 neutron interferometer 1 $\beta$–NMR

1 cold source

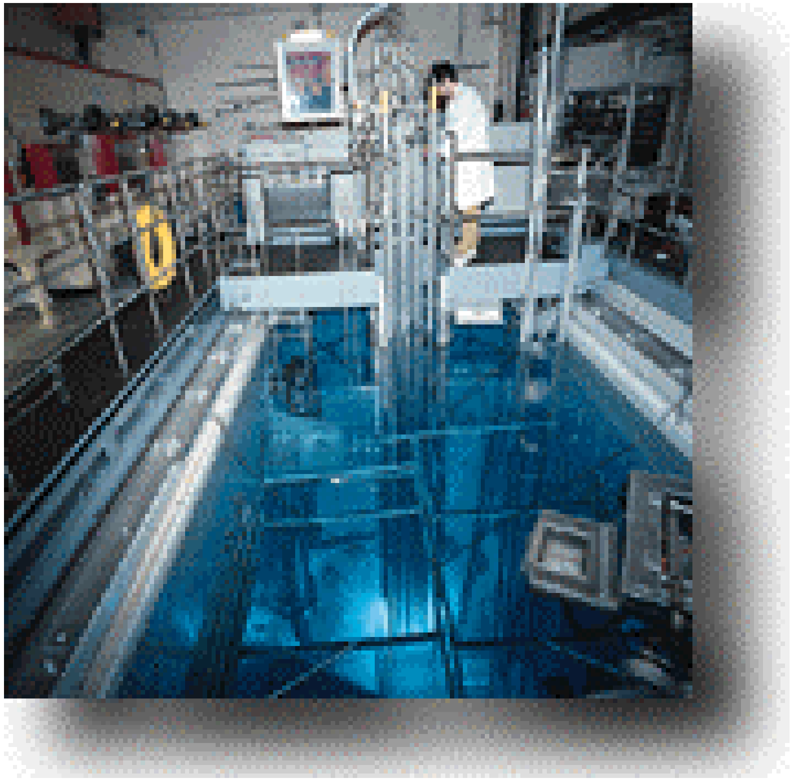
**NB:** For many instruments options include polarisation high fields, high pressures and low temperatures

# FRJ-2 Jülich


Forschungsreaktor
FRJ-2
Reaktortop
vertikaler Experimentenkanal
Grobsteuerarm
Graphitreflektor
Schwerbeton-abschirmung
Reaktor-tank
Brennelemente
horizontale Experementier-Kanäle
gekühlter Bleischild
therm. Säule
Ionisations-Kammerkanal
$D_2O$ - Vorratsbehälter


SV-30
SV-28
SV-7a
SV-7b
SV-29
UNIDAS
DNS
LAP
BSS
HADAS
β-NMR
EKN
KWS-1
KWS-3
KWS-2
DKD
NSE
0
10
20m

# FRG-2 Geesthacht



**Facility:** FRG-1

**Type:** Swimming Pool Cold Neutron Source

**Flux:** 8.7 x $10^{13}$ n/cm2/sec

**Operational days/year:** 210

**Total number of instruments:** 10

**Number of instruments available to external users:** 10

**Type of instruments available to external users:**

1 four circle texture diffractometer

2 residual stress diffractometers

2 SANS

2 reflectometers

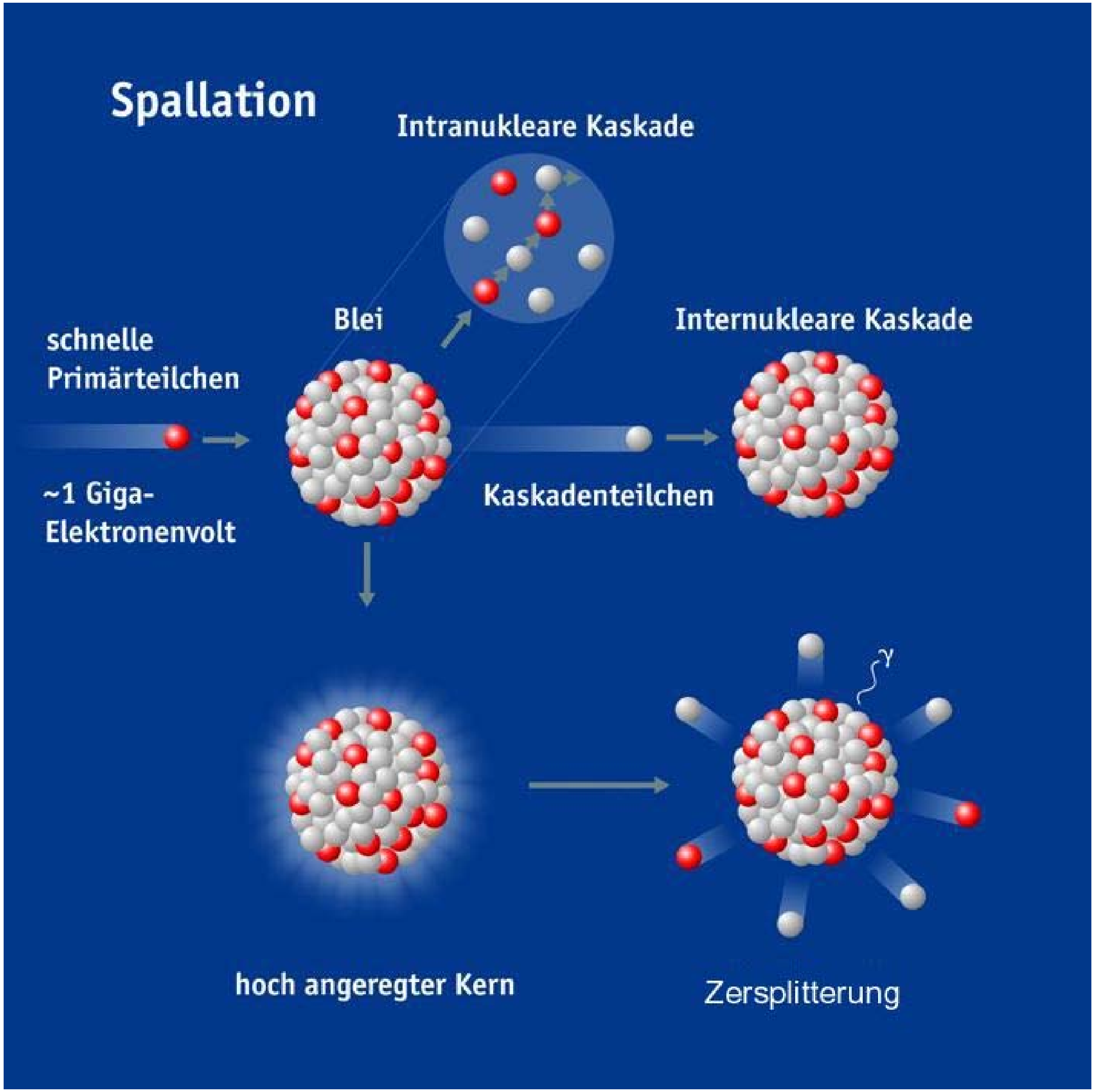
1 TOF spectrometer for basic research

1 Double crystal diffractometer for high resolution SANS

1 3-dimensional polarisation analysis diffractometer

Polarised neutrons available on 5 instruments

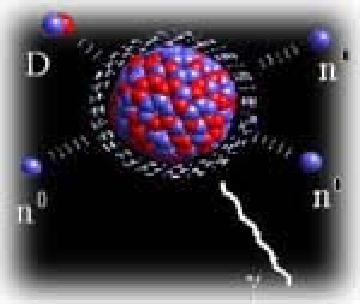
# Spallation

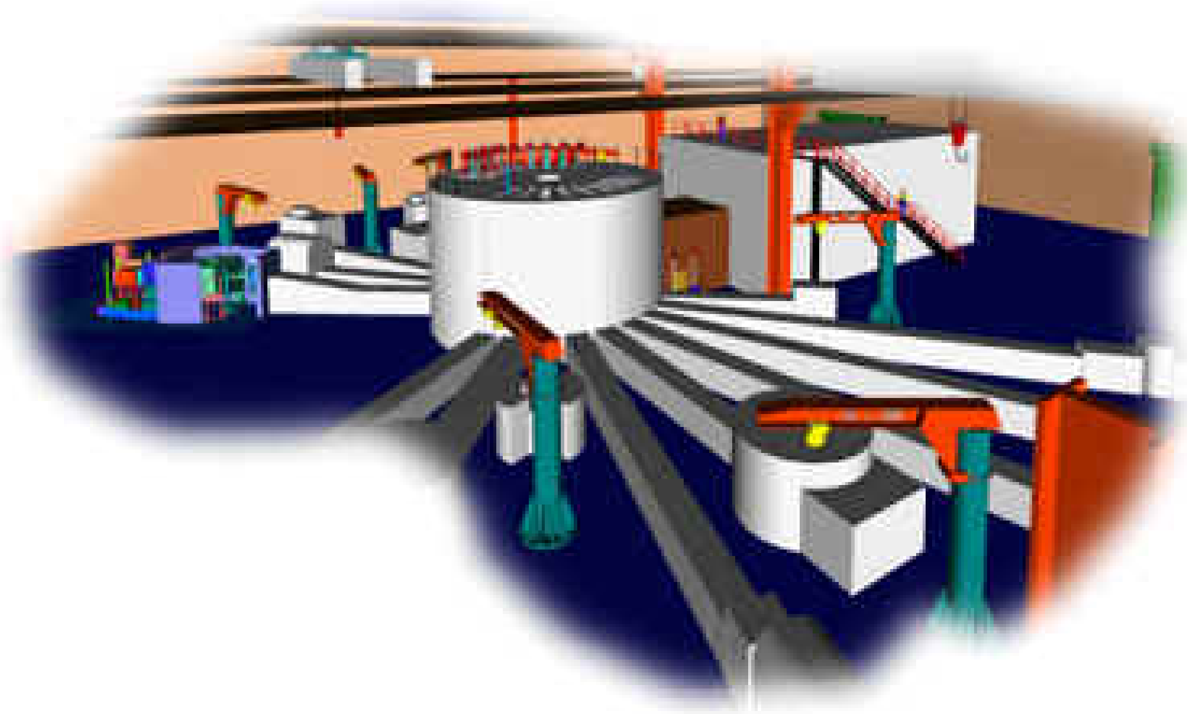


pro freigesetztem Neutron entsteht bei der Spallation weniger Wärme als bei der Kettenreaktion .... daher sind höhere Flüsse möglich: spitzenwerte thermische Neutronen $2x10^{17}n/cm^2s$ (geplant bei der ESS)

Pb: 20n/p +23MeV
$^{238}$U: 40n/p +50MeV
(vgl $^{235}$U:1n/spaltung
+ 200MeV)

# ISIS, Rutherford (Oxford)
# Winfried Kockelmann



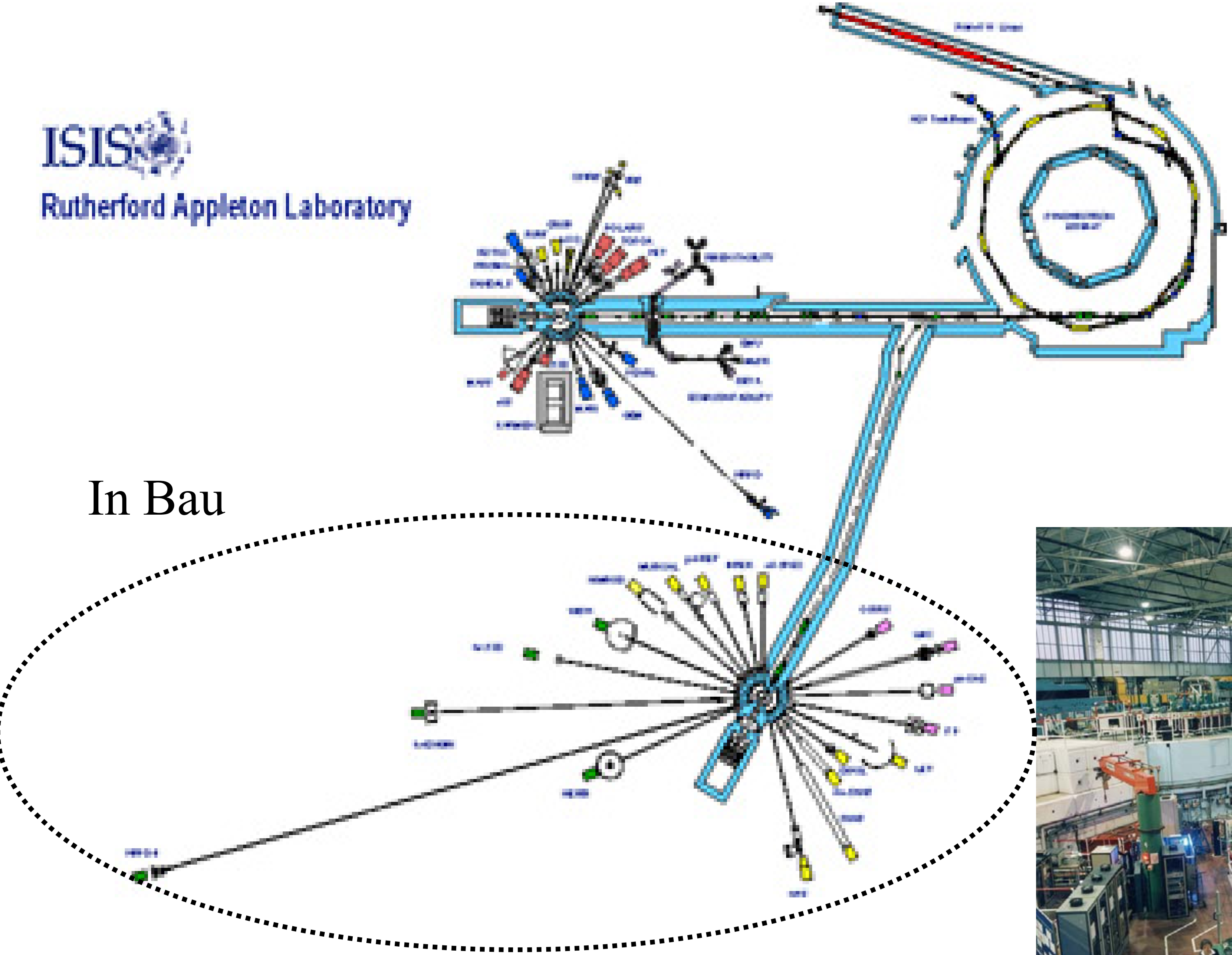


# Spallations-Neutronenquellen

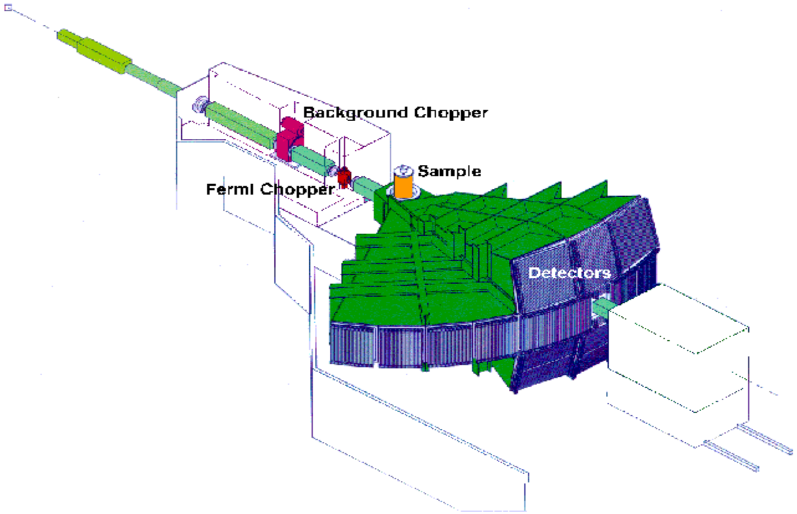
ISIS

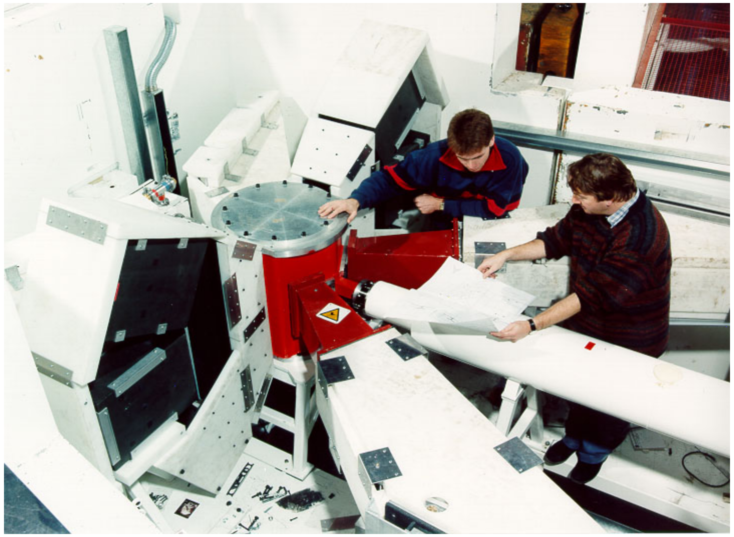
Rutherford Appleton Laboratory

Oxford, UK



In Bau


Background Chopper
Sample
Fermi Chopper
Detectors



SNS, Oakridge, USA

1.400.000$

**In Bau**

european
spallation
source

1.500.000€

**In Planung ?**

# Neutronen haben weltweit Zukunft ! ! !

# Reactor-Sources

- Budapest Neutron Centre, AEKI, Budapest, Hungary
- Berlin Neutron Scattering Center, Hahn-Meitner-Institut, Berlin
- Center for Fundamental and Applied Neutron Research (CFANR), Rez nr Prague, Czech Republic
- FRJ-2 Reactor, Forschungzentrum Jülich, Germany
- Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, Dubna, Russia
- GKSS Institute for Materials Research, Hamburg, Germany
- Institut Laue Langevin, Grenoble, France
- Interfacultair Reactor Instituut, Delft University of Technology, NL
- JEEP-II Reactor, IFE, Kjeller, Norway
- Laboratoire Léon Brillouin, Saclay, France
- Ljubljana TRIGA MARK II Research Reactor, J. Stefan Institute, Slovenia
- St. Petersburg Nuclear Physics Institute, Gatchina, Russia
- Studsvik Neutron Research Laboratory (NFL), Studsvik, Sweden
- Centro Atomico Bariloche, Rio Negro, Argentina
- Chalk River Neutron Program for Material Research, Chalk River, Ontario, Canada
- High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory, Tennessee, USA
- Los Alamos Neutron Science Center (LANSCE), New Mexico, USA
- McMaster Nuclear Reactor, Hamilton, Ontario, Canada
- MIT Nuclear Reactor Laboratory, Massachusetts, USA
- NIST Center for Neutron Research, Gaithersburg, Maryland, USA
- Peruvian Institute of Nuclear Energy (IPEN), Lima, Peru
- University of Missouri Research Reactor, Columbia, Missouri, USA
- University of Illinois Triga Reactor, Urbana-Champaign, Illinois, USA
- Institute, Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia
- High-flux Advanced Neutron Application Reactor (HANARO), Korea
- Japan Atomic Energy Research Institute (JAERI), Tokai, Japan
- KENS Neutron Scattering Facility, KEK, Tsukuba, Japan
- Kyoto University Research Reactor Institute (KURRI), Kyoto, Japan
- Malaysian Institute for Nuclear Technology Research (MINT), Malaysia
- Australian Replacement Research Reactor, Lucas Heights, Australia
- Canadian Neutron Facility, Chalk River, Ontario, Canada
- FRM-II Research Reactor, Garching, Germany

# Spallation Sources

- ISIS Pulsed Neutron Facility, Rutherford-Appleton Laboratory, Oxfordshire, UK
- Swiss Spallation Neutron Source (SINQ), Villigen SwitzerlandBragg
- Intense Pulsed Neutron Source (IPNS), Argonne National Laboratory, Illinois, USA
- Spallation Neutron Source, Oak Ridge National Laboratory, Tennessee, USA
- Japanese Spallation Source
- Austron Spallation Neutron Source, Vienna, Austria
- European Spallation Source (ESS)
- Japan Proton Accelerator Research Complex (J-PARC), Tokai, Japan

# Nachweis von Neutronen

**n nicht ionisierend – daher immer indirekter Nachweis**

(keine Energieanalyse bei Nachweis)

**schnelle Neutronen (MeV):** Stöße mit p-haltigen Substanzen

**thermische Neutronen (meV)**:

1. Aktivierung durch n – Einfang (z.B. n-γ Reaktionen in Au,In)

2. Kernreaktionen und anschließender Nachweis der (geladenen) Reaktions produkte – üblich in der Neutronenstreuung: Geiger Müller Zählrohr
   a) $BF_3$: $B^{10}(n, \boldsymbol{\alpha}) Li^7 + 2.79\mathrm{MeV}$
   b) $He^3$: $He^3(n,\mathbf{p}) H^3 + 0.765\mathrm{MeV}$
   Nachweiswahrscheinlichkeiten ca 95% (hängt von λ ab, $\lambda^2 \propto 1/v$)

3. Szintillationszähler: $n \rightarrow B \rightarrow \boldsymbol{\alpha} \rightarrow ZnS$ (Photomultiplier)

4. Imageplates : Gd-Schicht → n-γ Reaktionen → Detektion wie in x-ray

# Literatur

| | | |
|---|---|---|
| S. W. Lovesey | Theory of Neutron Scattering from Condensed Matter | Oxford (1981) |
| G. E. Bacon | Neutron Physics | Wykeham (1969) |
| **G. E. Bacon** | **Neutron Diffraction** | **Oxford (1979)** |
| Shirane, Sahpiro and Tranquada | Neutron Scattering with a triple axis spectrometer | |
| Izyumov, Ozerov | Magnetic Neutron Diffraction | Plenum (1970) |
| **Marshall and Lovesey** | **Theory of thermal neutron scattering** | |
| **Squires** | **Thermal Neutron scattering** | |

# Neutrons – Photons

| **Neutrons:** | **Photons:** |
|---|---|
| **Particle beam (neutral)** | **Light beam** |
| $E=h^2/2m_N\lambda^2=81.1meV/\lambda^2$ | $E=hf=hc/\lambda=12398eV/\ \lambda$ |
| **Low brilliance (particles/cm2/sr/meV)** | **High brilliance** |
| **Interactions with the nuclei and the magnetic moment of unpaired electrons** | **Interactions with the electrons surrounding the nuclei** |
| **Scattered by all elements, also the light ones like the hydrogen isotopes** | **Mainly scattered by heavy elements** |
| **Deep penetration depth (bulk studies of samples)** | **Small penetration depth (surface studies of samples)** |
| **Less intense beam measuring larger samples** | **Very intense beam measuring small or ultra-dilute samples** |
| ***Applications:*** | ***Applications:*** |
| **Magnetic structures & excitations, critical scattering** | **Surface studies, element and shell sensitive resonant magnetic scattering, magnetic dichroism, magnetic Materials with high neutron absorption** |