HELMHOLTZ GEMEINSCHAFT

Kick-off meeting of DETI.2 project,
12th-14th September 2012, Rossendorf

РФФИ

Synchrotron radiation in studies of structures & magnetism

Dr. A. Smekhova

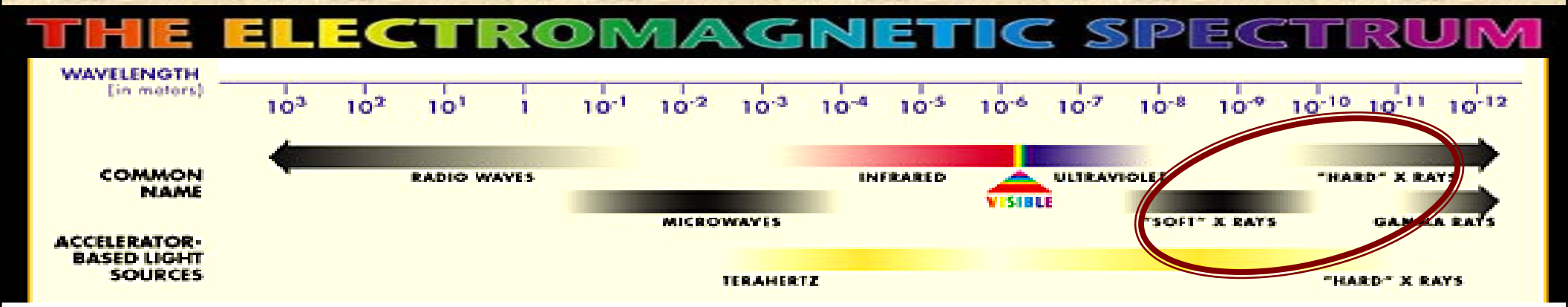
Moscow State University, 119991, Moscow, Russia;
Faculty of Physics;

X-rays...

W.C.Roentgen:

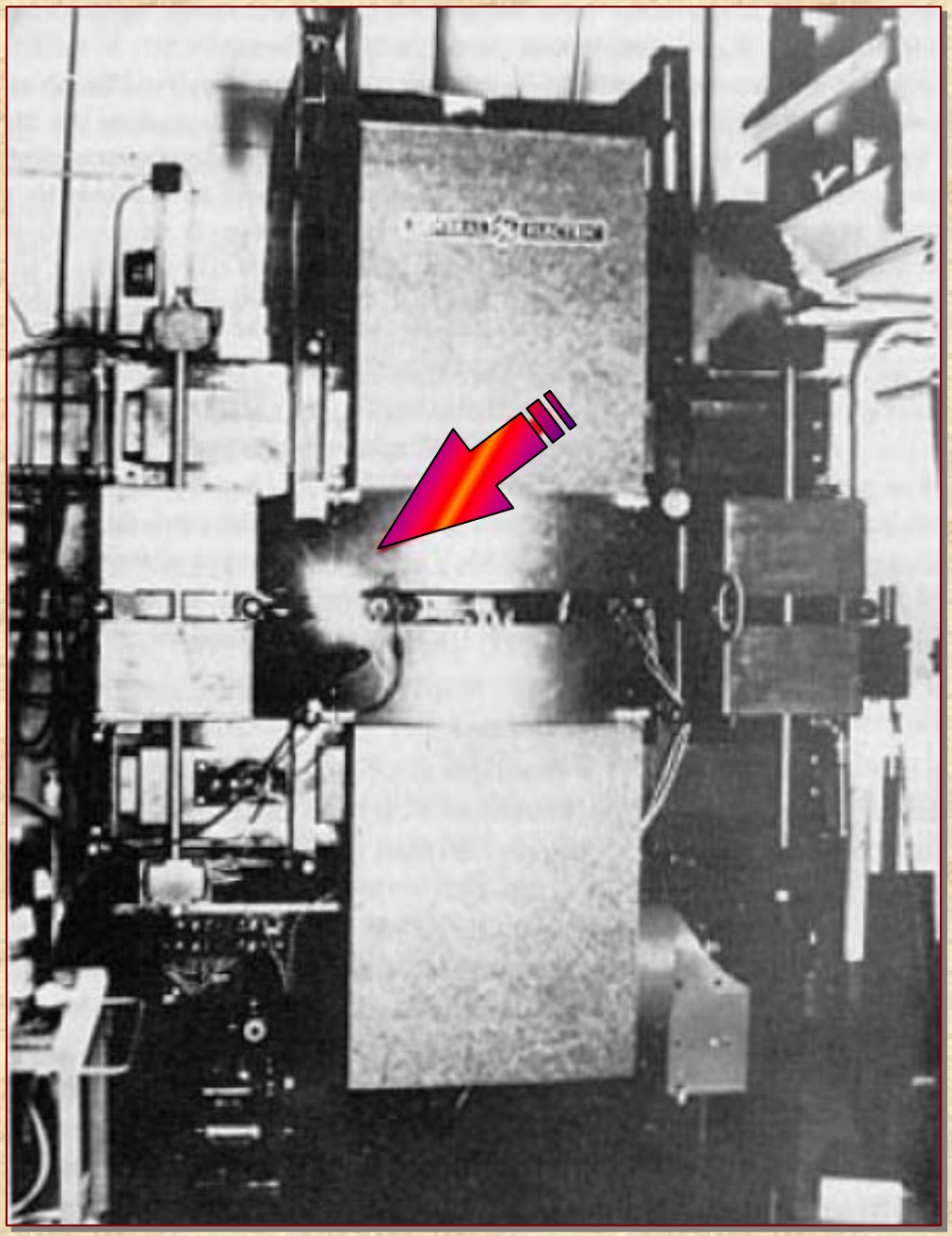
in 1895 he did his famous discovery of a short-wave ray, named X-rays, for which he received the first Nobel Prize in Physics (1901).

X-rays are actually electromagnetic waves situated between ultraviolet light and gamma rays on the wavelength scale. Their wavelengths are comparable to interatomic distances.



Although these results were remarkable, the X-ray tubes were limited: the light was emitted in all directions with no possibility of focusing it or making the rays parallel. This light was also only intense on particular wavelengths, which restricted its use, particularly in the field of spectroscopy.

The first experimental evidence of SR in laboratory:



April the 24th 1947

At the synchrotron in General Electric laboratory (USA)

by

Frank Elder,
Anatole Gurewitsch,
Robert Langmuir,
and Herb Pollock

(PhD F. Haber)

The title "synchrotron" for the radiation is from the name of the machine, at which it was observed…

Energy losses in magnetic fields...

PHYSICAL REVIEW VOLUME 65, NUMBERS 11 AND 12 JUNE 1 AND 15, 1944

Letter to the Editor

PROMPT publication of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is the third of the month. Because of the late closing date for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not in general exceed 600 words in length.

On the Maximal Energy Attainable in a Betatron

D. IWANENKO AND I. POMERANCHUK
Physical Institute of the Moscow State University, Moscow, and Physico-Technical Institute of the Academy of Sciences of the U. S. S. R., Leningrad, U. S. S. R.

May 18, 1944

BY means of a recently constructed induction accelerator-betatron, Kerst succeeded in obtaining electrons up to 20 Mev.[1] The principle of operation of the betatron is the acceleration of electrons by a tangential electric field produced by a changing magnetic flux, which is connected with the magnetic field keeping electrons on the orbit by a simple relation. In contrast to a cyclotron, whose applicability is essentially limited to the non-relativistic region on the ground of defocusing of orbits due to the change of mass at high energies, there is no such limitation for the betatron.

We may point out, however, that quite another circumstance would lead as well to the existence of a limitation for maximal energy attainable in a betatron. This is the radiation of electrons in the magnetic field. Indeed, electrons moving in a magnetic field will be accelerated and must radiate in accordance with the classical electrodynamics. One can easily see that quantum effects do not play here any important role as the dimension of the orbit is very great. As was shown by one of us[2] an electron moving in a magnetic field **H** radiates per unit of path the energy

$$-(dE/dX) = 2/3(e^2/mc^2)^2(E/mc^2)^2[(\mathbf{V}/c)\mathbf{H}]^2 \qquad (1)$$

where e is the charge, m the mass, **V** the velocity, and E the energy of the electron; E is assumed much greater than mc^2.

In the betatron **V** is normal to H and practically for the whole path equal to c. Then we have

$$-(dE/dX) = 2/3(e^2/mc^2)^2(EH/mc^2)^2. \qquad (2)$$

The limiting value of energy E_0 is to be determined from the condition that the radiated energy (2) will be equal to energy gained by the electron in the electric field produced by magnetic flux per unit of path:[3]

$$\frac{2}{3}r_0^2\left(\frac{E_0 H}{mc^2}\right)^2 = \frac{e|d\phi/dt|}{2\pi R_0 c} = \frac{e}{c}R_0|\dot{H}| \qquad (3)$$

$$\dot{H} = dH/dt \qquad r_0 = e^2/mc^2.$$

Here R_0 is the radius of the orbit, ϕ is the induction flux.[1]

Hence:

$$\frac{E_0}{mc^2} = \left(\frac{3eR_0}{2r_0^2 c}\frac{\dot{H}}{H^2}\right)^{\frac{1}{3}}. \qquad (4)$$

Taking for H and E the values now being in use we get $E_0 \approx 5\times 10^8$ ev, which is only five times as great as the energy which one expects to obtain in the betatron now under construction. From (4) one sees that E_0 is inversely proportional to the magnetic field applied and proportional to the square root of energy gained in the rotation electric field per unit of path. All this requires the using of smaller H or of higher frequencies with the purpose of getting higher limiting values of E_0.

The radiative dissipation of energy of electrons moving in a magnetic field must be also of importance for the discussion of the focusing of the electronic beam, as the energy of particles being accelerated will grow more slowly with the growth of H if the radiation is taken into account. This latter question may deserve a separate discussion.

[1] D. W. Kerst, Phys. Rev. **61**, 93 (1942).
[2] I. Pomeranchuk, J. Phys. **2**, 65 (1940).
[3] D. W. Kerst and R. Serber, Phys. Rev. **60**, 53 (1941).

D.D. Iwanenko, I.Ya. Pomeranchuk, Phys Rev 1944

Energy loss on synchrotron radiation is like:

$$W \sim \frac{I}{R}\left(\frac{E}{m_0 c^2}\right)^4$$

When a charged particle is accelerated, it radiates...

ELECTROMAGNETIC RADIATION

AND THE MECHANICAL REACTIONS ARISING FROM IT

BEING AN ADAMS PRIZE ESSAY IN THE UNIVERSITY OF CAMBRIDGE

by

G. A. SCHOTT, B.A., D.Sc.

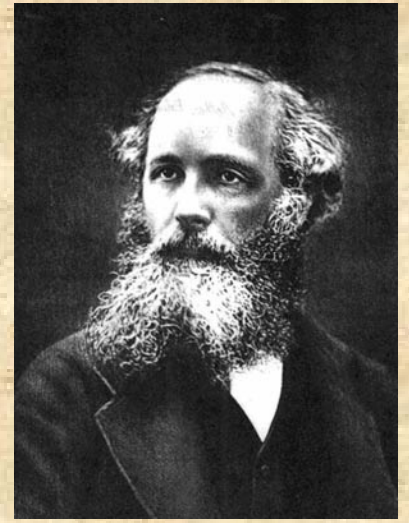
Professor of Applied Mathematics in the University College of Wales, Aberystwyth
Formerly Scholar of Trinity College, Cambridge

Cambridge:
at the University Press
1912

In 1912 *George Schott* published his article, where the polarization properties and angular distribution of radiation from electrons on circular orbit are described.

Before this, in 1898, *Alfred-Marie Liénard* predicted that charged particles undergoing acceleration would emit energy.

La théorie de Lorentz (*Éclairage électrique*, t. XIV, 1898).



The Scottish physicist and mathematician *James Clerk Maxwell* published his paper "On Physical Lines of Force" between 1861 and 1862.

$$\nabla \times \vec{E} + \frac{1}{c}\frac{\delta \vec{B}}{\delta t} = 0, \text{ and}$$

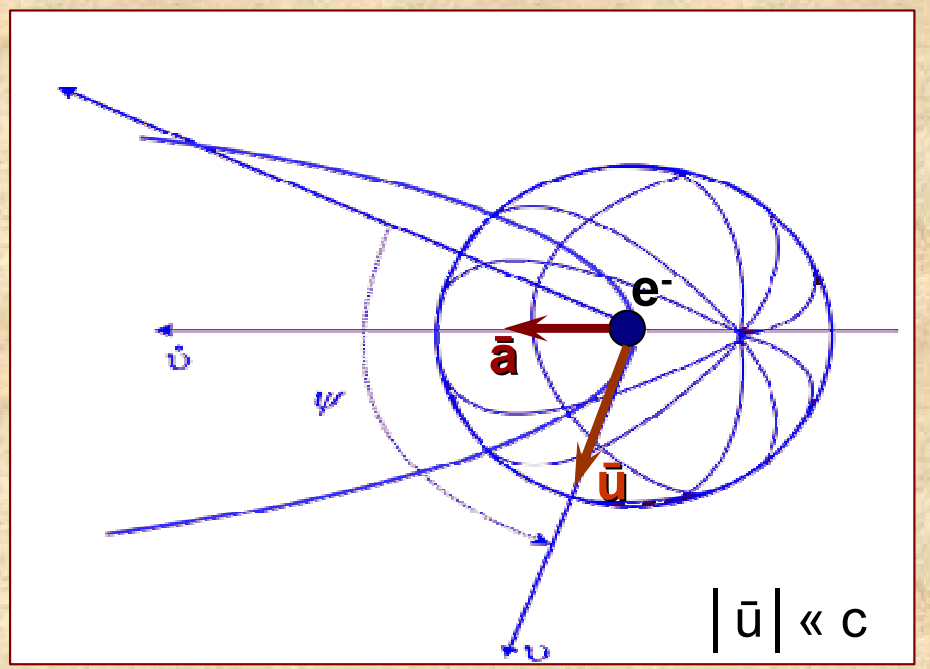
$$\nabla \times \vec{H} - \frac{1}{c}\frac{\delta \vec{D}}{\delta t} = \frac{4\pi}{c}\vec{J}$$ "

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = 4\pi\rho$$

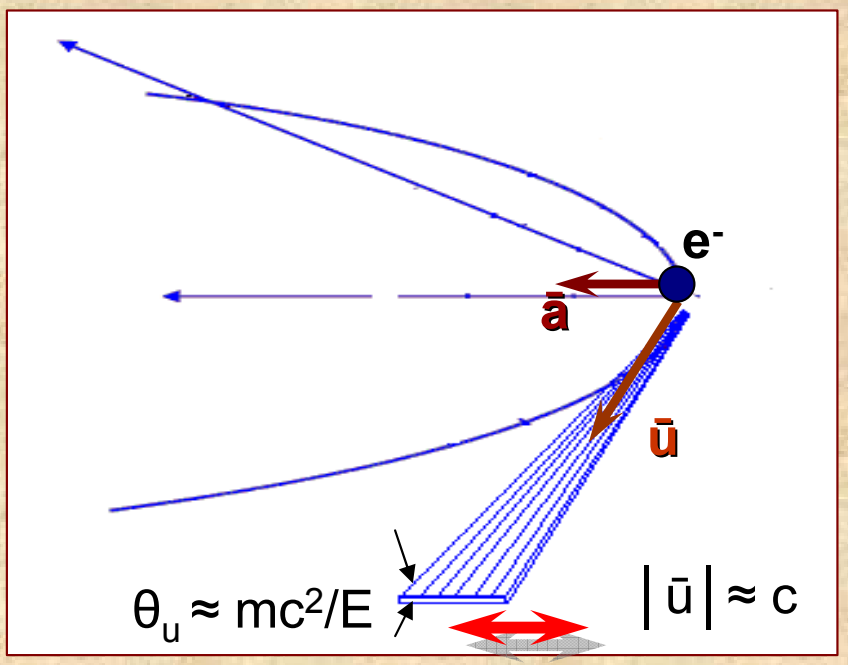
When a charged particle is accelerated, it radiates...

the case of non-relativistic particles:



cyclotron radiation

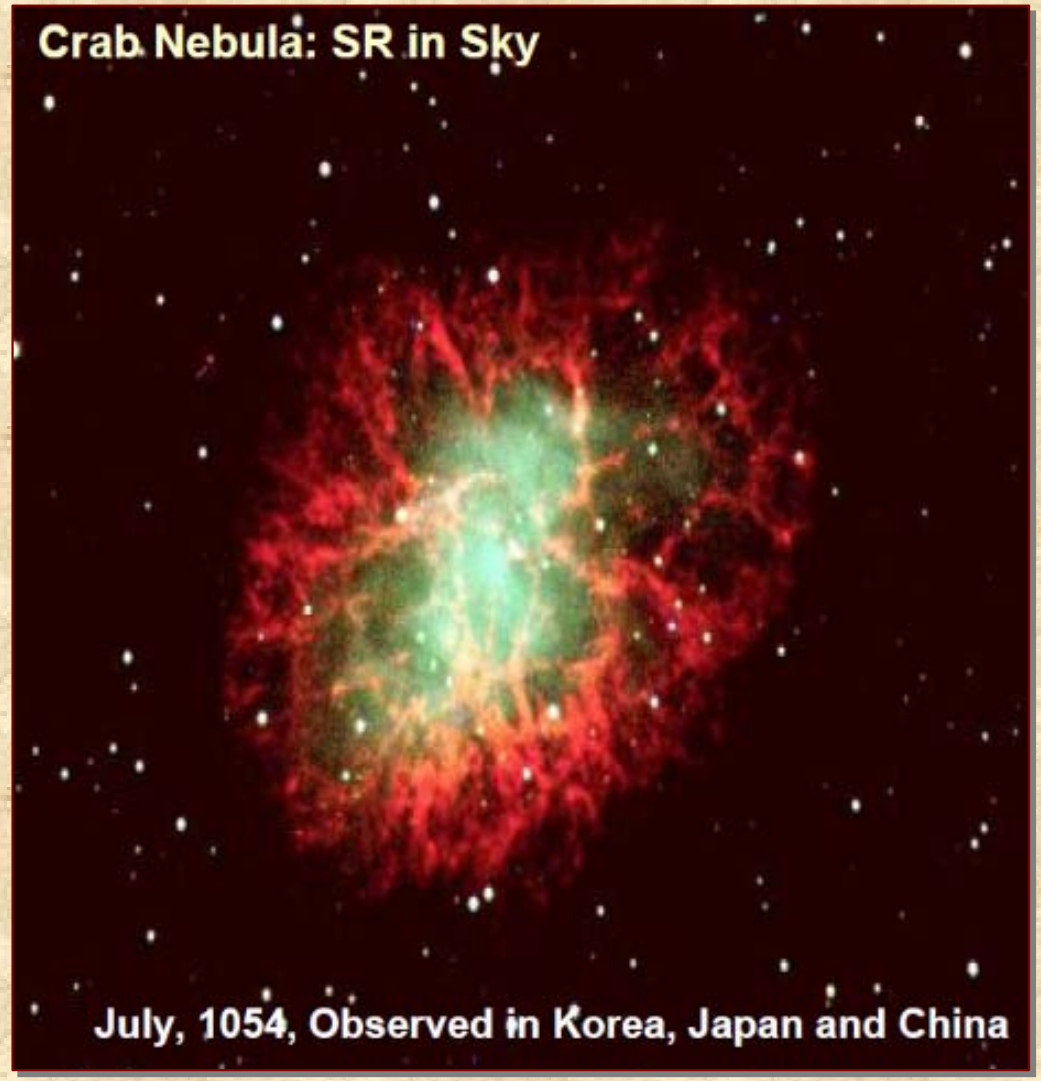
the case of relativistic particles:



synchrotron radiation

Синхротронное излучение — это *магнитотормозное* электромагнитное излучение, испускаемое *релятивистскими* зараженными частицами, когда постоянное магнитное поле заставляет их двигаться по круговым орбитам

The synchrotron radiation in nature:



- The supernova was observed by ancient astronomers
- Relativistic electrons passing through the magnetic fields of the nebula, give rise to Synchrotron radiation
- This is confirmed by the polarization properties of radiation from the Crab Nebula

Main features of SR:

- **Broad Spectrum (which covers from microwaves to hard X-rays): the users can select the wavelength required for their experiment and tune it with a high accuracy**

  before: only several characteristic wavelengths in X-ray tubes

- **High Flux: high intensity of photon beam allows rapid experiments or use of weakly scattering crystals**

  before: low intensities

- **High Brilliance: highly collimated photon beam generated by a small divergence and small size source (spatial coherence)**

  before: scattering in 4π solid angle

- **High Stability: submicron source stability**

- **Polarization: both linear and circular (up to 100%)**

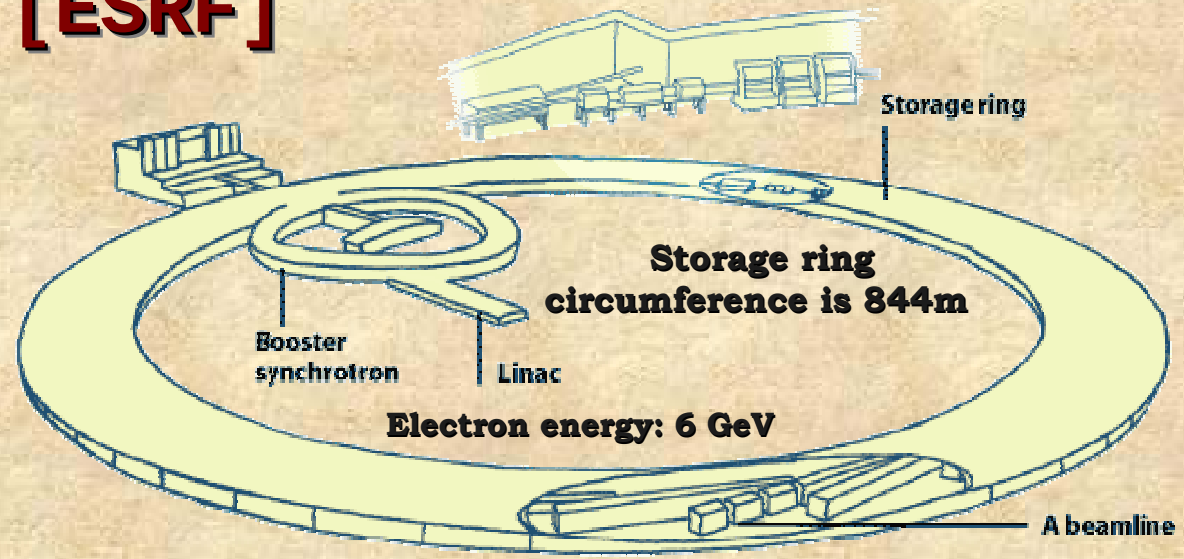
  before: non-polarized radiation

- **Pulsed Time Structure: pulsed length down to tens of picoseconds [10^{-12} c] allows the resolution of process on the same time scale.**

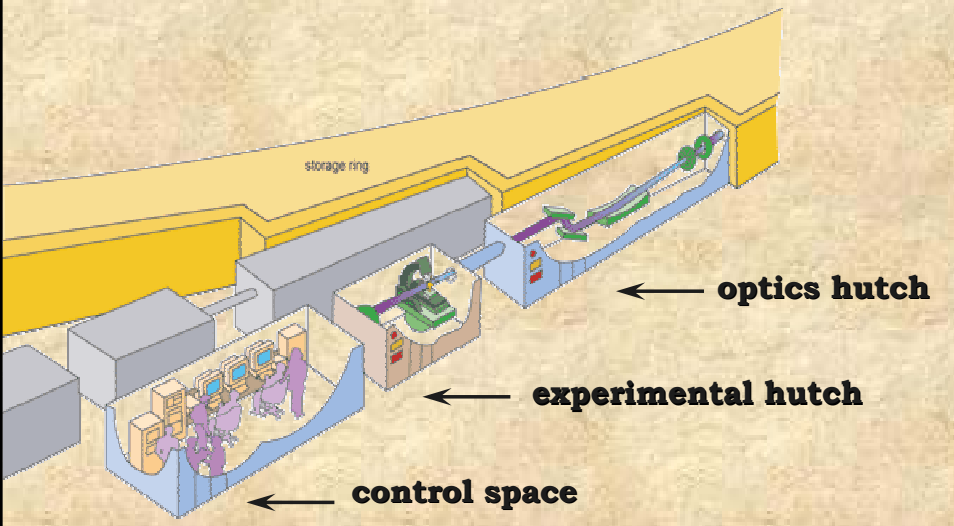
  before: no any time structure

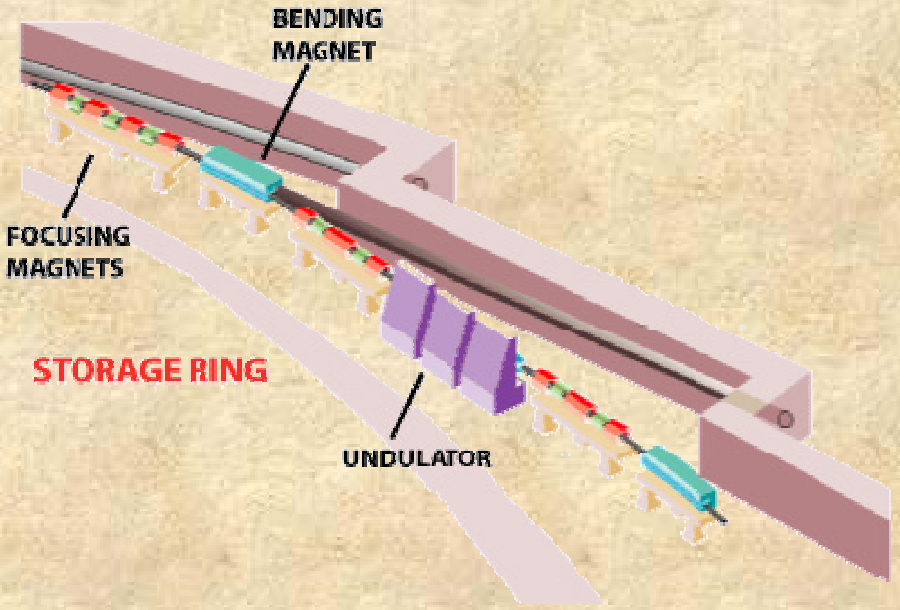
How it is possible to produce SR?

[ESRF]



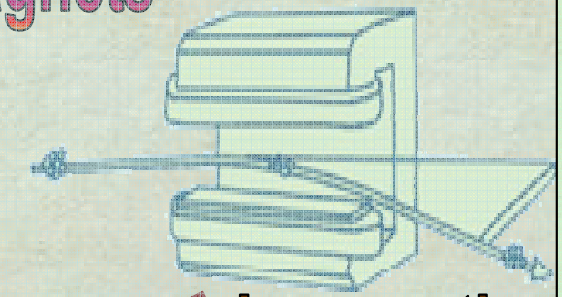
High vacuum: 10^{-9}Torr !!!





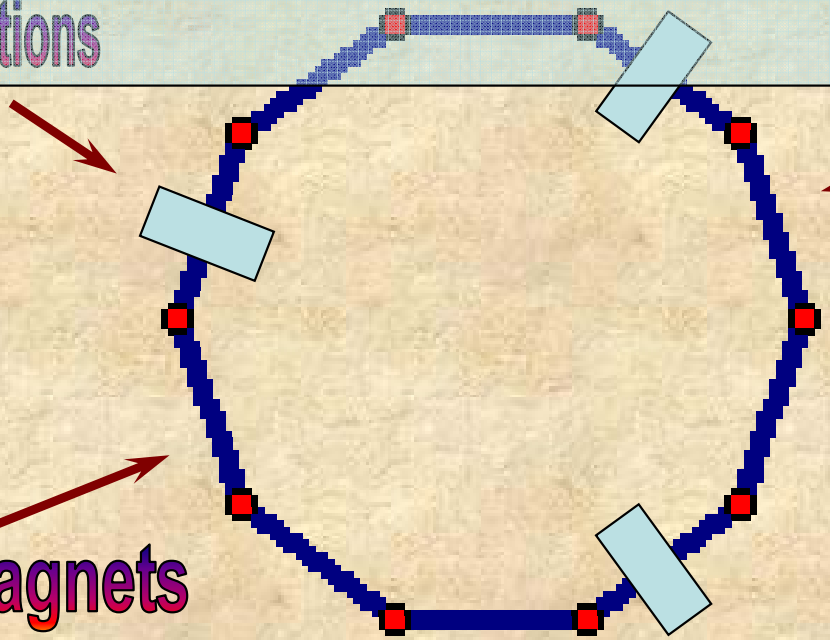
Bending magnets

Elements of the ring:



I generation

Accelerating stations

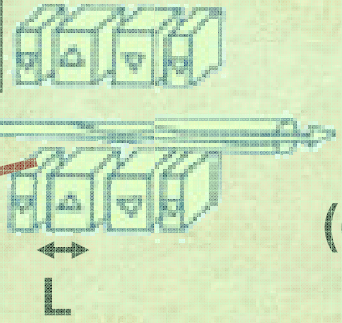


Focusing magnets

Insertion devices:

II generation

Wigglers



L

$B_{wiggler} \leq 10 Tesla$

$N_{wiggler} \leq 10$

$(e/mc)*(BL/2\pi) \gg 1$

Large deviation;
Non-coherent radiation
from each period;
"Wide" spectra;
$I_{wiggler} \sim N$

Undulators

III generation

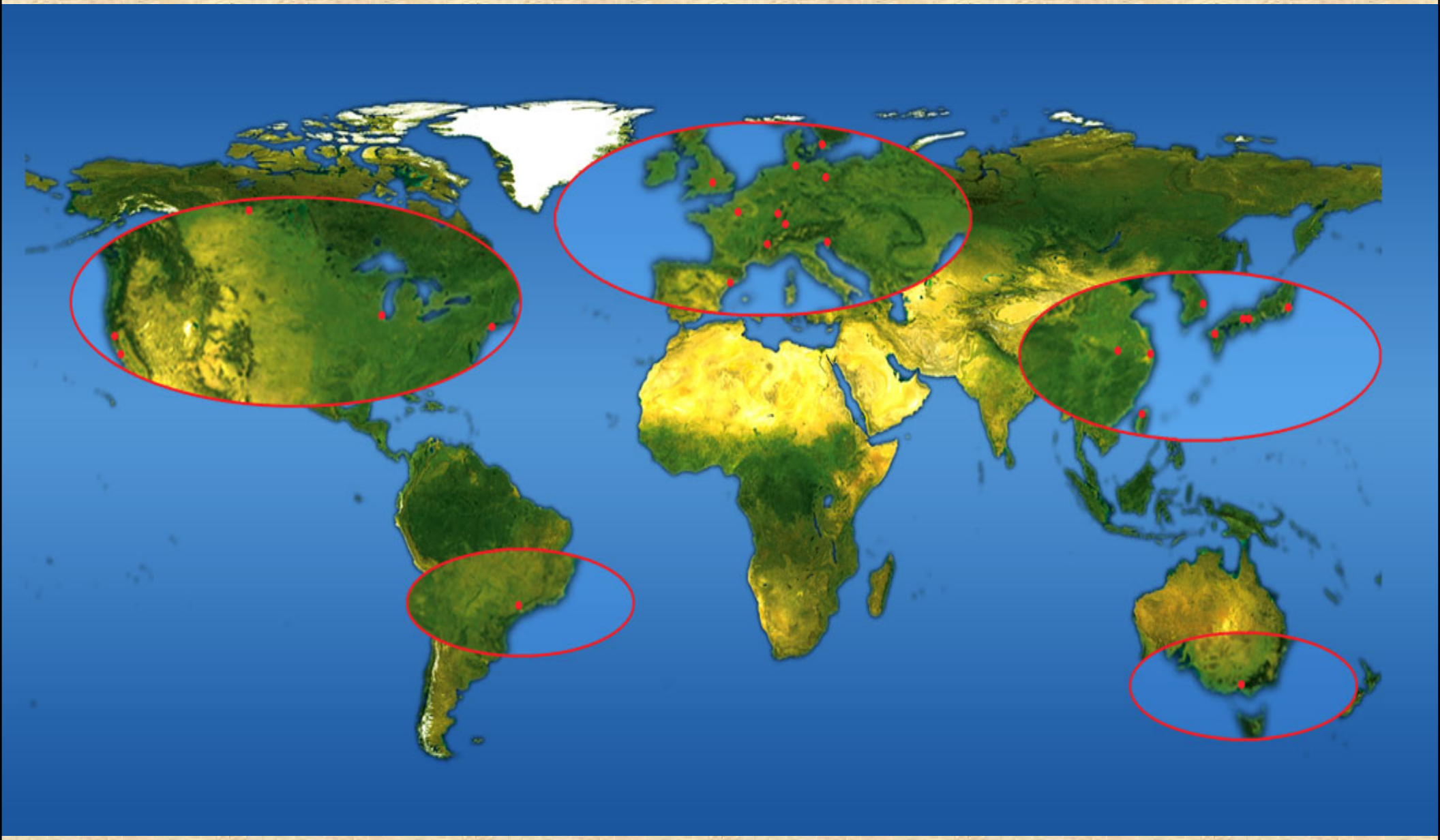
1.5 meters

$(e/mc)*(BL/2\pi) \leq 1$

Polarizations!!!

Small deviation;
Coherent radiation
from each period;
"Narrow" spectra;
$I_{undulator} \sim N^2$

Synchrotrons in the world:



Synchrotrons in the world:

Asia-Oceania: 26, Europe: 25, US: 18, Russia: 2÷4

III generation!!!

The three largest and most powerful synchrotrons:

ESRF, France

6Gev, 844m

since 1994

APS, USA

7Gev, 1436m

since 1996

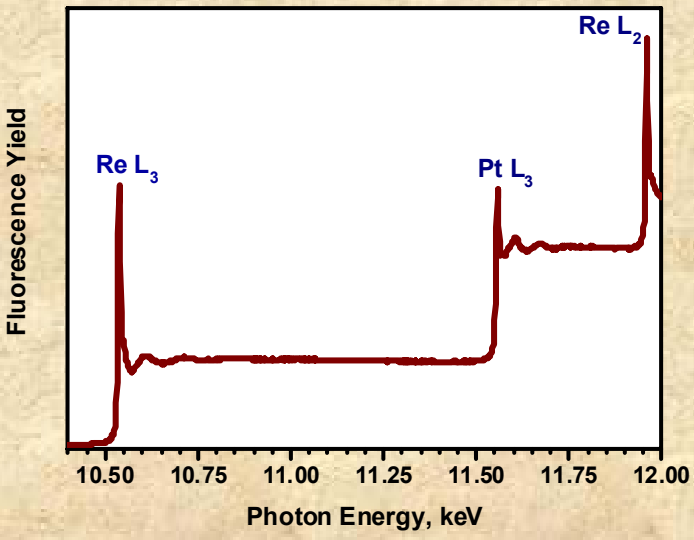
Spring8, Japan

8Gev, 1104m

since 1997

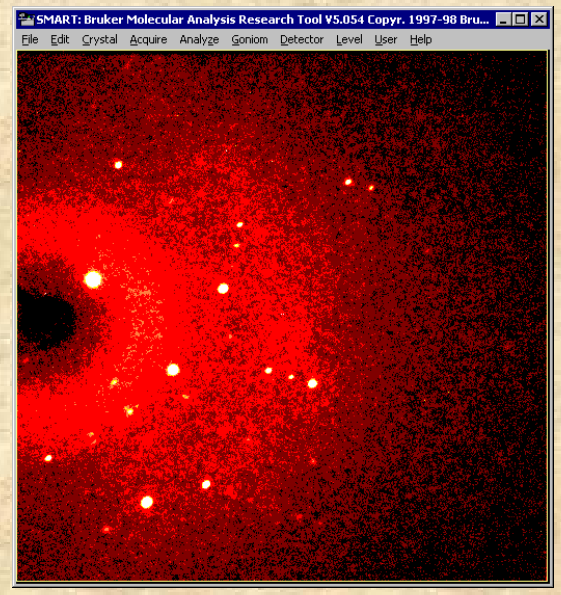
Methods, that are exploited the X-rays from synchrotrons:

X-ray spectroscopy



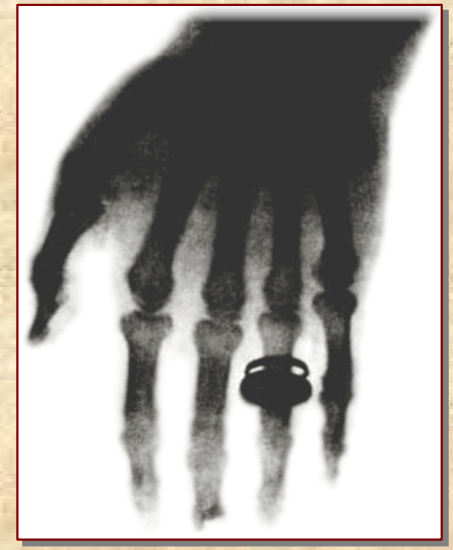
electronic structure,
crystal structure,
magnetic structure

X-ray diffraction



crystal structure

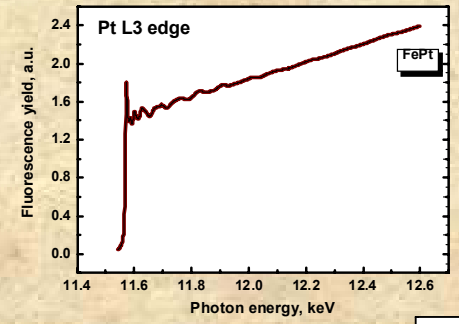
Visualization with X-rays

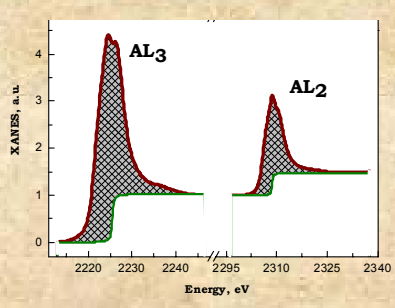


X-ray microscopy

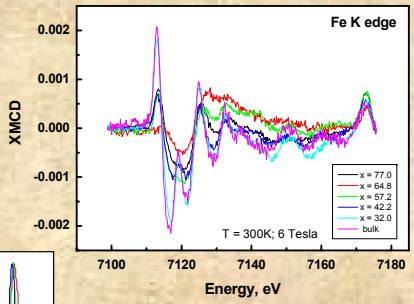
1. X-ray spectroscopy

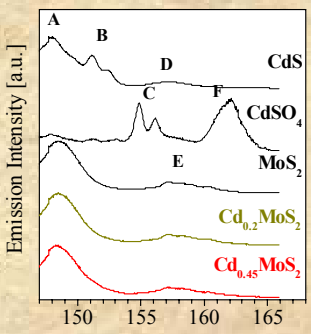
- **Absorption spectroscopy**
  XAFS: XANES + EXAFS



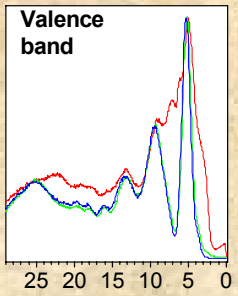


- **Polarization-depended absorption spectroscopy**
  XMCD, XLD, XMLD, XND, *etc*…

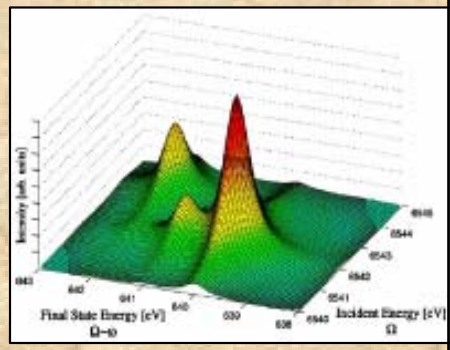




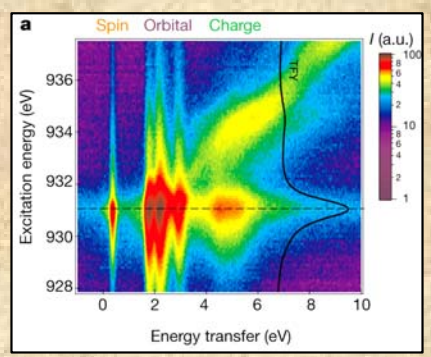
- **Emission spectroscopy**
  X-ray fluorescence analysis



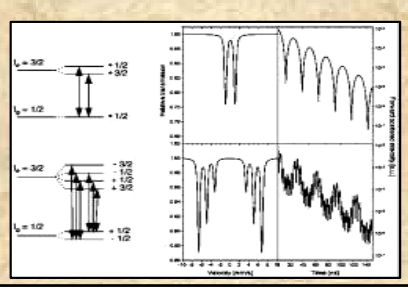
- **Photoelectron spectroscopy**



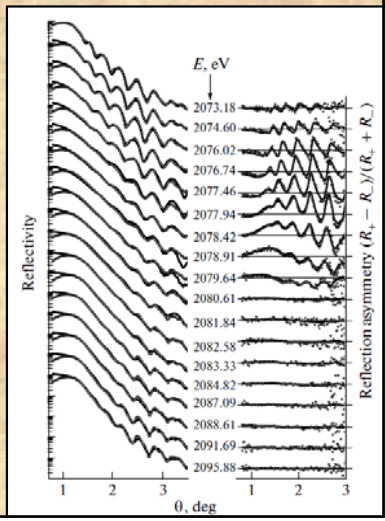
- **Inelastic scattering of X-Rays**
  Compton profiles, phonon structure, RIXS



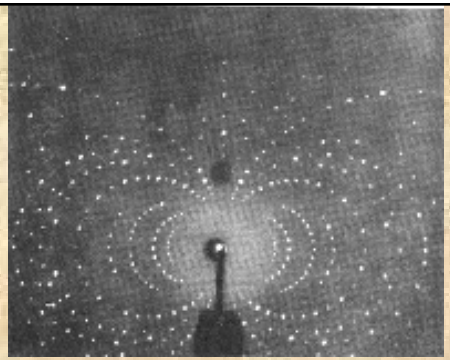
- **γ-resonance spectroscopy**
  NFS



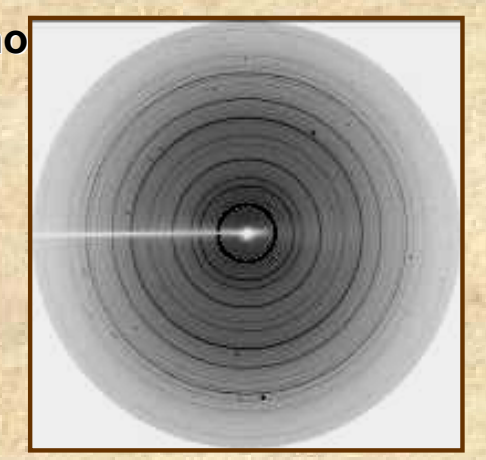
- **X-ray resonance magnetic scattering** (??!!)
  XRMR



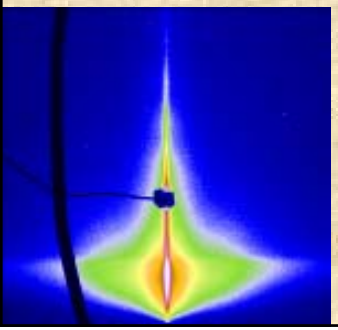
2. X-ray diffraction

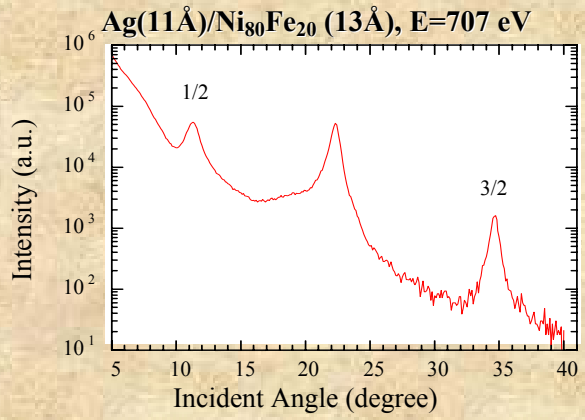


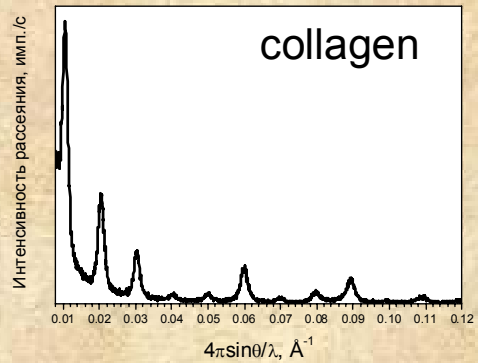
- **Monocrystal diffraction**
  Laue diffraction
  Protein crystallography (Multi-wavelength Anomalous Dispersion metho



- **Powder diffraction**
- **Diffuse scattering**
  (Roentgen-radiometry analysis)
- **X-ray small angle scattering, X-ray wide angle scattering**
- **X-ray reflectometry**







courtesy to A.Veligzhanin

3. Visualization with X-rays

- **X-ray microscopy**
  Scanning microscopy
  Spectro-microscopy (PEEM, etc.)

- **Tomography**

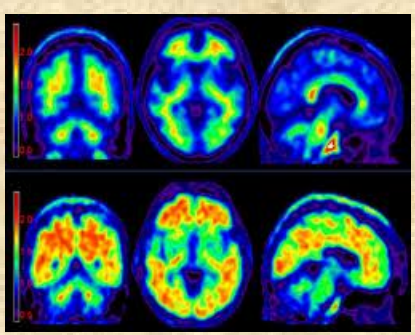
- **Diffraction topography (defectoscopy)**

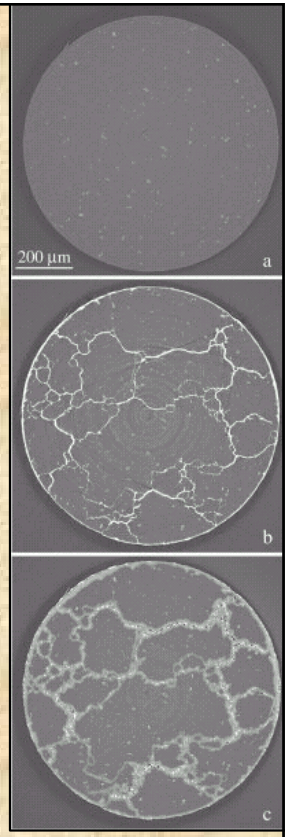
- **Methods of medical diagnostics**

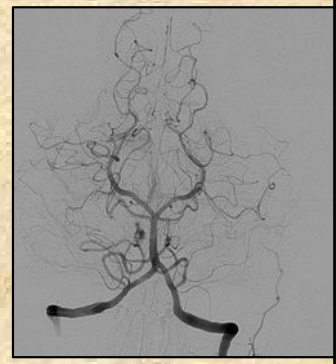
Fluorography, differentional angiography, mammography, *etc*…

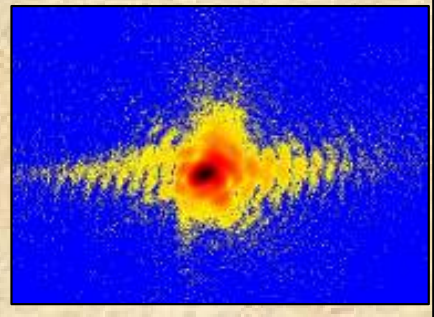
- **Methods of coherent visualization**

Coherent diffraction, holography with X-rays, photon-correlation spectroscopy









courtesy to A.Veligzhanin

Why all of this is possible?

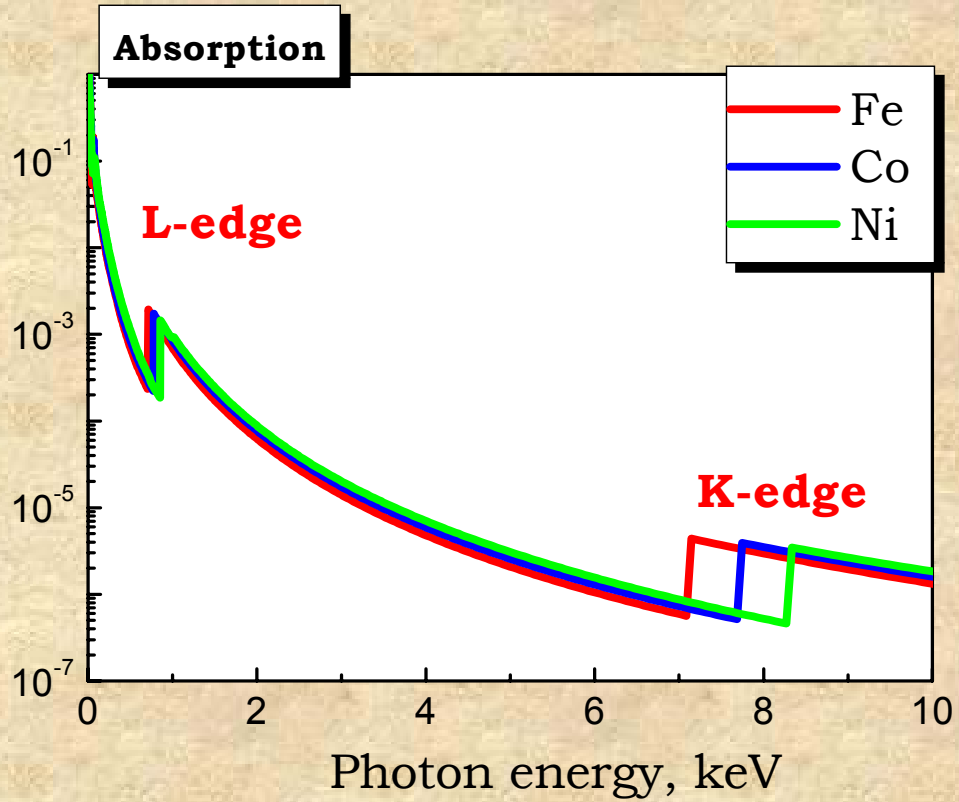
X-ray absorption:

$$dI/I = -\mu dx$$

$$I = I_0 \exp(-\mu x).$$

$$\mu = \frac{\ln(I_0/I)}{x}[\text{см}^{-1}],$$

$$\mu_m = \frac{\mu}{\rho}[\text{см}^2/\text{г}],$$

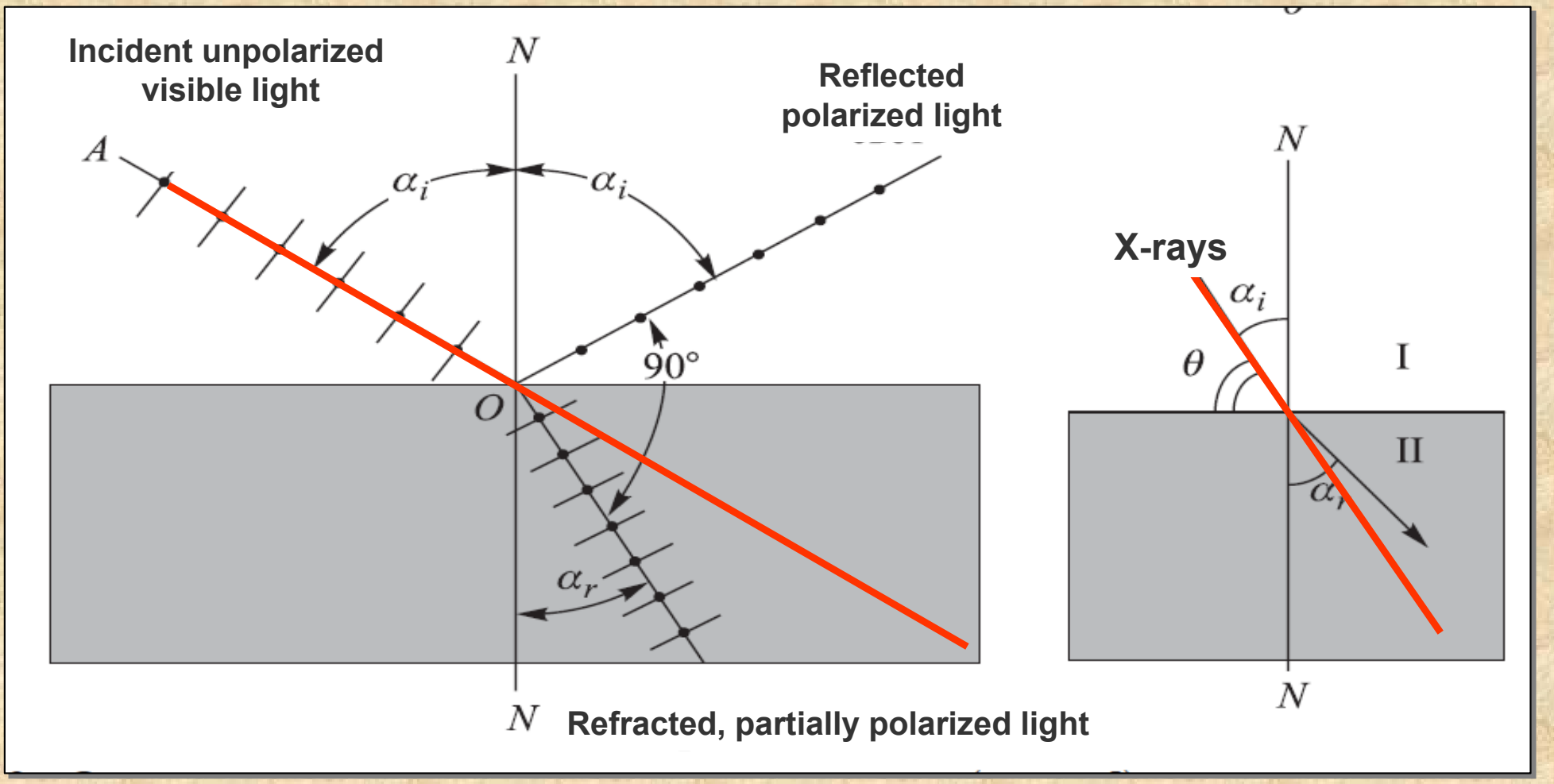


X-ray refraction:

$n = c/v$

Visible light: $n > 1$

X-rays: $n \leq 1$, $n = 1 + \chi$,

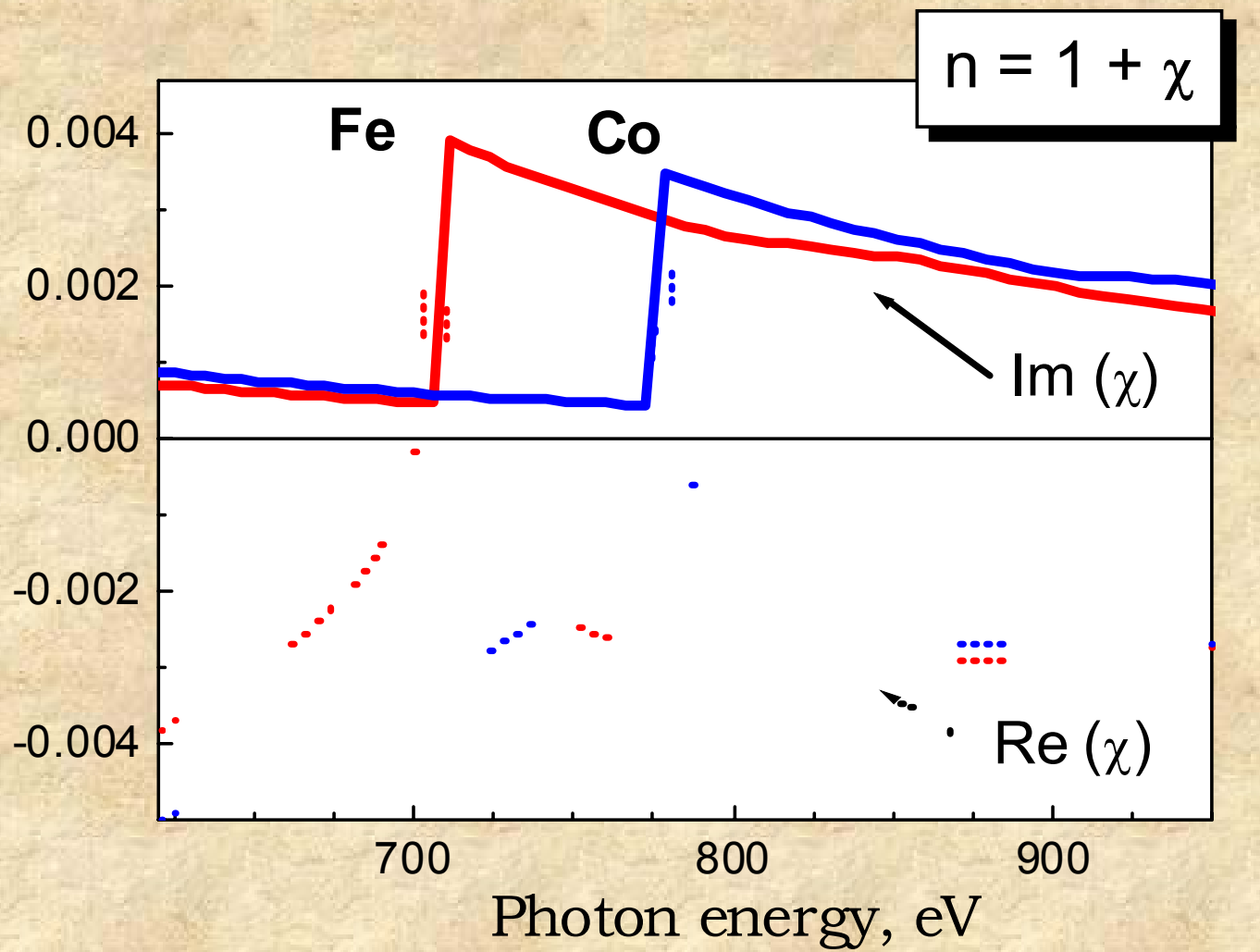


total <u>internal</u> reflection

total <u>external</u> reflection

X-ray susceptibility near the absorption edges:

$\chi = Re(\chi) + i*Im(\chi)$,



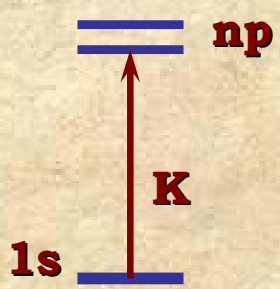
Near absorption edges the susceptibility χ isn't more a scalar: it becomes a tensor!

The possibility to observe magneto-optical properties!!!

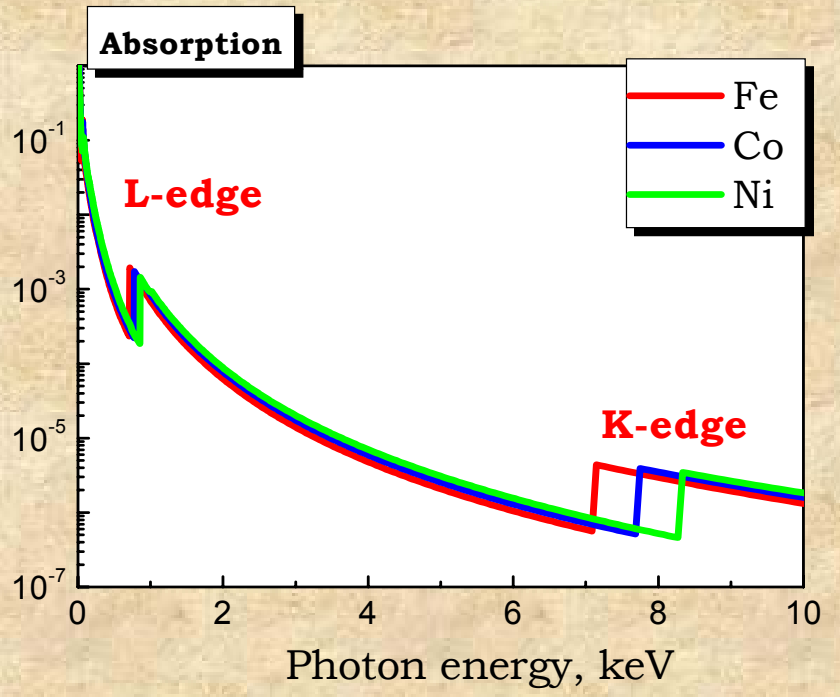
Recapitulation of SR main features:

- wide spectra + the possibility to tune energies across the absorption edges of every element with high accuracy → element-selective studies of complex systems
- high brilliance → studies of weak effects or studies diluted samples
- high collimation → small beam size + possibilities of nanofocusing
- polarization (linear or circular) → access to magnetism and anisotropy
- pulsed time structure → studies of dynamical processes

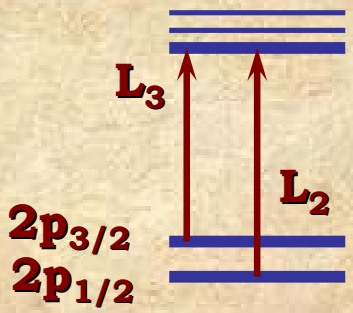
Absorption edges:



K -edge corresponds to transitions from 1s core level to unoccupied 4d states



$L_{2,3}$-edges correspond to transitions from $2p_{1/2}$ and $2p_{3/2}$ core levels to unoccupied nd states near Fermi energy in valence band



Spectroscopy:

- absorption spectroscopy:

  XAS ≡ XANES + EXAFS

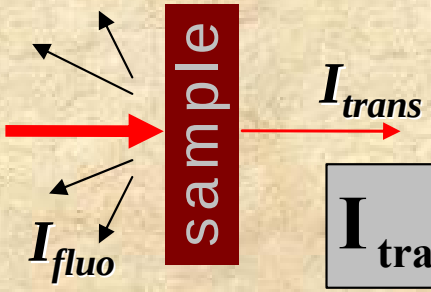
- polarization-dependent absorption spectroscopy:

  XMCD = XANES $^{(+)}$ – XANES $^{(-)}$;

  XLD = XANES $^{(\parallel)}$ – XANES $^{(\perp)}$

- ~~magnetic reflectivity from periodic multilayers & X-ray diffraction~~

X-ray absorption spectra:

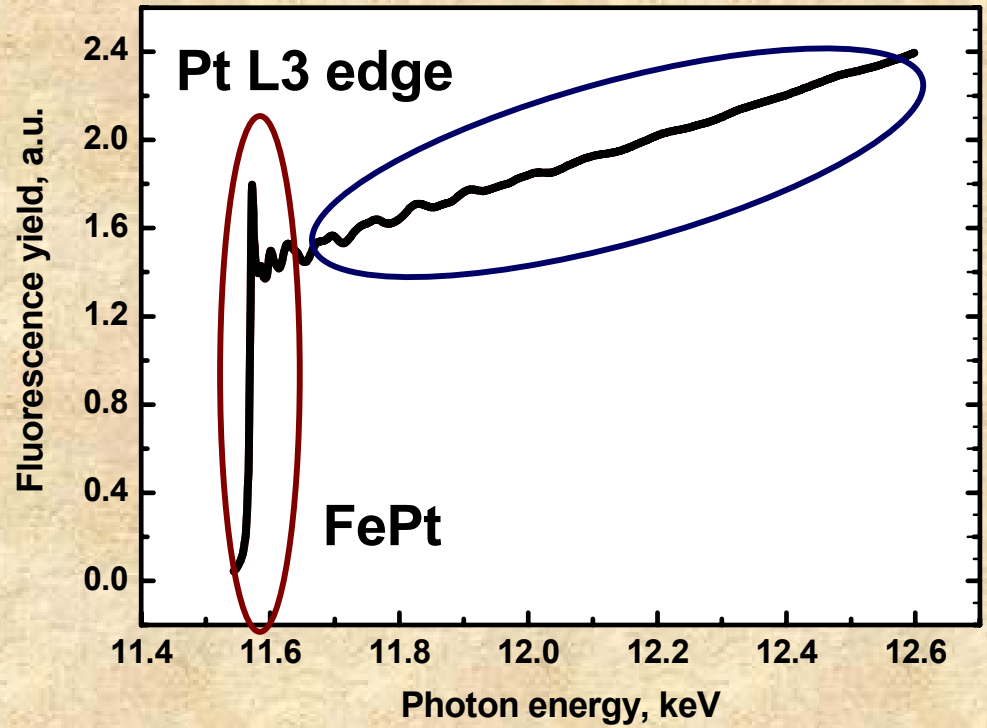


$$I_{trans} = I_0 e^{-\mu d}$$

$$\mu(E) \propto I_f / I_0$$

XANES

X-ray Absorption Near Edge Structure



30÷50eV

up to 1keV

Studies of electronic structures:

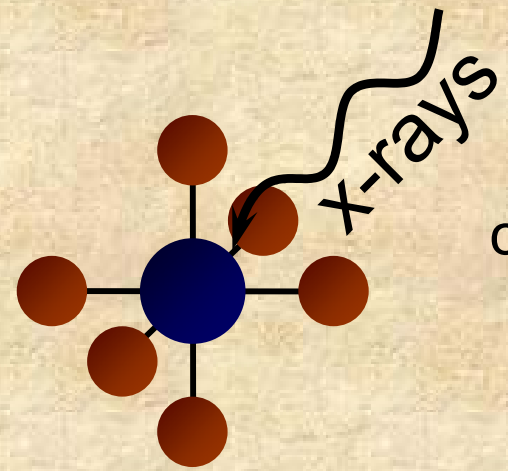
- Valence (oxidation) states;
- Local enviroment (+ crystal structure)

EXAFS

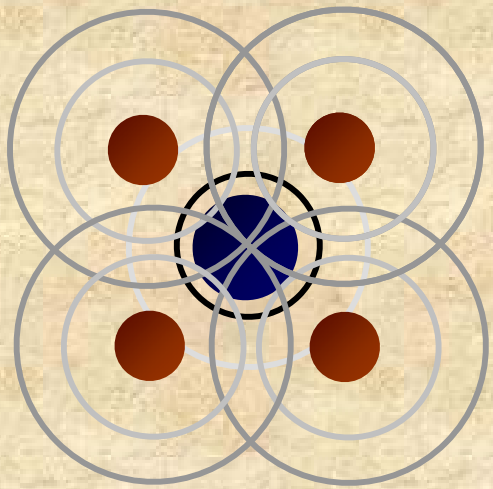
Extended X-ray Absorption Fine Structure

distances between atoms in the system

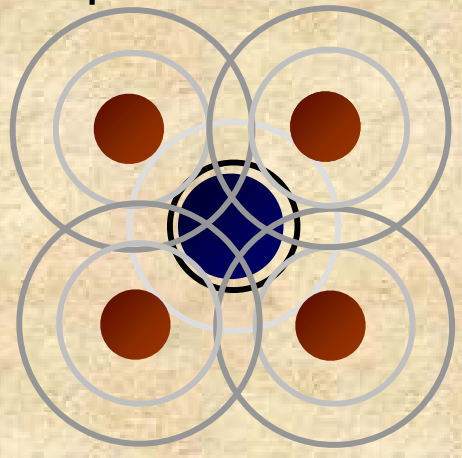
Why we have such oscillations?



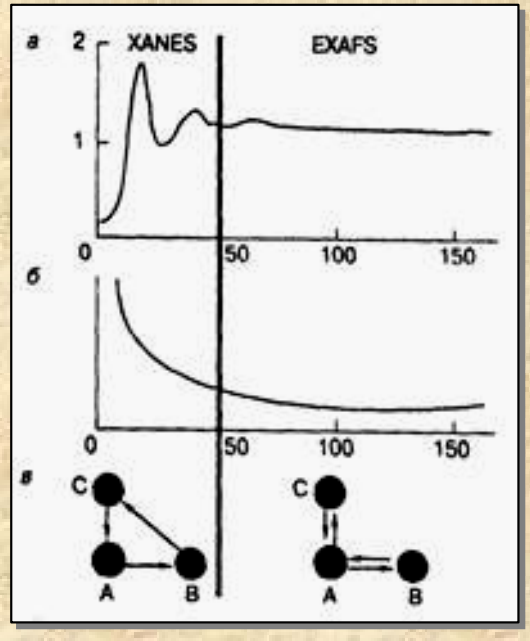
constructive interference – absorption maximum



destructive interference – absorption minimum



XANES



EXAFS

Multuple scattering on neighbor atoms; Large free lengh

Singlele scattering on neighbor atoms; Small free lengh

Theoretical description:

Fermi's Golden Rule in one-electron approximation:

$$\mu(E) \propto \sum_{f}^{E_f > E_F} \left|\langle f|T|i\rangle\right|^2 \delta(E_f - E_i - E)$$

$|i\rangle$ is an initial deep core state (e.g. $1s$),

$\langle f|$ is an unoccupied state in the presence of a core hole.

T is the electron transition operator.

For deep-core excitations, the dipole approximation is valid.

None of the calculation methods can give multiple-electron effects.
The shift due to core-hole involves many assumptions.

Good x-ray absorption theory is still a challenge.

K edges

XANES: Qualitative analysis

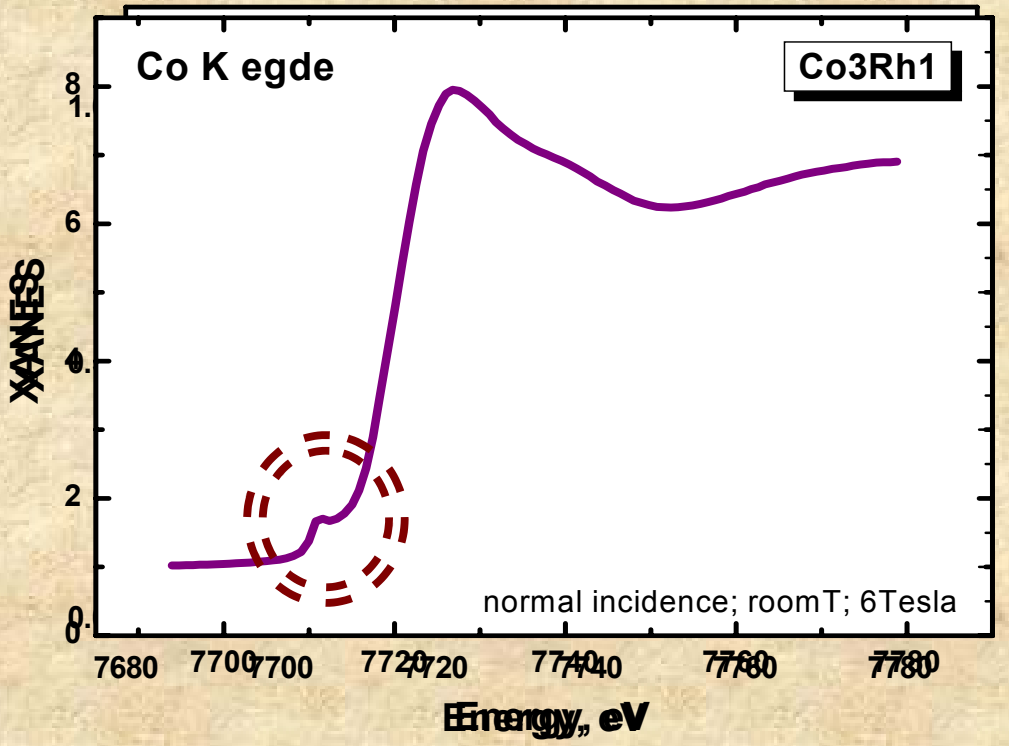
Dipole selection rule (only in central-symmetric case!): $\Delta l = \pm 1$

Consider *K*-absorption for transition metals:

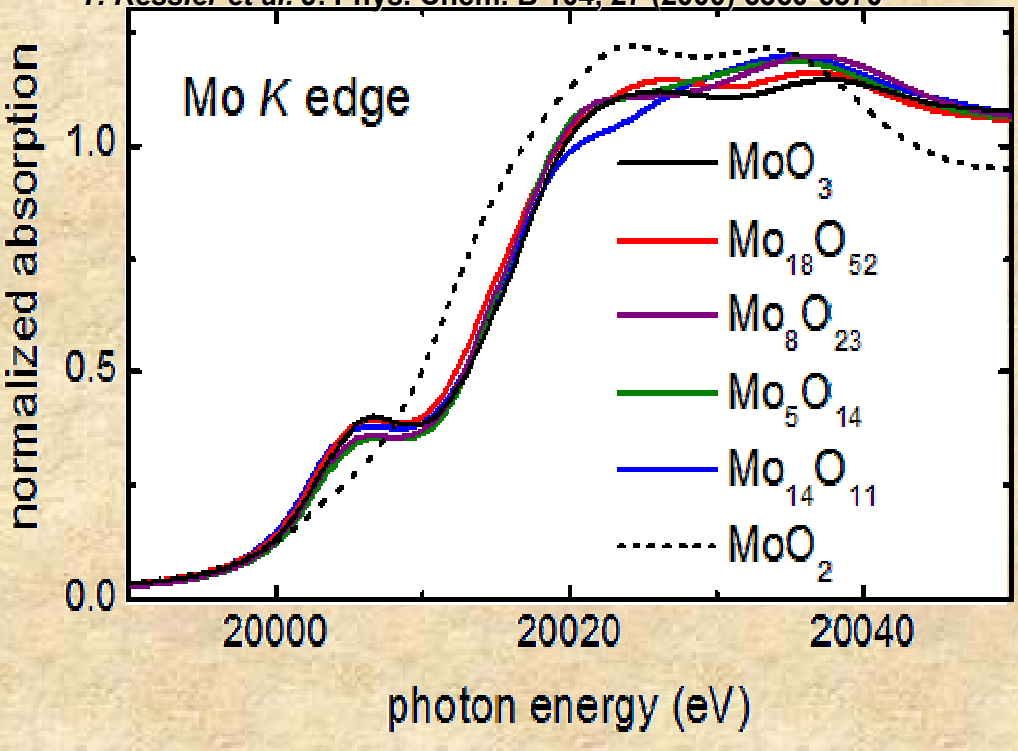
pre-peak:

- **initial state = $1s$ (l=0)**
- **states near E_F are formed by nd electrons (l=2)**

central-symmetry	non-central symmetry
no any peaks	There is a pre-edge peak



T. Ressler et al. J. Phys. Chem. B 104, 27 (2000) 6360-6370

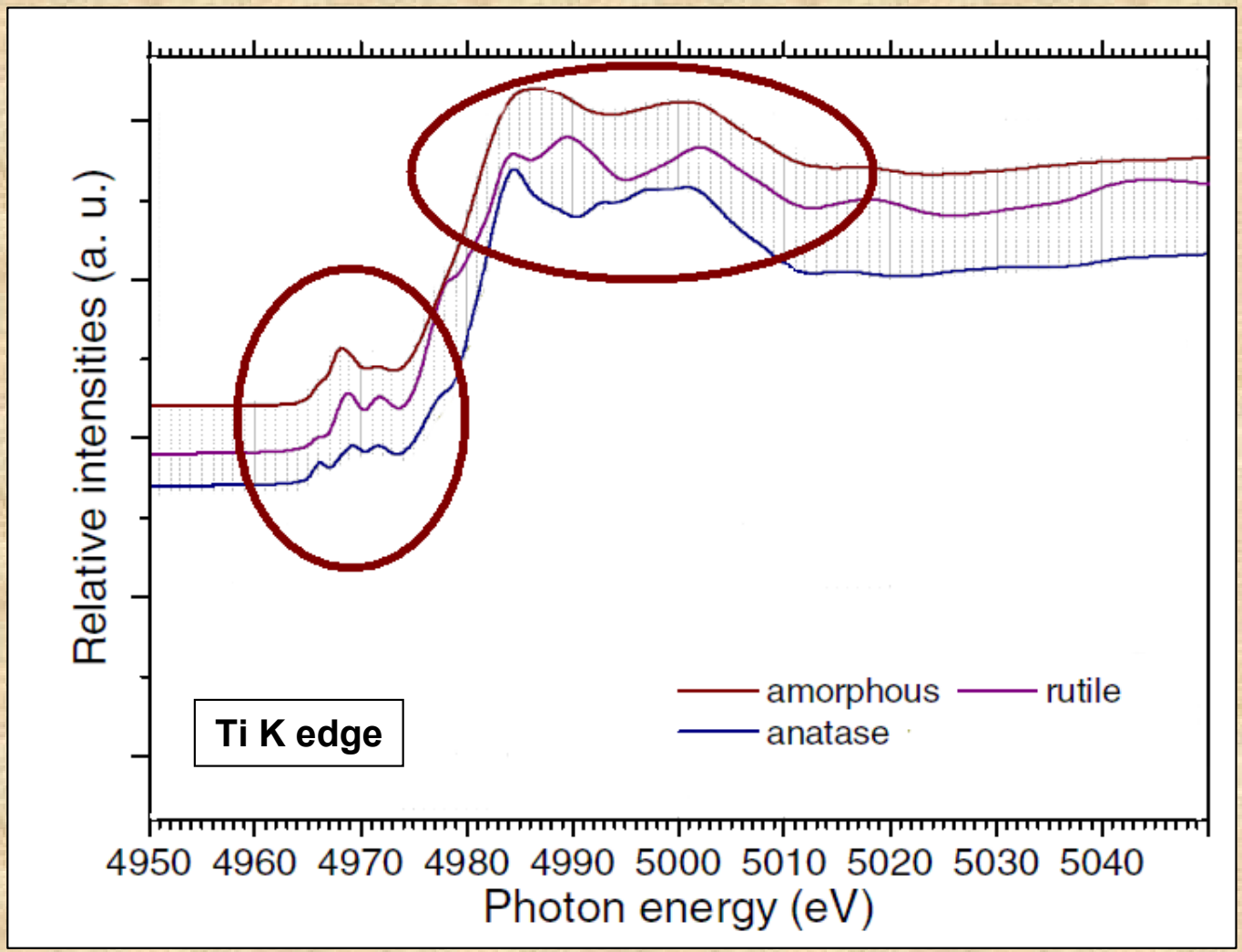


K edges

XANES: Qualitative analysis

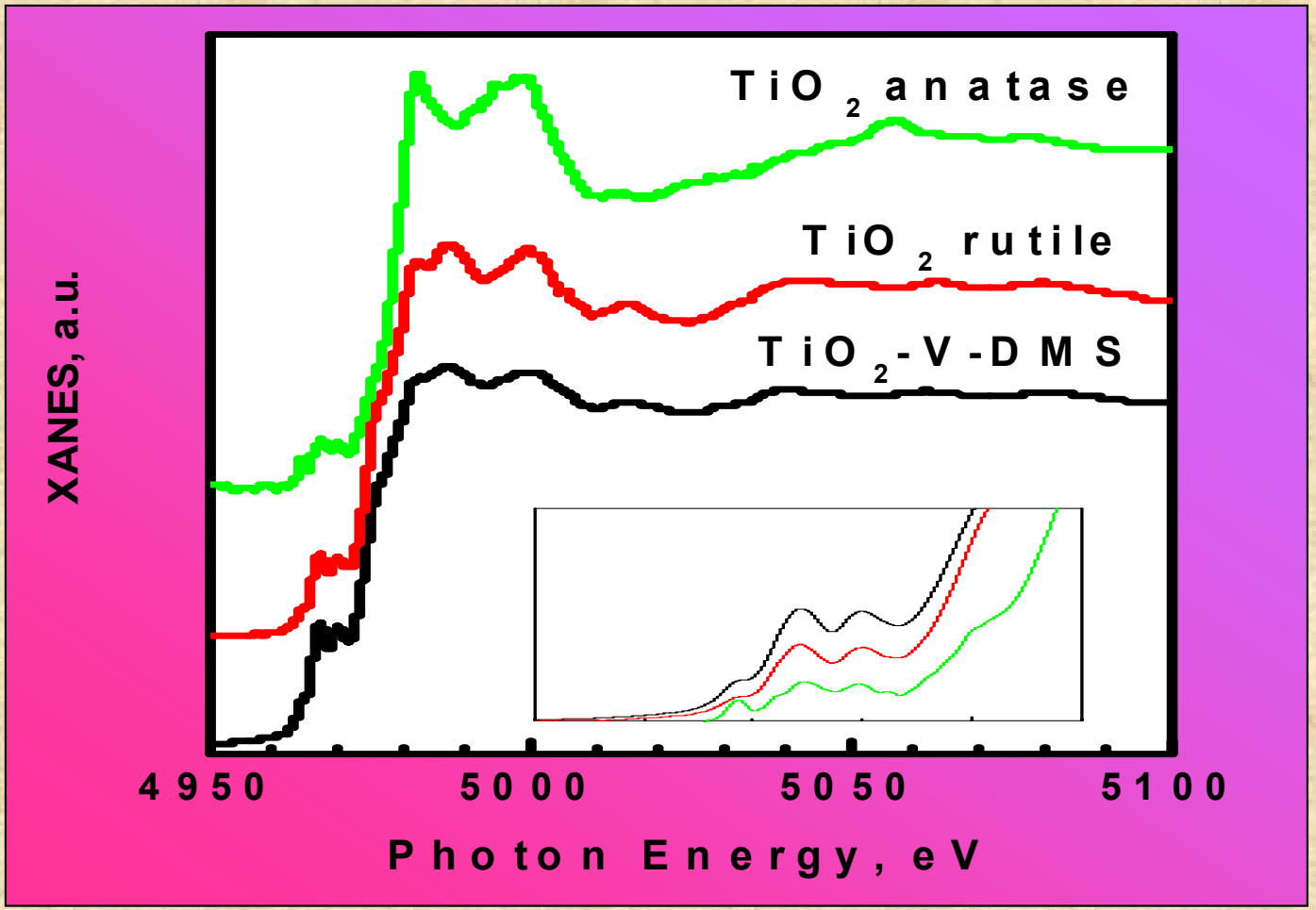
pre-peak:

TiO2



Ti K edge

XANES: Qualitative analysis

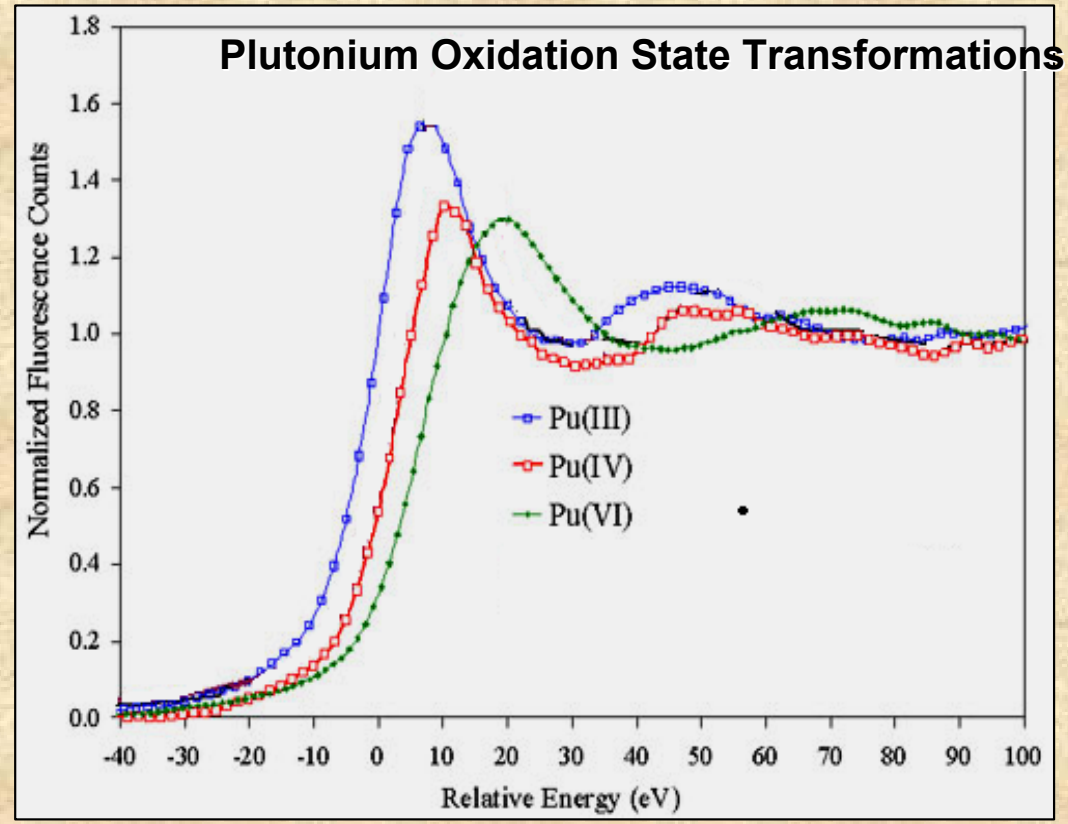


XANES spectra recorded at the Ti K edge for TiO2:V(3%) thin film [experiment has been done at the Kurchatov Institut (Russia)]

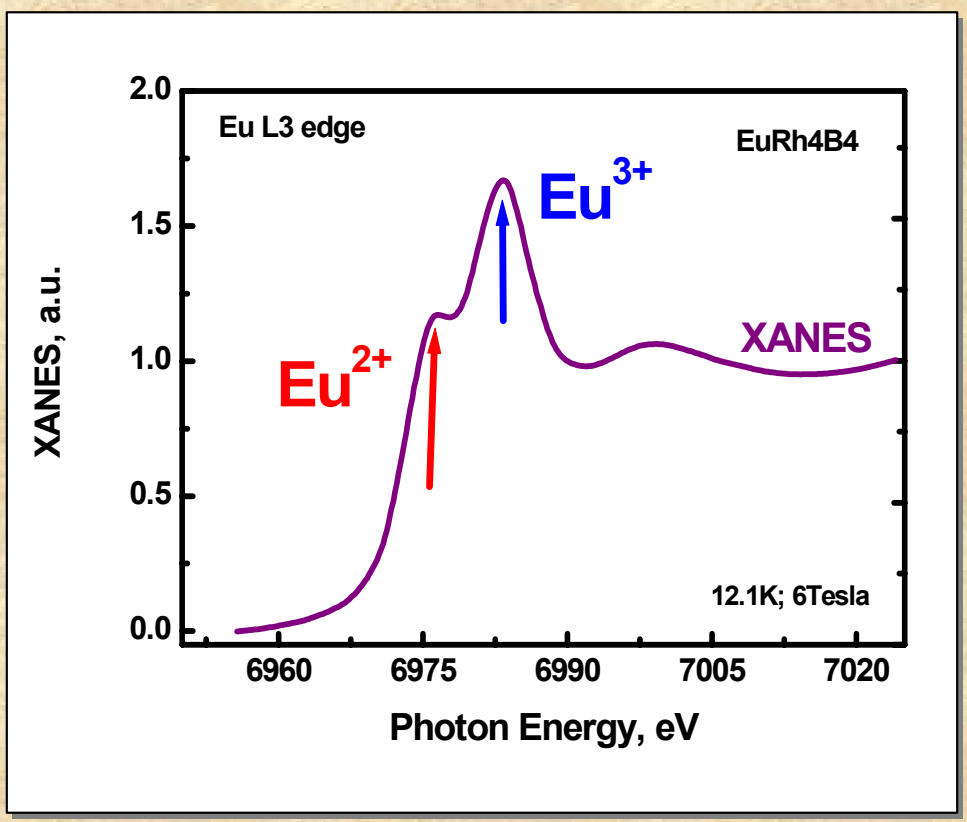
valence states: XANES: Qualitative analysis

Why does it shift?

- **Electrostatic: it is harder for the photoelectron to leave an oxidized atom**
- **Shorter bonds at higher oxidation states ⇒ Fermi energy is higher**



Environ. Sci. Technol., 41(21): 7417–7423 (2007)



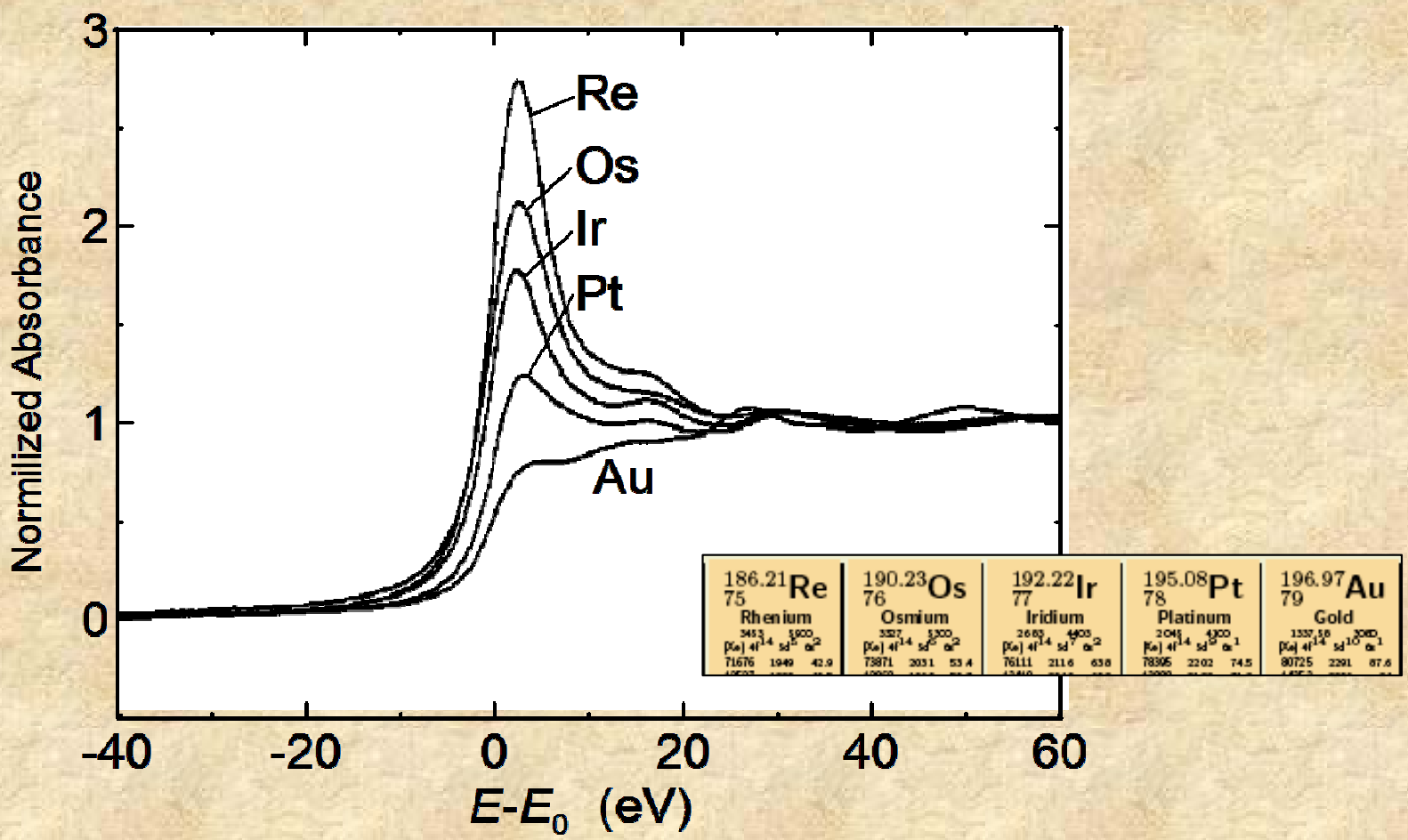
A. Smekhova et al. Solid State Phenomena, 190, pp.421-424 (2012)

White line intensity

XANES: Qualitative analysis

L_3 absorption edges for 5*d* metals:

(transition $2p_{3/2} \rightarrow 5d$)



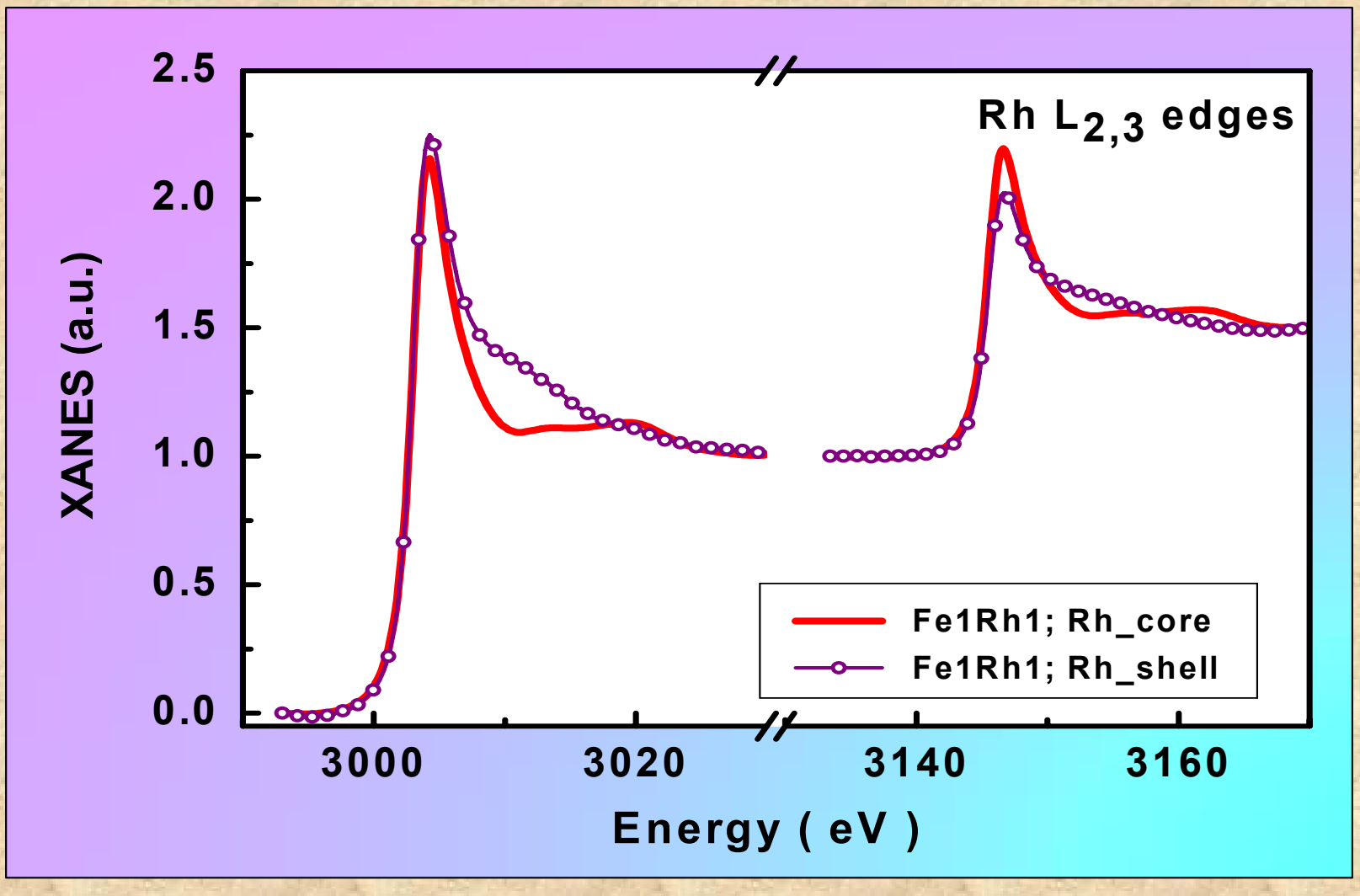
Intensity is proportional to the number of free 5*d* *st*ates + it depends on valence state

G. Meitzner, G. H. Via, F. W. Lytle, and J. H. Sinfelt,
J. Phys. Chem. 96 (1992) 4960

XANES: Qualitative analysis

White line shape

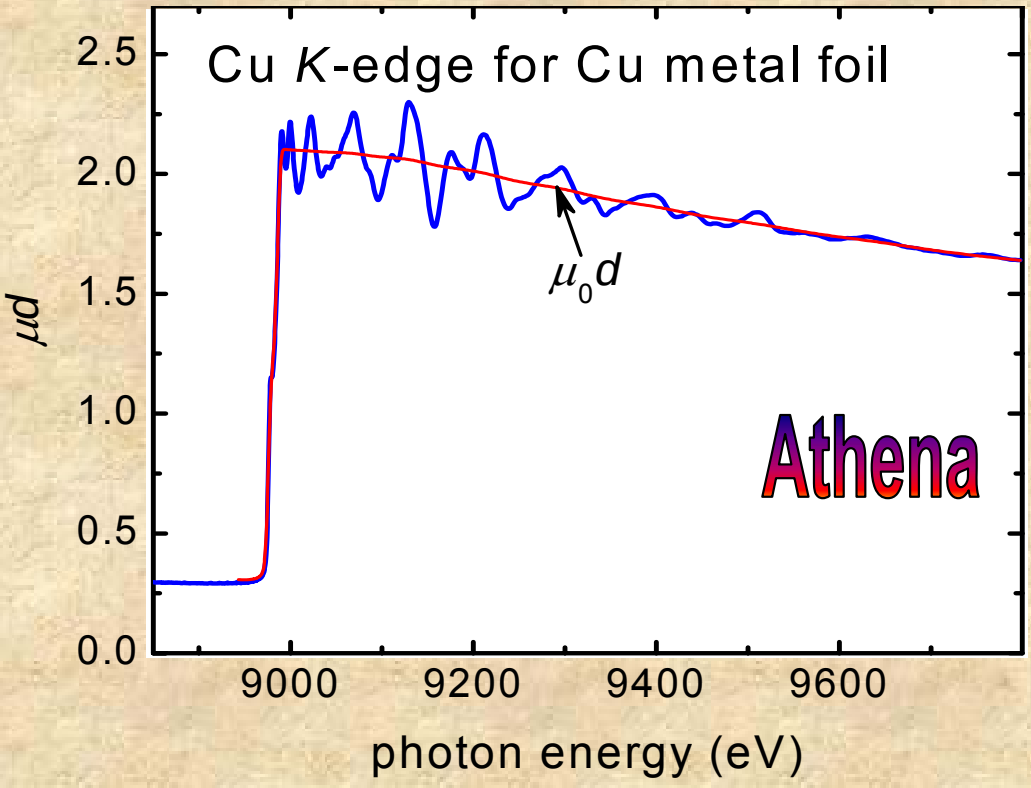
Rh@Fe and Fe@Rh

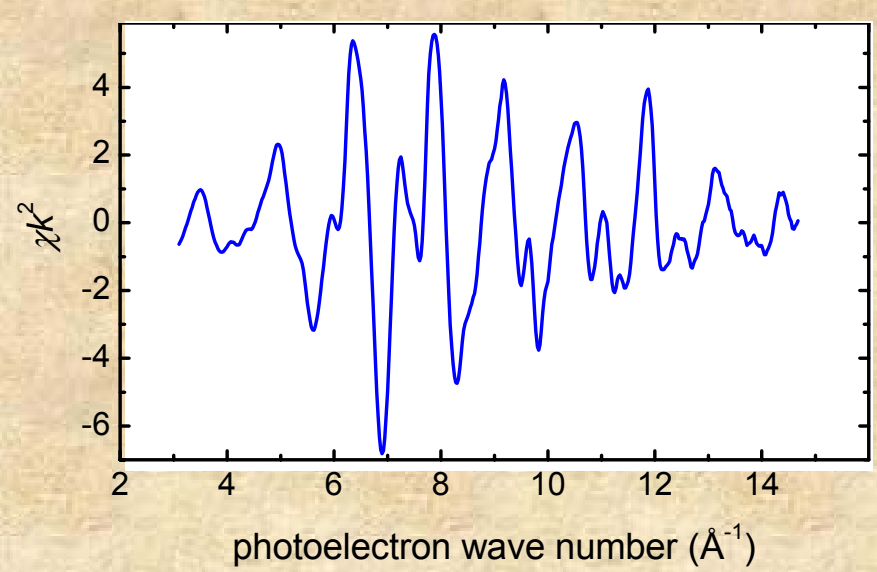


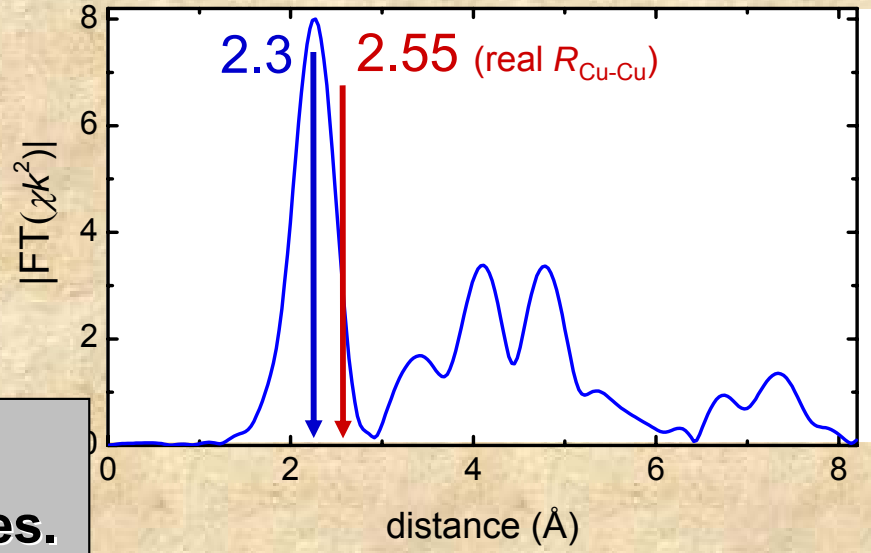
A. Smekhova et al., J. of Physics.: Conference Series, 200, p.072091 (2010)

EXAFS: Data analysis

$$\mu = \mu_0 (1 + \chi),$$







Unpleasant things:

FT positions are shifted towards small distances.

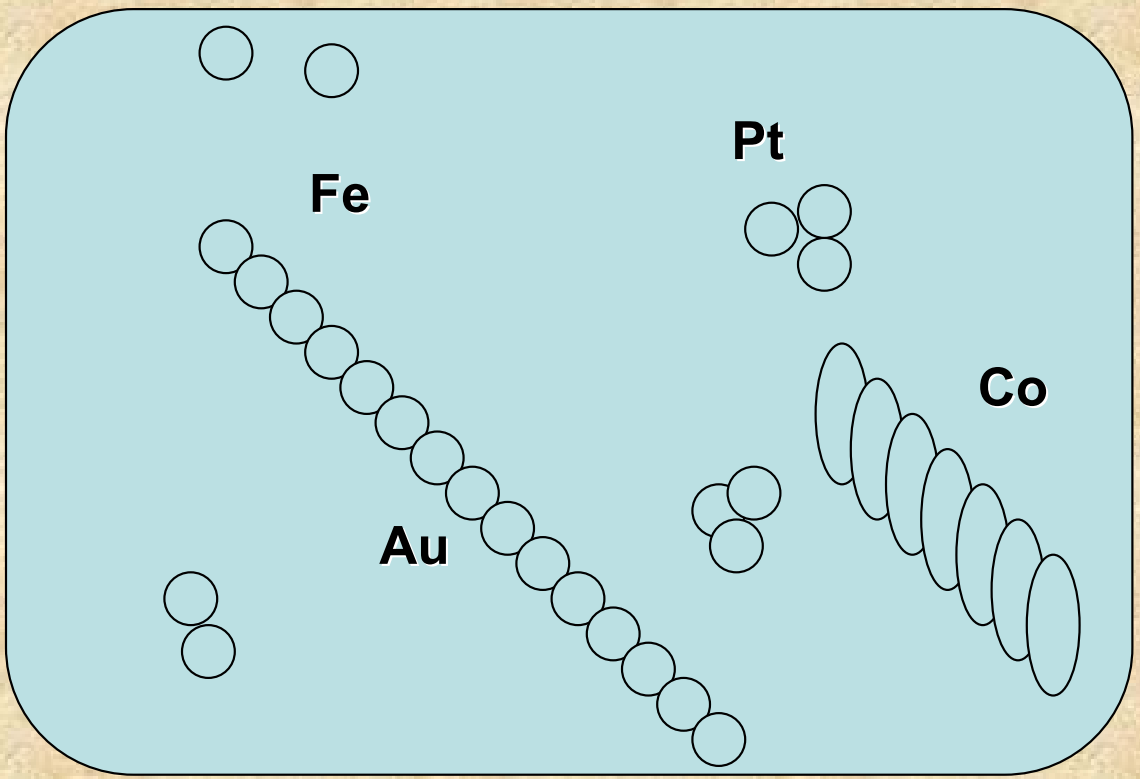
More unpleasant: Each FT peak has its own shift.

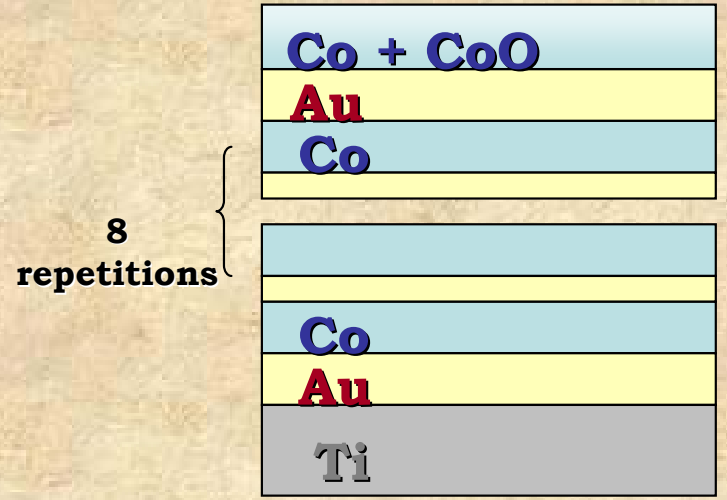
Samples:

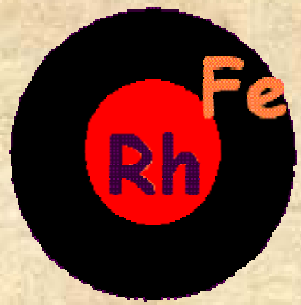
- **General requirements**
  - uniform on a scale of the absorption length of the material (typ. ~ 10 μm)
- **Shape, aggregative state**
  - Solids: powders, foils etc.; single crystals and thin foils can utilize polarization properties of SR.
  - Liquids
  - Gases
- **Concentrations**
  - for transmission: typ. >1 wt%
  - for fluorescence: typ. >100 ppm

TiO_2 : V (?%)

When you have a complex object...







... the spectroscopy could help you...

XAS for magnetism:

XAS for magnetism:

On a question about the magnetic rotation of plane polarised primary X-rays

Zeitschrift fur Physik, 39, 886-900 (1926)

886

Zur Frage nach der magnetischen Drehung der Polarisationsebene primärer Röntgenstrahlen.

Von W. Kartschagin und E. Tschetwerikowa in Moskau.

Mit 3 Abbildungen. (Eingegangen am 16. September 1926.)

In der vorliegenden Arbeit wurde eine Wirkung des magnetischen Feldes auf die Polarisationsebene der Röntgenstrahlen bei ihrem Durchgang durch Paraffin und Eisen untersucht. Auf Grund der Resultate der Arbeit und der Versuche bei einigen Annahmen, die Folgerungen der Elektronentheorie der Dispersion auf die zu behandelnde Frage anzuwenden, ziehen wir folgenden Schluß: Beim Durchgang primärer Röntgenstrahlen durch Paraffin kann die magnetische Drehung der Polarisationsebene wegen der Kleinheit des Drehungswinkels nicht beobachtet werden. Beim Durchgang der primären Strahlen durch Eisen kann man eine Drehung der Polarisationsebene erwarten, aber eine genaue Messung des Drehungswinkels ist sehr schwierig.

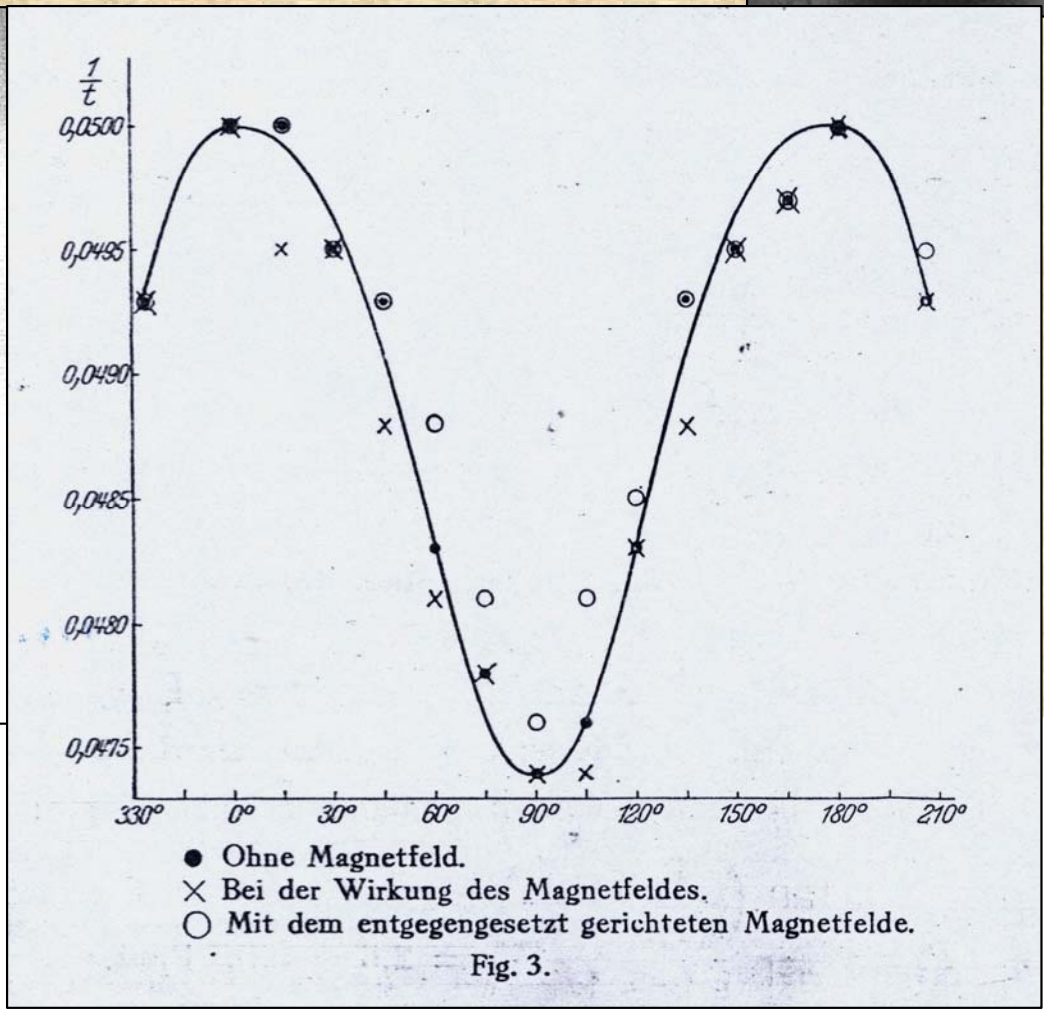


Fig. 3.

In this work, an effect of a magnetic field on plane polarised X-rays scattered by Paraffin and Iron is studied. Far from the absorption edge the rotation can not be observed due the weakness of the rotation angle. Whereas at an absorption edge of ferromagnetic materials one can expect to measure the magnetic rotation eventhough precise measurements are very difficult.

courtesy to A.Rogalev

XAS for magnetism:

The first serious theoretical approach to the problem

PHYSICAL REVIEW B VOLUME 12, NUMBER 11 1 DECEMBER 1975

Calculation of the M_{23} magneto-optical absorption spectrum of ferromagnetic nickel

J. L. Erskine*
Department of Physics, University of Illinois, Urbana, Illinois 61801

E. A. Stern†
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 28 April 1975)

The M_{23} magneto-optical absorption spectrum of ferromagnetic nickel is calculated using an approach similar to the component state-density method that has been successfully used in obtaining valence-band emission and absorption x-ray spectra of metals. The M_{23} magneto-optical effects result predominantly from spin-orbit splitting of the $3p$ core state in conjunction with the final d-state spin polarization. The calculated spectrum exhibits features that are directly related to electronic structure parameters including the $3p$ core spin-orbit splitting, and the unfilled d-band spin polarization. Temperature variations in the magneto-optical structure can be used to determine separately the exchange-splitting variation and spin-wave excitation contributions to the decrease in the magnetization. Experimental verification of these predictions should provide insight into the applicability of the Stoner model to ferromagnetic nickel and may be helpful in resolving some of the apparently conflicting results of other experimental probes of the spin polarization near the Fermi level in nickel.

courtesy to A.Rogalev

XAS for magnetism: XMCD technique

XMCD is a major discovery in magnetism during the last 20 years

First experimental evidence

VOLUME 58, NUMBER 7 PHYSICAL REVIEW LETTERS 16 FEBRUARY 1987

Absorption of Circularly Polarized X Rays in Iron

G. Schütz, W. Wagner, W. Wilhelm, and P. Kienle [a]
Physik Department, Technische Universität München, D-8046 Garching, West Germany

R. Zeller
Institut für Festkörperforschung der Kernforschungsanlage Jülich, D-5175 Jülich, West Germany

and

R. Frahm and G. Materlik
Hamburger Synchrotronstrahlungslabor am Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg 52, West Germany

(Received 22 September 1986)

The transmission of synchrotron radiation through magnetized iron at energies above the *K*-absorption edge shows relative differences for right and left circular polarization of several times 10^{-4}. The observed spin dependence of the near-edge photoabsorption is proportional to the difference of the spin densities of the unoccupied bands. In the extended absorption region up to 200 eV above the Fermi level a small spin-dependent absorption is observed and thus is expected to give information on the magnetic neighborhood of the absorbing atom.

PACS numbers: 75.50.Bb, 75.10.Lp, 75.25.+z, 78.70.Dm

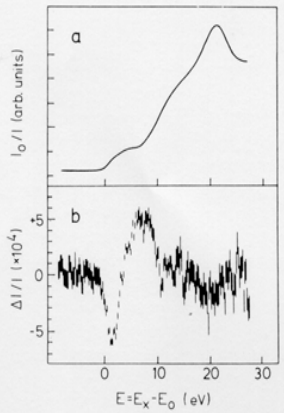


FIG. 1. (a) Absorption I_0/I of x rays as function of the energy E above the K edge of iron and (b) the difference of the transmission $\Delta I/I$ of x rays circularly polarized in and opposite to the direction of the spin of the magnetized d electrons.

XMCD is a new approach to study ferromagnetic system

RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 42, NUMBER 11 15 OCTOBER 1990-I

Rapid Communications

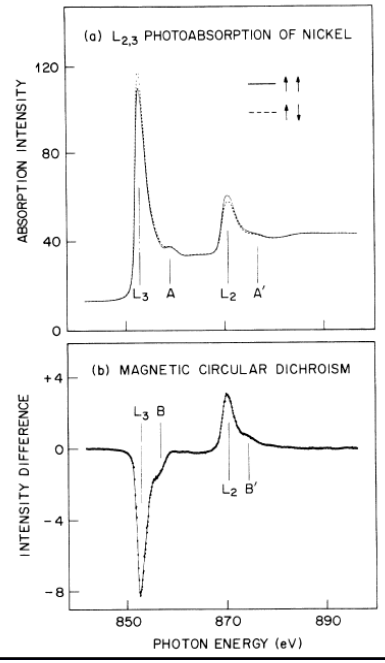
Rapid Communications are intended for the accelerated publication of important new results and are therefore given priority treatment both in the editorial office and in production. A Rapid Communication in **Physical Review B** *should be no longer than 4 printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

Soft-x-ray magnetic circular dichroism at the $L_{2,3}$ edges of nickel

C. T. Chen, F. Sette, Y. Ma, and S. Modesti
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

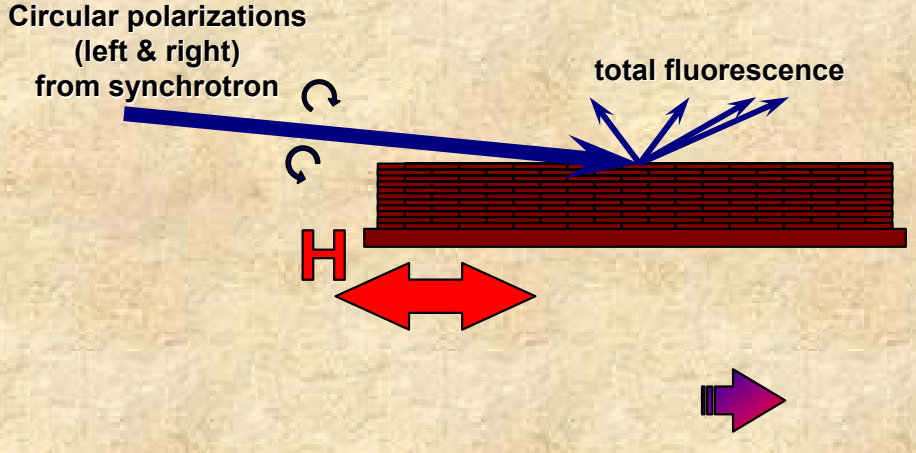
(Received 2 March 1990)

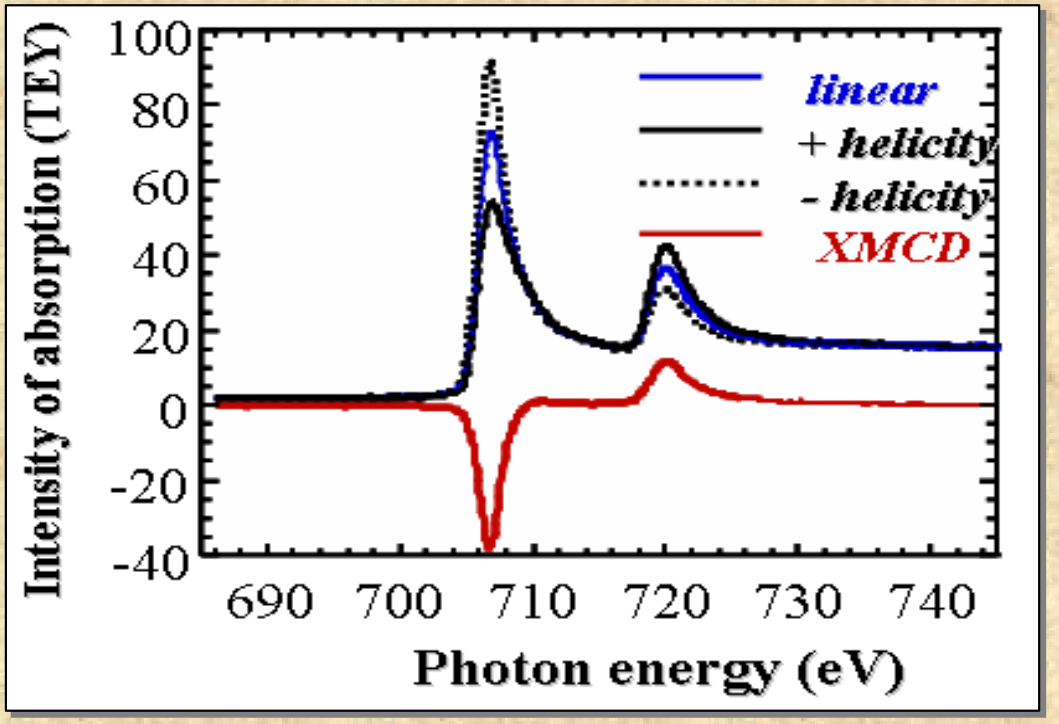
Magnetic circular dichroism (MCD) has been observed at the $L_{2,3}$ absorption edges of ferromagnetic nickel by use of circular-polarized soft-x-ray synchrotron radiation. The MCD intensity ratio between the L_2 and the L_3 edges is found to differ appreciably from that predicted by a simple exchange-split-valence-band model. Fine MCD features, imperceptible in the absorption spectra, are also observed and a tentative interpretation is given. This work, demonstrating the feasibility of MCD measurements in the soft-x-ray region, provides a new approach to study $3d$ and $4f$ ferromagnetic systems with their respective dipole-permitted $2p \rightarrow 3d$ and $3d \rightarrow 4f$ transitions.



courtesy to A.Rogalev

XMCD (X-Ray magnetic circular dichroism) technique:





XMCD is the difference in absorption of right and left circular polarizations, when the wave vector of incidence radiation is collinear to sample magnetization, and allows one

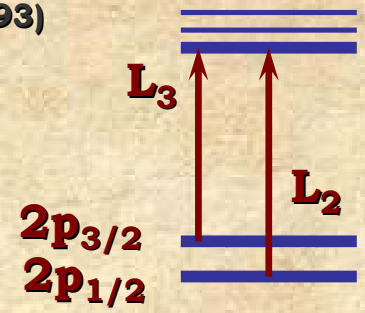
to determine directly from the experimental L2.3 absorption spectra the amplitude and the direction of the spin and orbital contributions into the total magnetic moment of atoms by means of Sum Rules

Sum Rules analysis:

B.T. Thole, P. Carra , F. Sette, G. van der Laan; PRL68, 1943 (1992)
P. Carra, B.T. Thole, M.Altarelly, X.Wang; PRL70, 694 (1993)

L- edges!!!

$L_{2,3}$-edges correspond to transitions from $2p_{1/2}$ and $2p_{3/2}$ core levels to unoccupied nd states near Fermi energy in valence band



→ **probe spin and orbital magnetism of n*d* states**

in dipolar approximation $\Delta l=\pm1$; $\Delta s=0$; $\Delta m_l=\pm1$; $\Delta m_s=0$

$$M_L = -\frac{2}{3}C(\Delta L_3 + \Delta L_2)$$

$$M_S^{eff} = -C(\Delta L_3 - 2\Delta L_2) + 7\langle T_Z^d \rangle$$

$$C \propto \frac{n_h}{A_{L_3} + A_{L_2}}$$

Spin magnetic dipole operator, which is associated with an asphericity of the spin density distribution

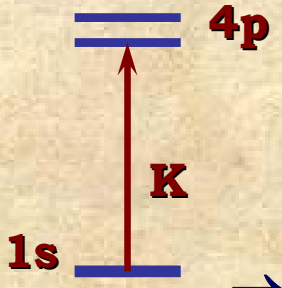
Tz is important for low-dimensional and anisotropic samples (up to 30 %)

ΔL ~ difference in the integrated intensity for right and left polarisations

A_L ~ integrated intensity of transitions

n_h - number of 4*d*- holes

Sum Rules analysis:



K -edge corresponds to transitions from 1s core level to unoccupied nd states

→ **probe only orbital magnetism of n*p* states**

! sensitivity to the local magnetic environment !

K- edge

$$M_L = -C\Delta K, \qquad C \propto \frac{n_h}{A_K}$$

...but, since core level doesn't split, we havn't information about spin moment...

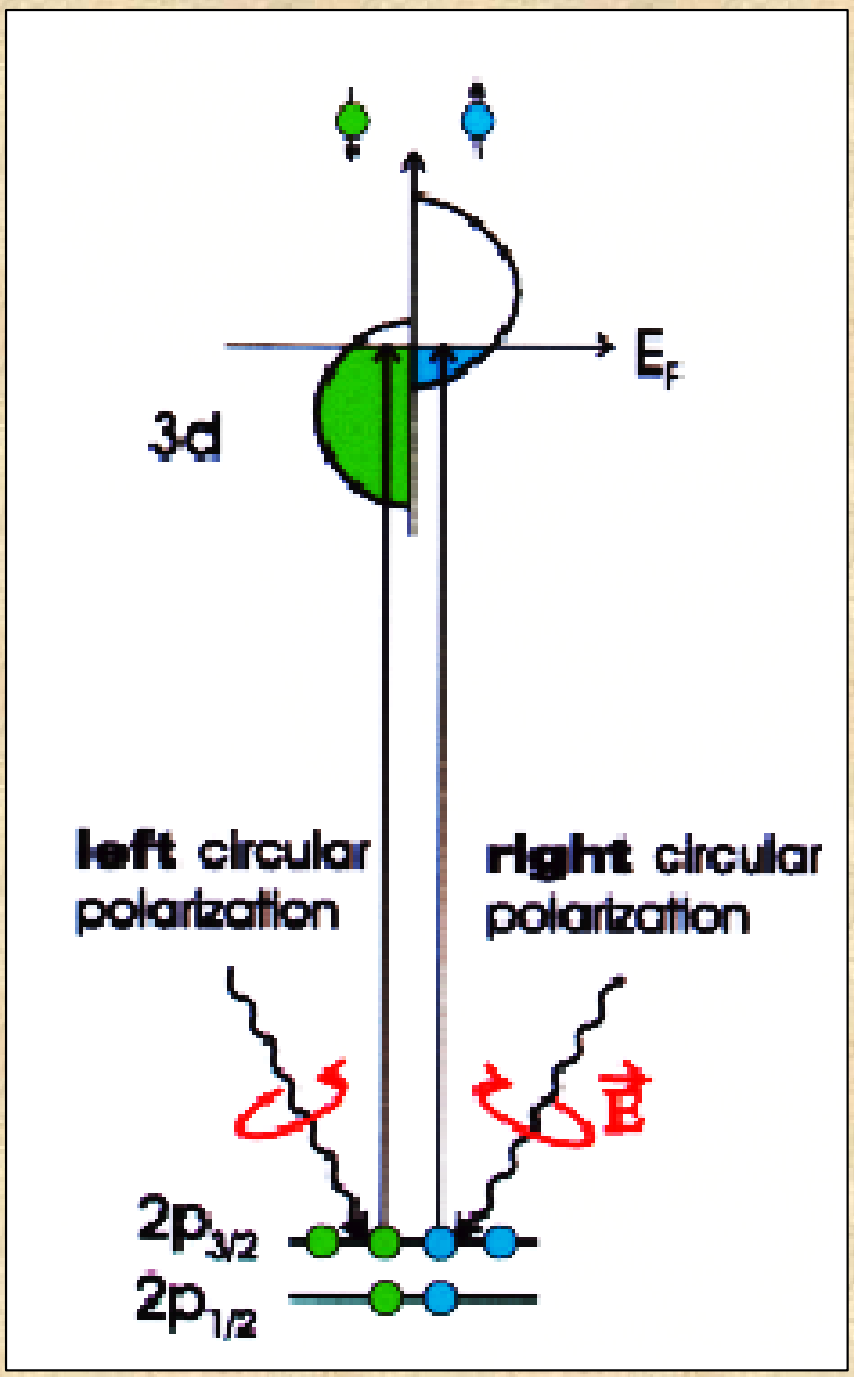
+ ...magnetic effects are much smaller than at L edges...

only qualitative analysis is possible

Difficulty:

- **determination of area A**
- **quadrupolar transitions not negligible**

XMCD:



XMCD is the direct probe of unoccupied spin up and spin-down density of states

Macroscopic Susceptibility Measurements

ESRF

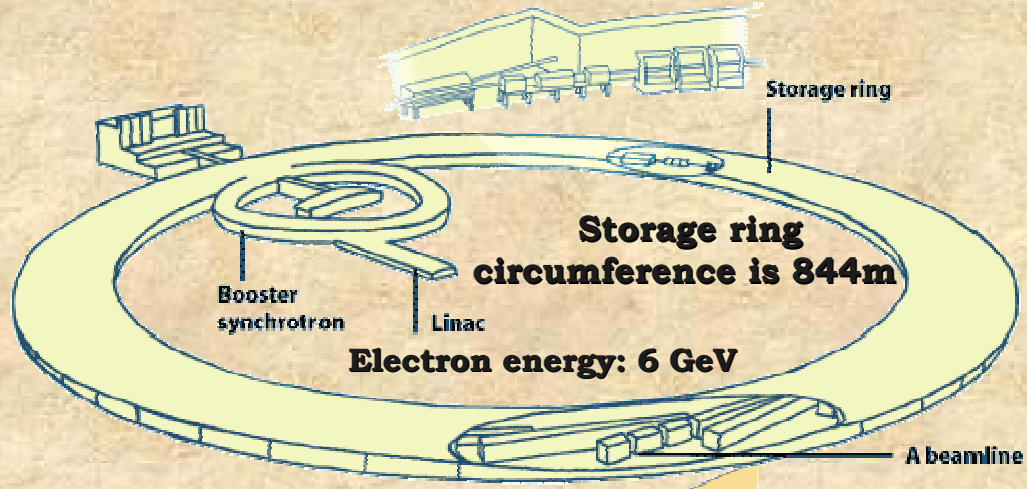
- Diamagnetic contribution
- All electrons (*s*, *p* and *d*) contribute
- Contribution of magnetic impurities

XMCD

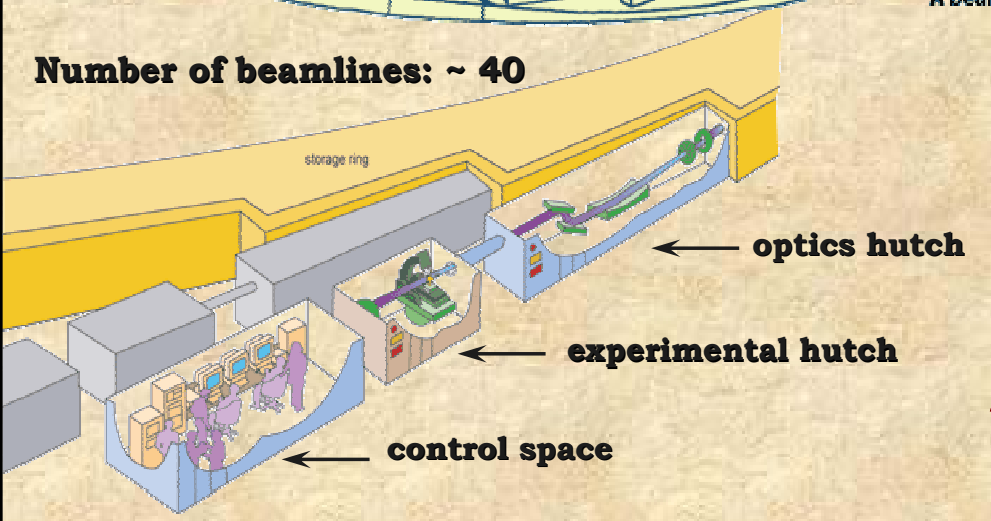
Proposed by H. Ebert *et al.*, *Synchrotron and Magnetism* , Lectures Notes in Physics (2001)

- to measure mainly magnetism of *d* states
- the separation of the *spin* and *orbital* susceptibilities
- *A priori is* not sensitive to diamagnetism

courtesy to A.Rogalev

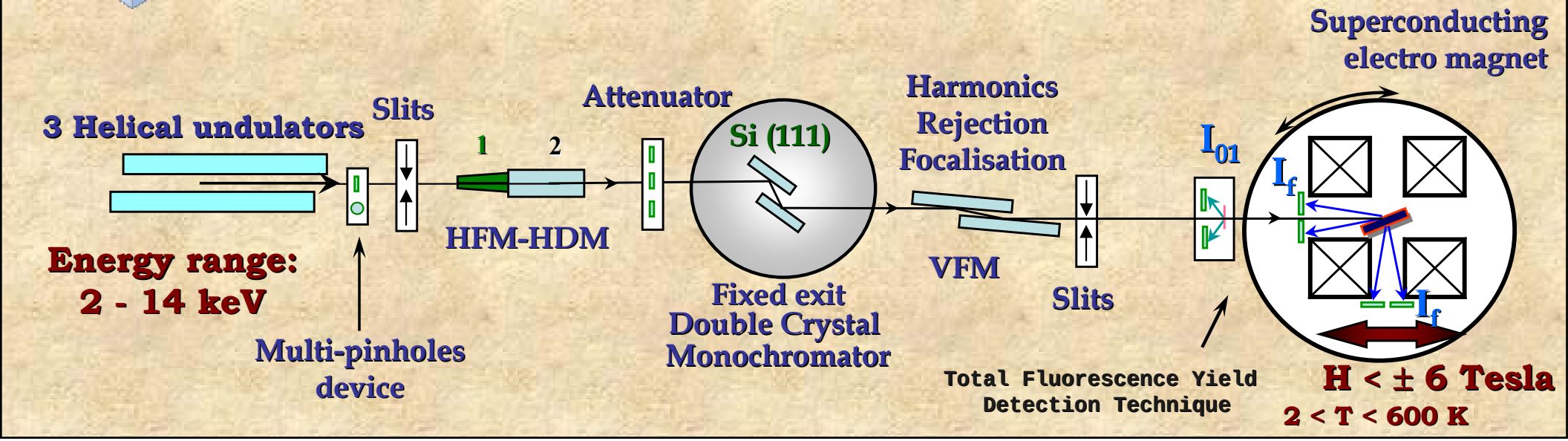


Number of beamlines: ~ 40

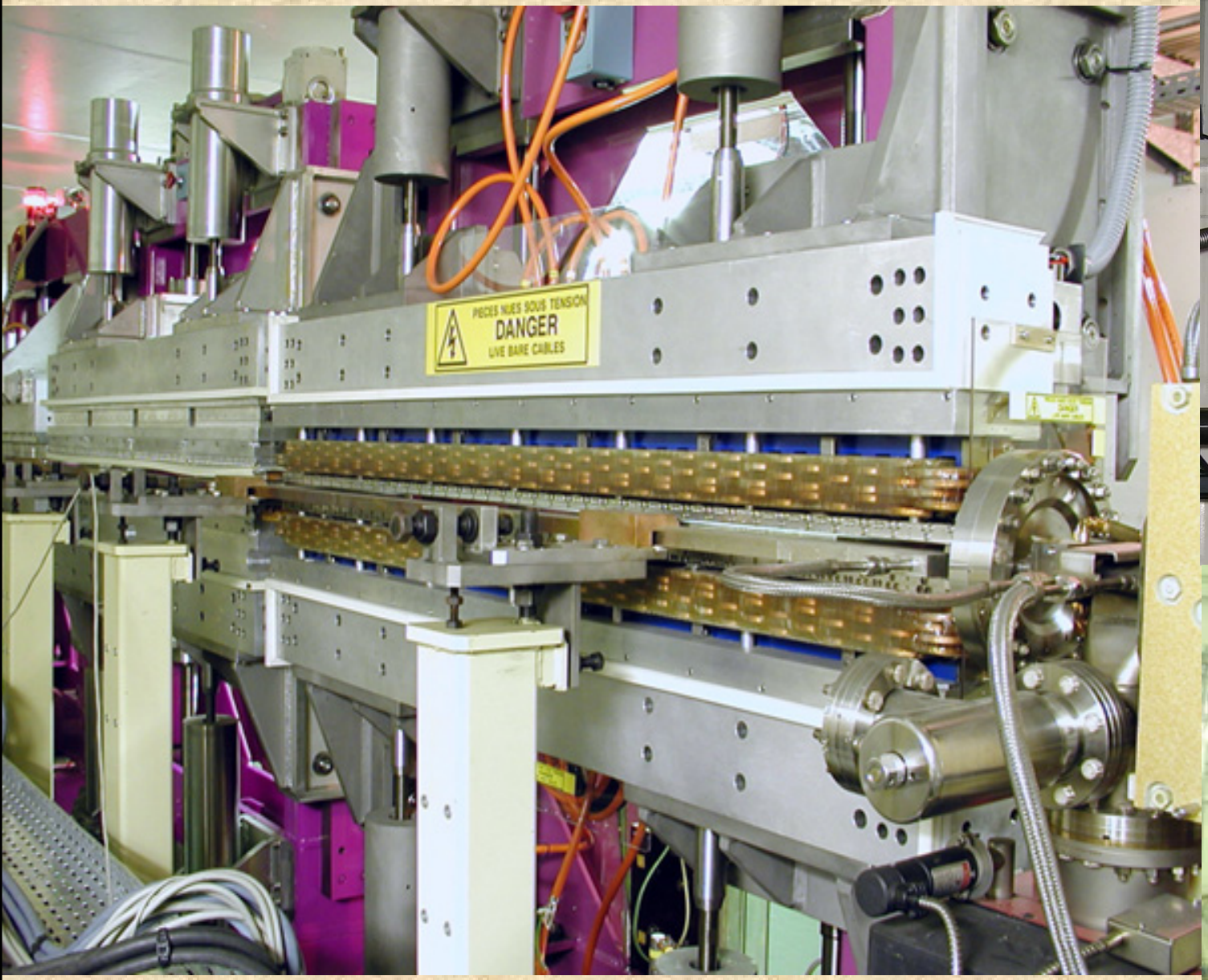


ID12 Beamline at the ESRF:

(main part)



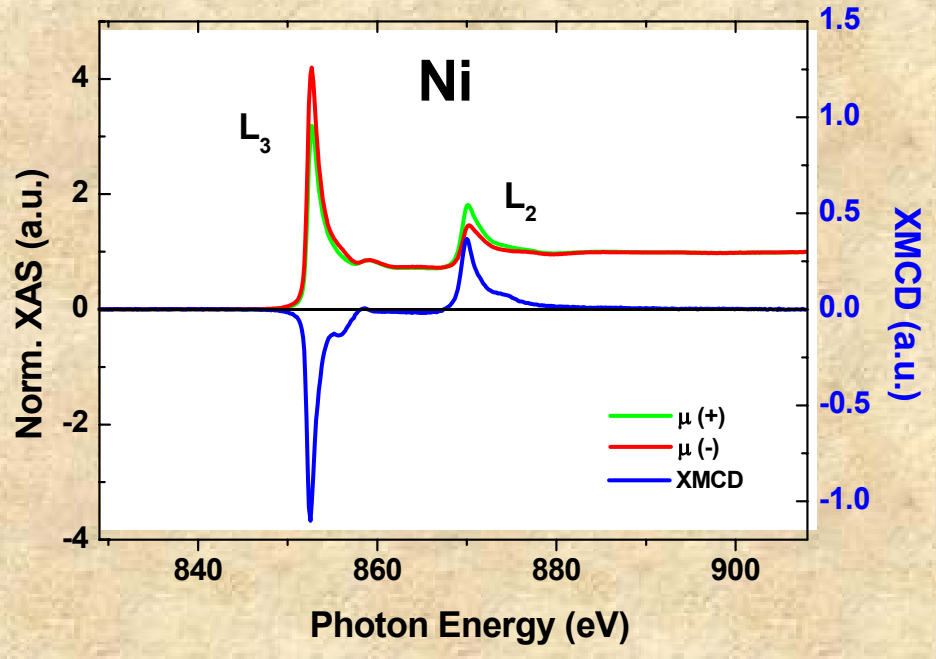
Undulator

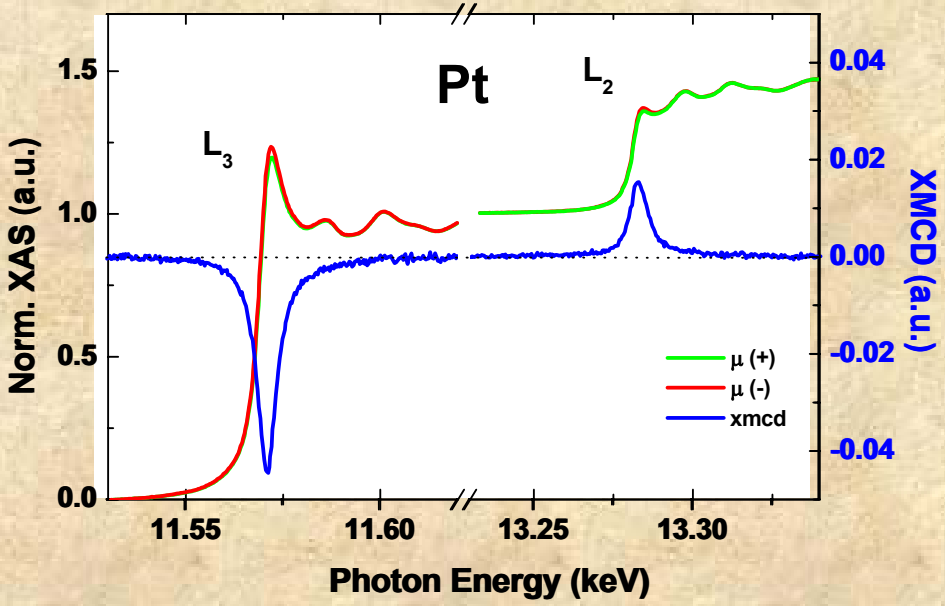


17 Tesla magnet

Element and Orbital Selectivity of XMCD:

ESRF



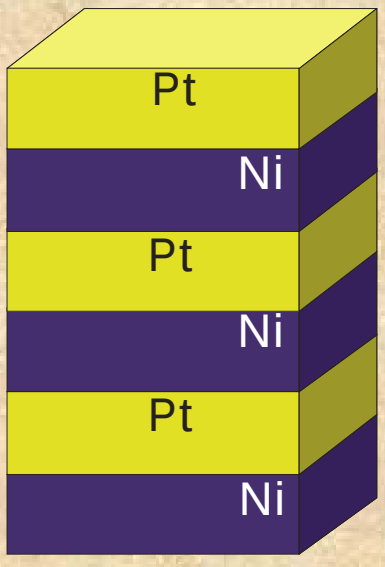


Induced magnetic moments:

Ni_2 / Pt_2 multilayer

T ~ 10K

H = ± 5 T



- **Ni magnetic moments:**

  μ_S^{3d}=0.35 μ_B/atom

  μ_L^{3d}=0.038 μ_B/atom

  μ_L^{3d}/μ_S^{3d} = 0.11

- **Pt induced magnetic moments:**

  μ_S^{5d}=0.14 μ_B/atom

  μ_L^{5d}=0.03μ_B/atom

  μ_L^{5d}/μ_S^{Pt} = 0.21

hybridization the Pt(5*d*)-Ni(3*d*)

F. Wilhelm et al., Phys. Rev. Lett., 85, 413 (2000)

courtesy to A.Rogalev

Induced Orbital and Spin moments of W:

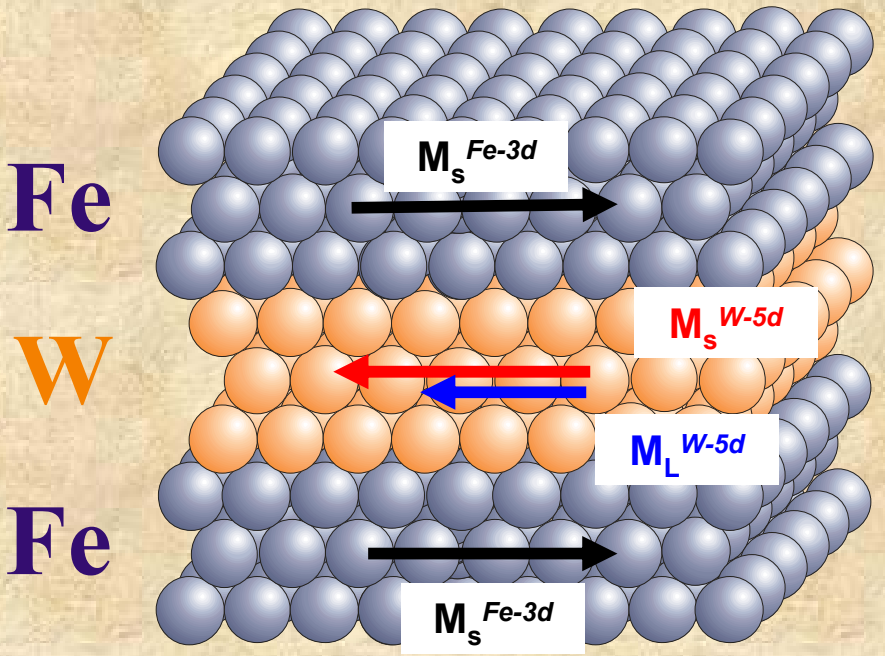
ESRF

$M_{spin}^{W\text{-}5d} = -0.17\ \mu_B/atom$

$M_{orbital}^{W\text{-}5d} = -0.015\ \mu_B/atom$

$M_{tot}^{W\text{-}5d} = -0.185\ \mu_B/atom$

$M_{orbital}^{W\text{-}5d}/M_{spin}^{W\text{-}5d} = +0.09$

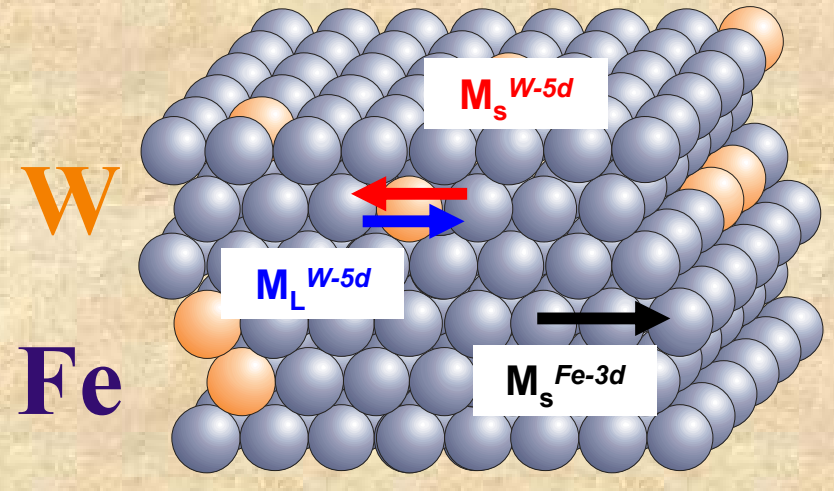


$M_{spin}^{W\text{-}5d} = -0.70\ \mu_B/atom$

$M_{orbital}^{W\text{-}5d} = +0.03\ \mu_B/atom$

$M_{tot}^{W\text{-}5d} = -0.67\ \mu_B/atom$

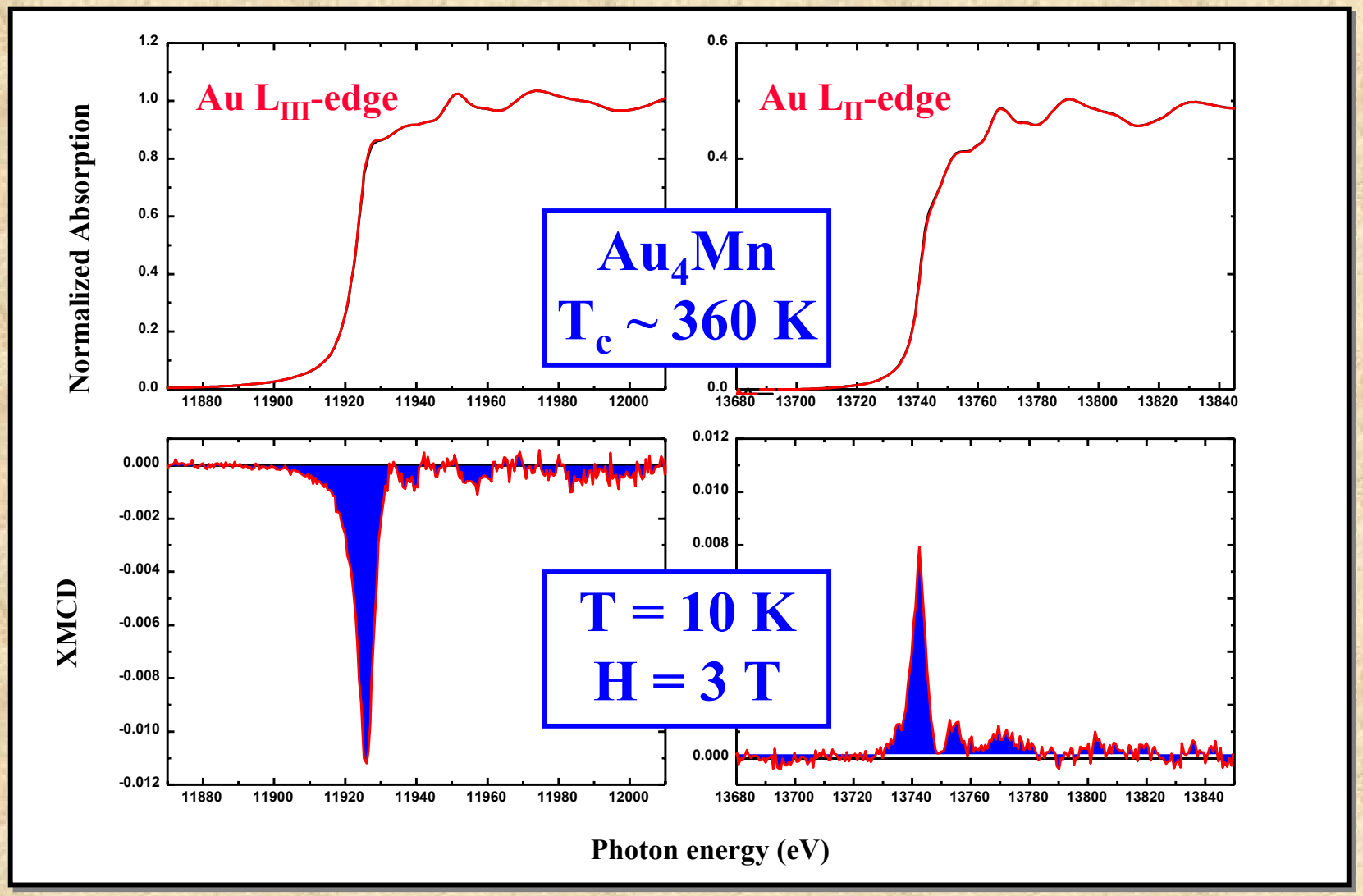
$M_{orbital}^{W\text{-}5d}/M_{spin}^{W\text{-}5d} = -0.043$



Dimensionality might break even the well-established atomic rules (third Hund's rule)

courtesy to A.Rogalev

Sensitivity of the XMCD technique:



$\langle S_z \rangle = 0.0353(5) m_B$ $\langle L_z \rangle = 0.0054(5) m_B$ (per Au atom)

(to compare with $4.15 m_B$ per Mn atom)

courtesy to A.Rogalev

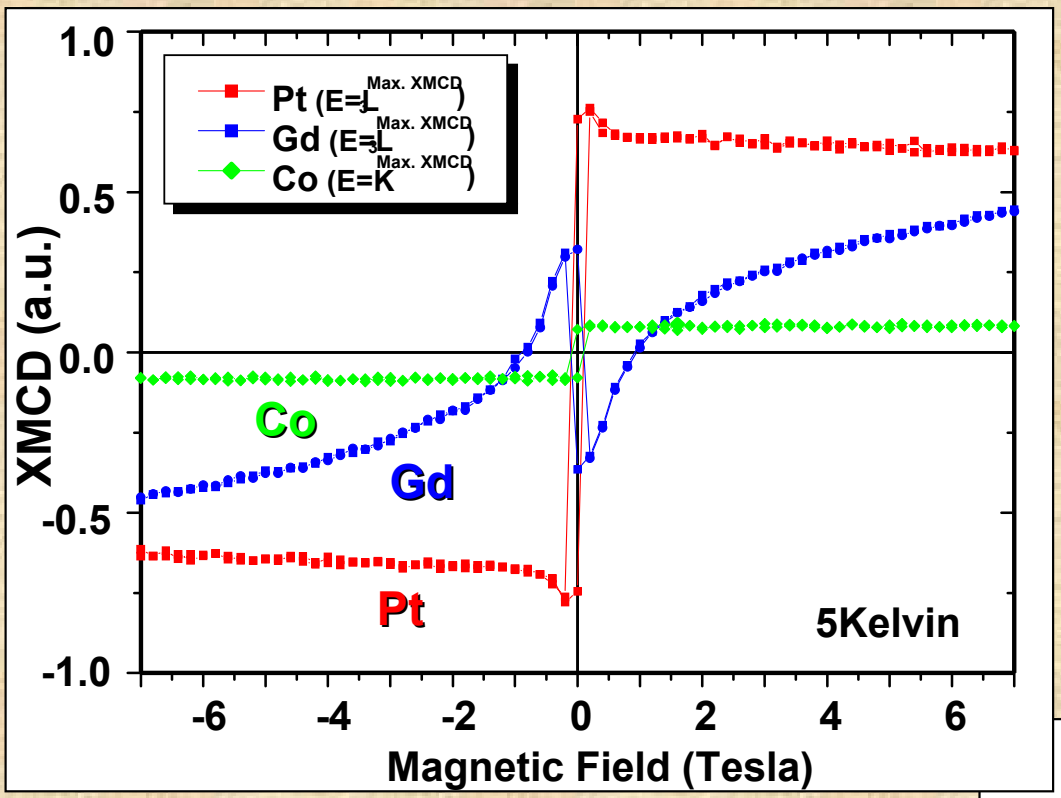
Element selective Hysteresis-loops in Co(17)/Pt(7)/Gd(16)/Pt(7) multilayer

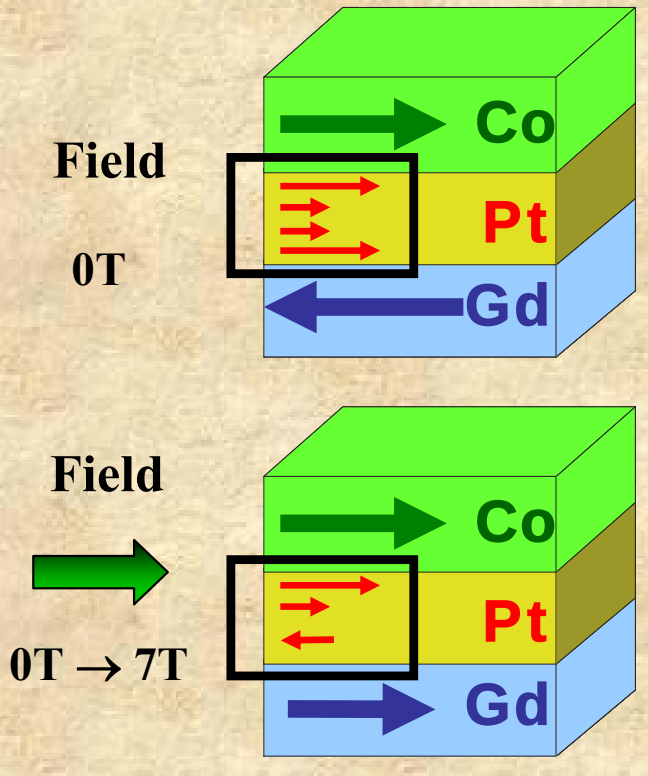
ESRF

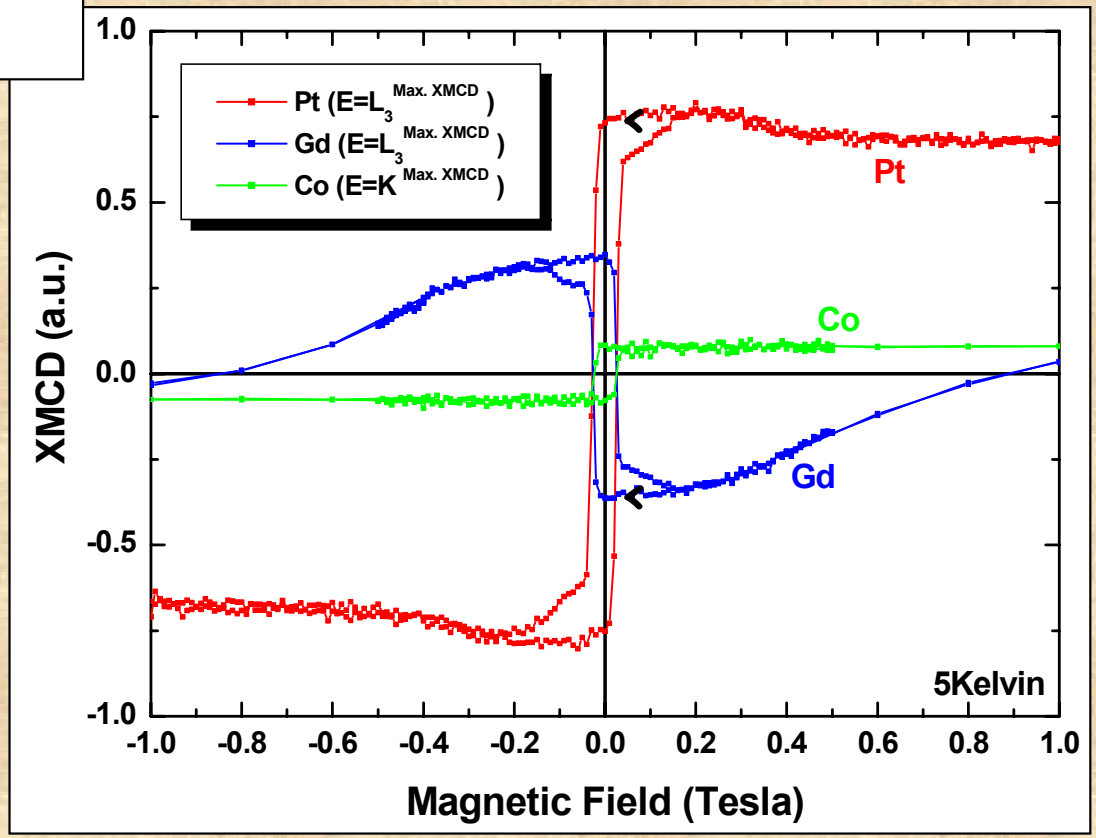
grazing incidence measurements

$\vec{H} \,//\, \vec{k}$

parallel geometry



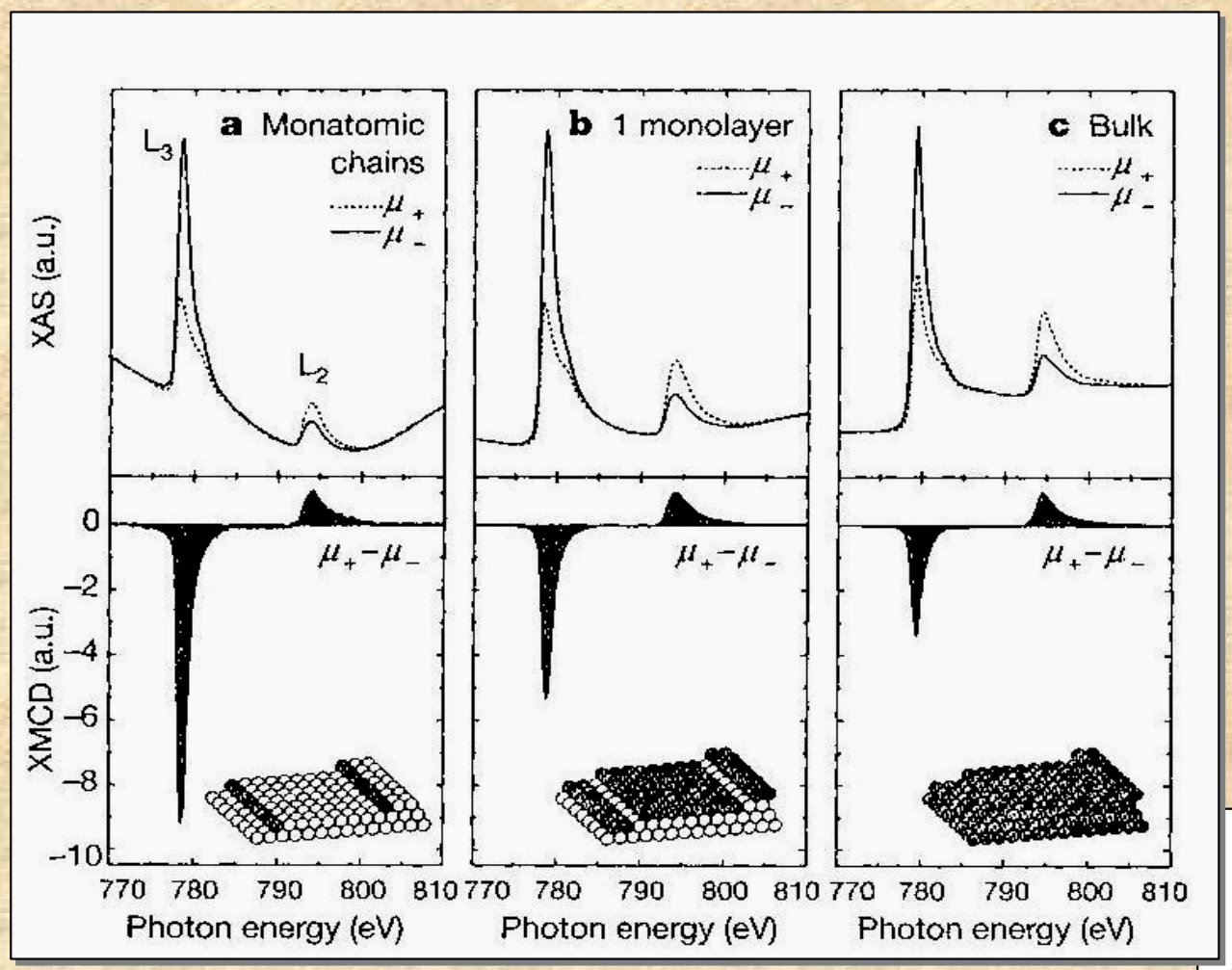


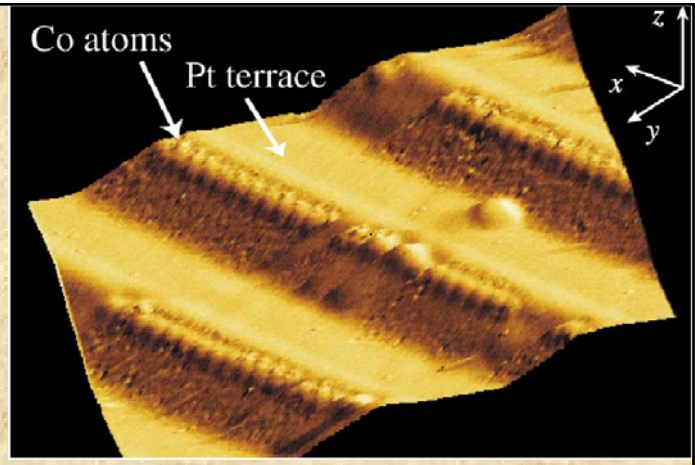


courtesy to A.Rogalev

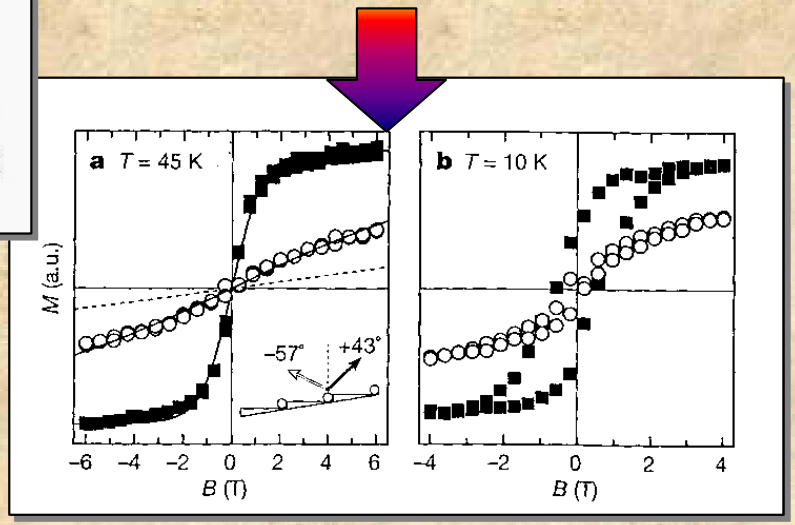
XMCD & size-effects:

Co atoms on Pt



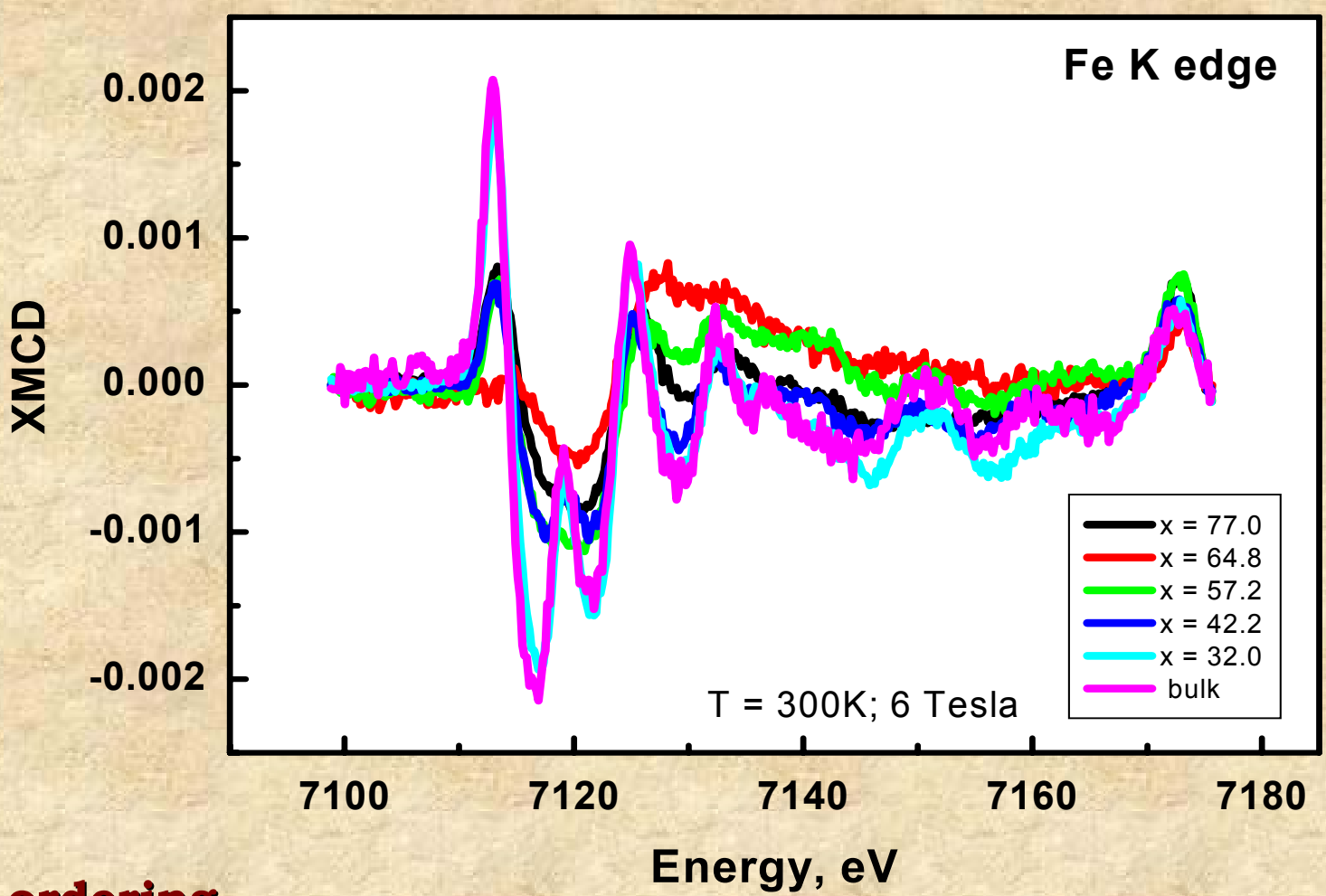


Magnetization of a monatomic wire array recorded at the Co L_3 edge along the easy direction (filled squares) and at 80o away from the easy direction (open circles)



P. Gambardella et al., Nature 416, 301 (2002)

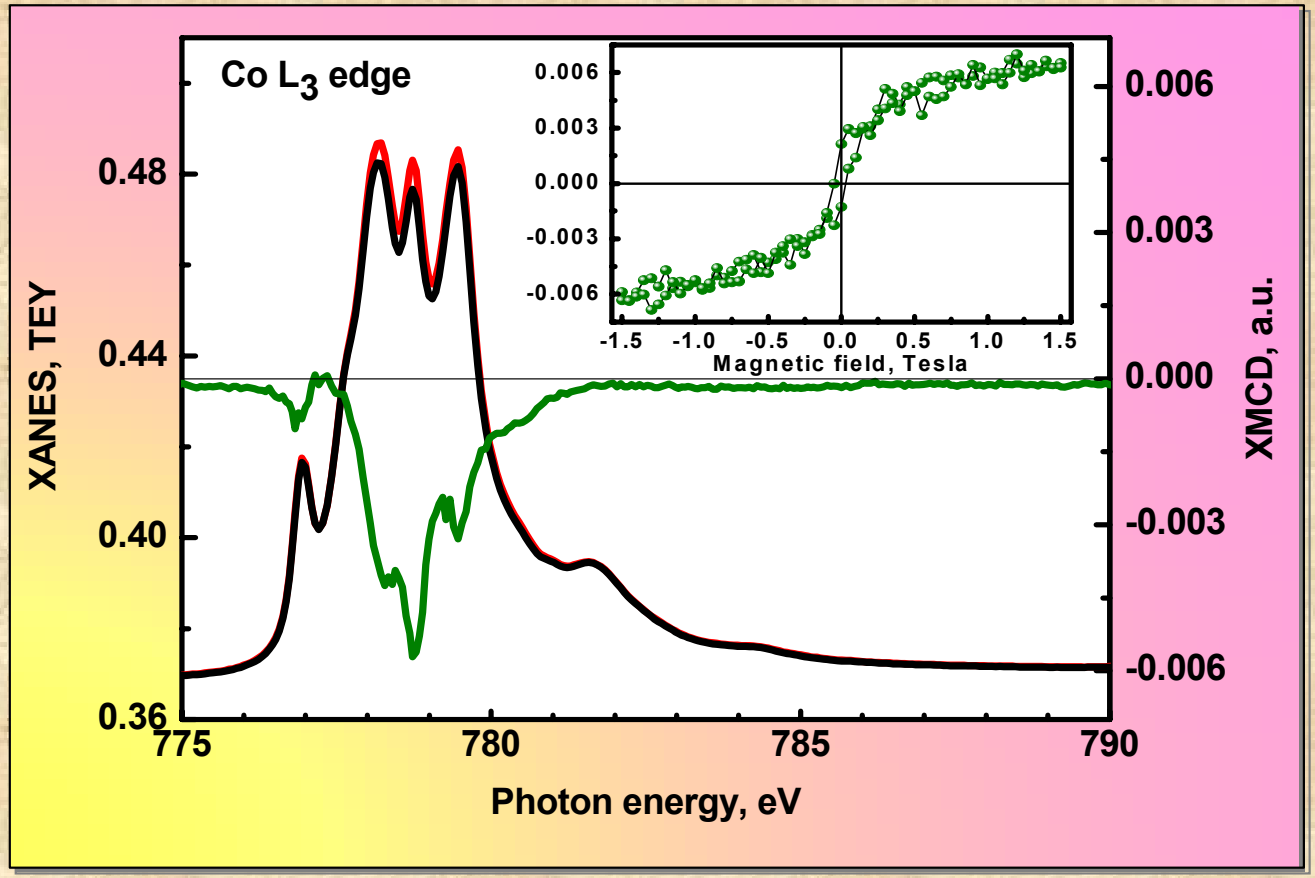
XMCD at K-edge:



- **probe of ordering**

$(FePt)_{100-x}(SiO2)_x$ granular thin films:

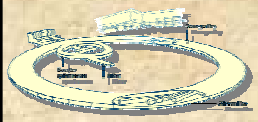
XMCD at L3-edge for DMS:



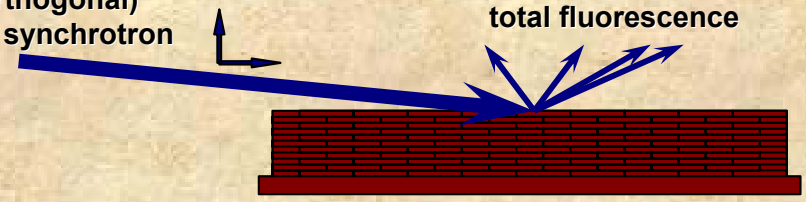
XANES (left scale) and XMCD (right scale) spectra and corresponded element-selective hysteresis loop (inset) recorded at the Co L3 edge for TiO2:Co(8%) thin film [experiment has been done at the ESRF (France)]

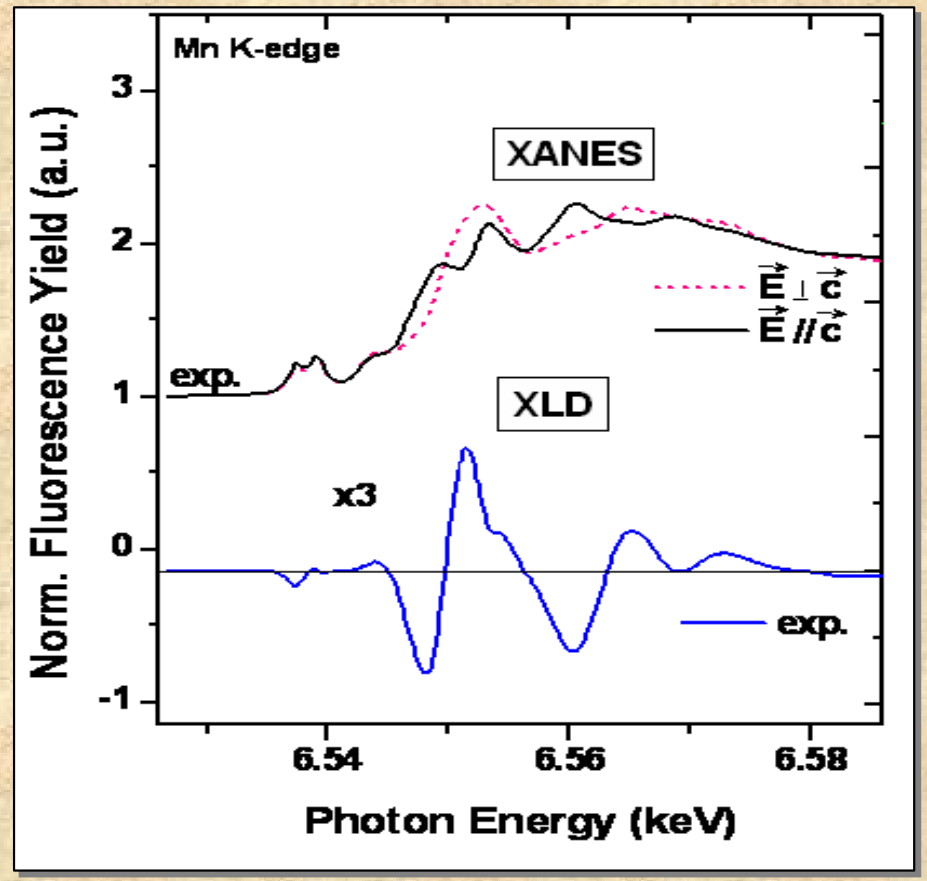
A. F. Orlov, et. al, Physics of the Solid State, 53 (3), pp. 482-484 (2011)

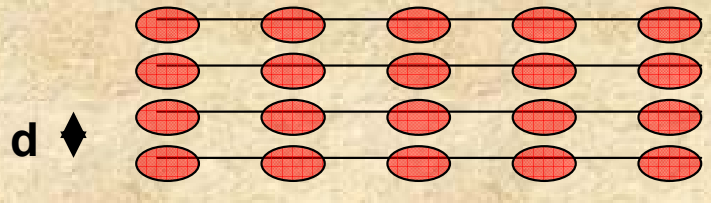
XLD (X-Ray linear dichroism)



Linear polarizations
(orthogonal)
from synchrotron







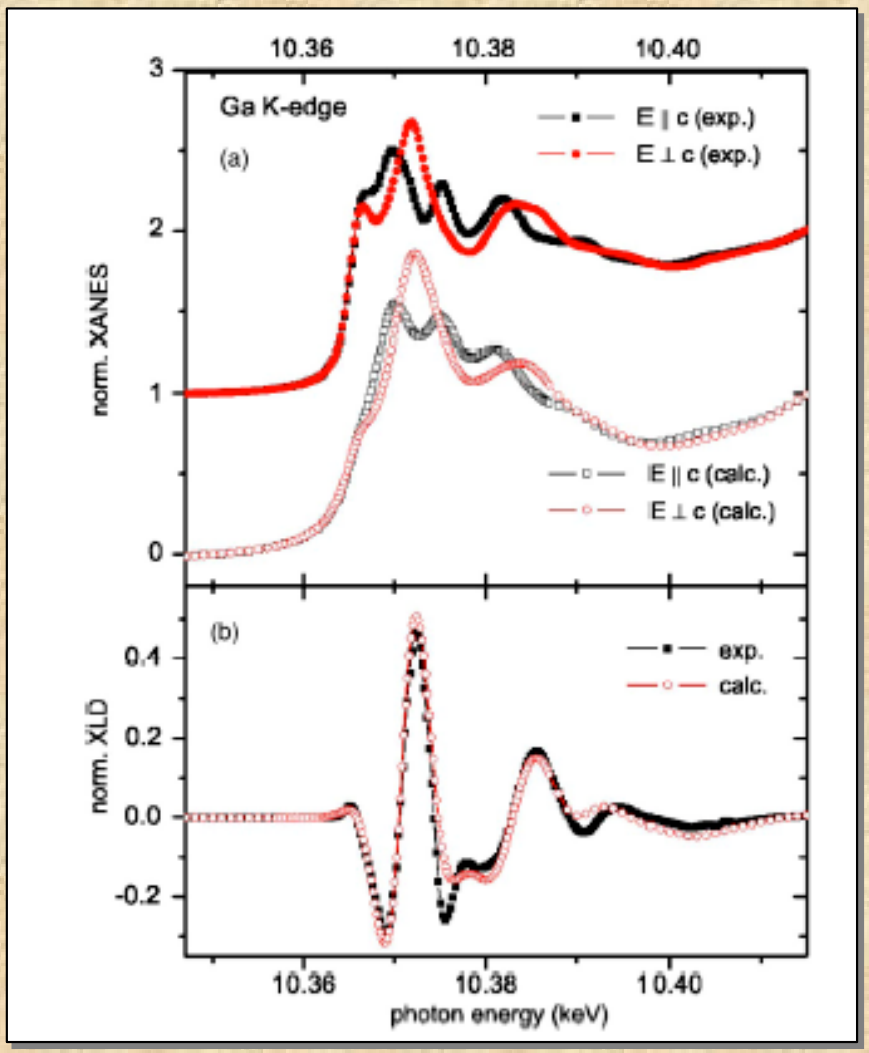
XLD is the difference in absorption of two orthogonal polarizations

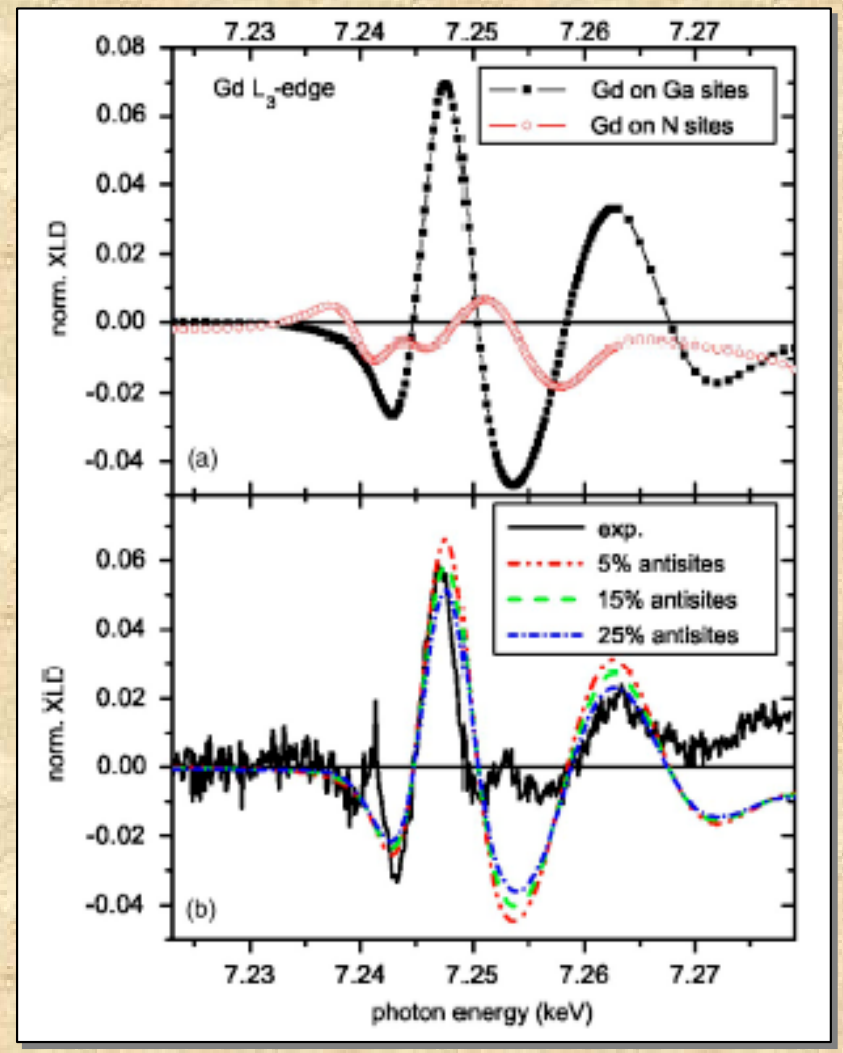
XLD (X-Ray linear dichroism) :

Element specific investigations of the structural and magnetic properties of Gd:GaN

APPLIED PHYSICS LETTERS **90**, 252515 (2007)

A. Ney,[a)]





Element-selective techniques like XANES & XMCD could help us to study DMS...

Thanks a lot for your attention!