HESEB Helmholtz-SESAME
Soft X-Ray Beamline
für SESAME

SESAME

DESY. JÜLICH FORSCHUNGSZENTRUM HZB Helmholtz Zentrum Berlin HZDR KIT

Soft X-Ray Spectroscopy at HESEB

Wolfgang Eberhardt
DESY

X-Ray spectroscopy at HESEB

Introduction---synchrotron radiation properties

Photon-matter interactions

Absorption (yield) spectroscopy

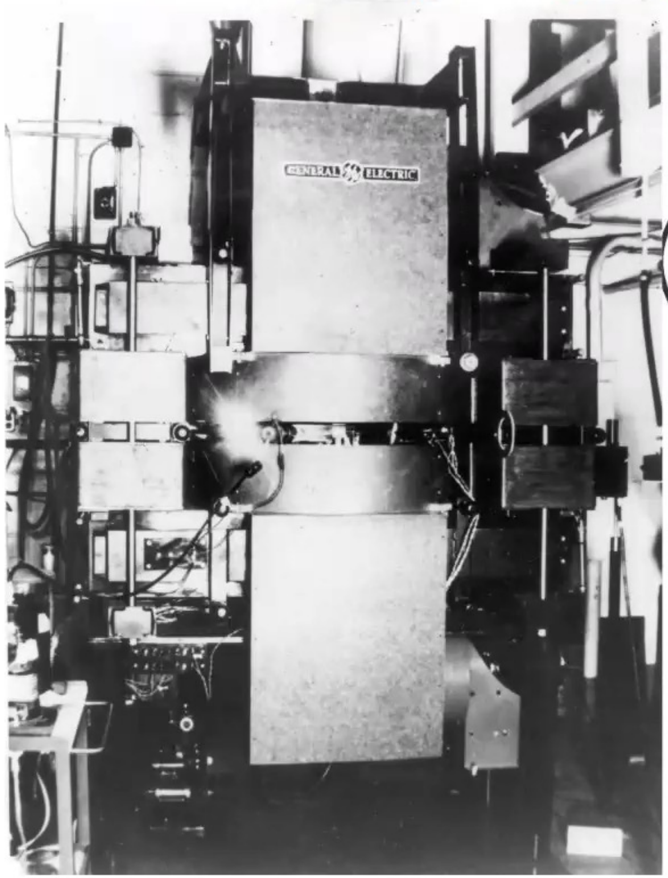
X-ray-Magnetic-Circular-Dichroism XMCD

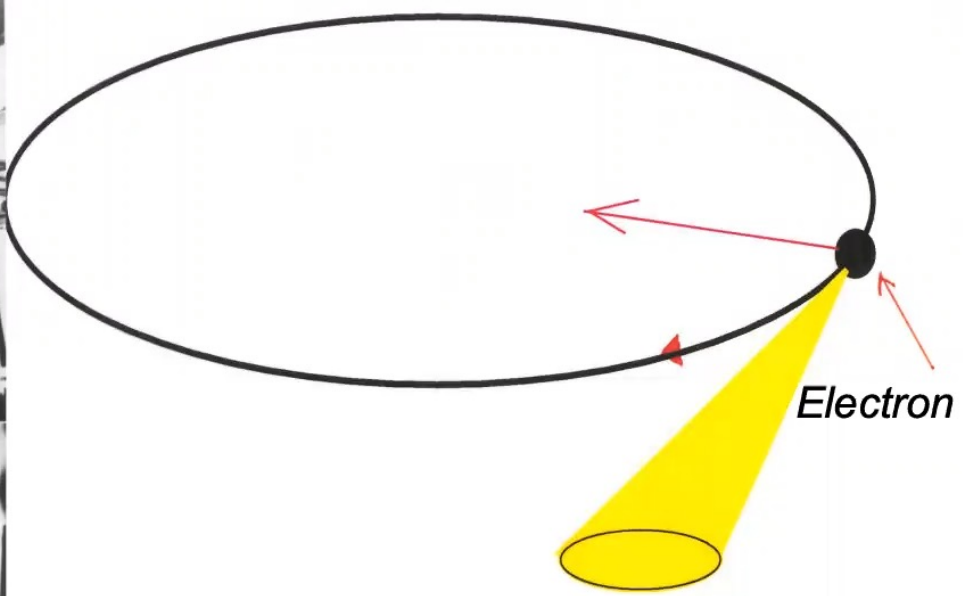
Photoemission and RIXS (short)

Coherent scattering

SYNCHROTRON-RADIATION

Electrons moving at nearly the speed of light on a circular path

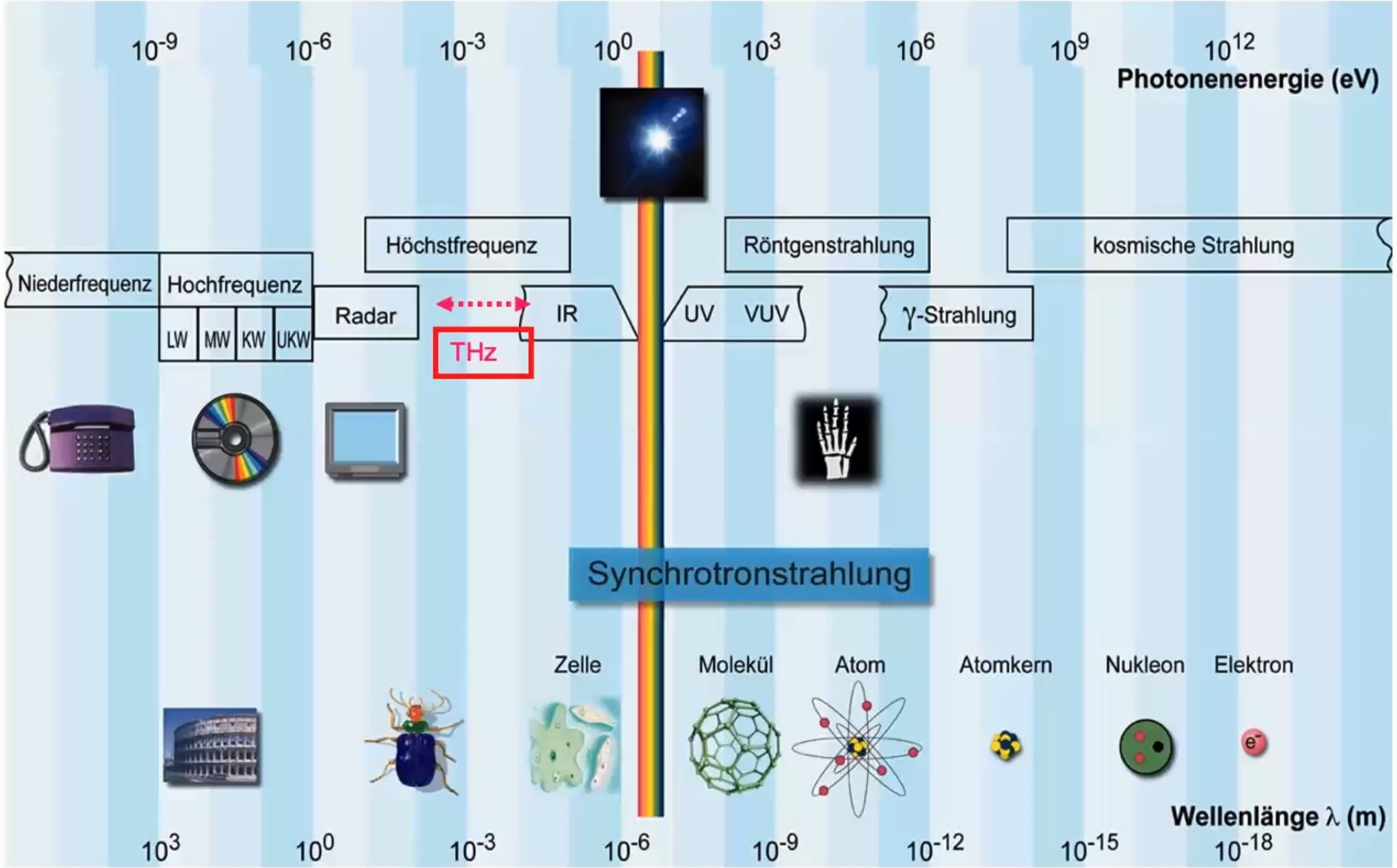




…. radiate a special light

Synchrotron-Radiation

Spectral Range of Synchrotron-Radiation



HESEB

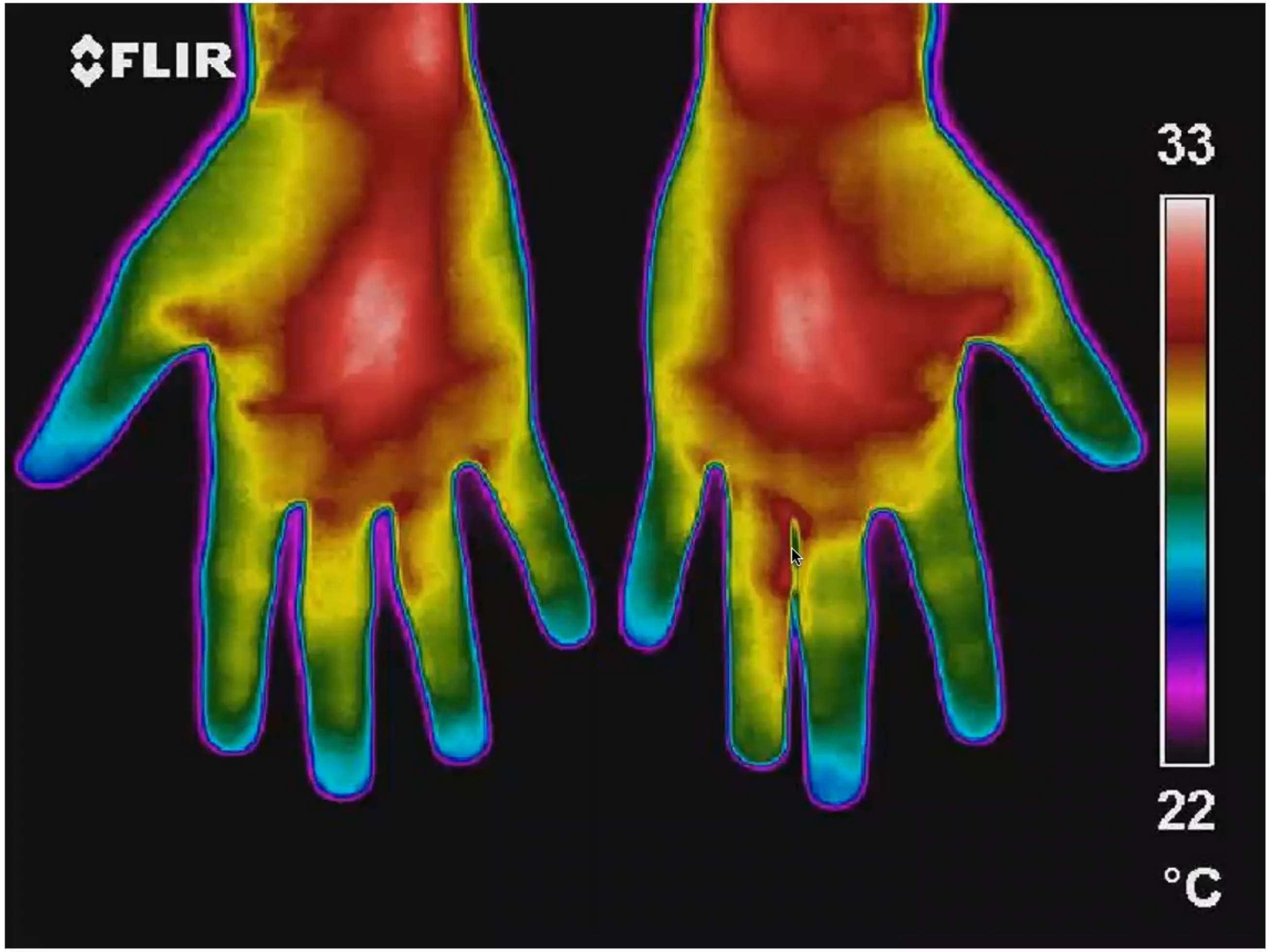
Hand illuminated by X-Rays

Josef Albert impr.

Hand des Anatomen Geheimrath von Kölliker in Würzburg.
Im Physikalischen Institut der Universität Würzburg
am 23. Januar 1896 mit X-Strahlen aufgenommen
von
Professor Dr. W. C. Röntgen.

Verlag der Stahel'schen k. Hof- und Universitäts-Buch- und Kunsthandlung in Würzburg.

Hand----IR emission Spectrum



Synchrotron Radiation: Brightness -- the quality factor

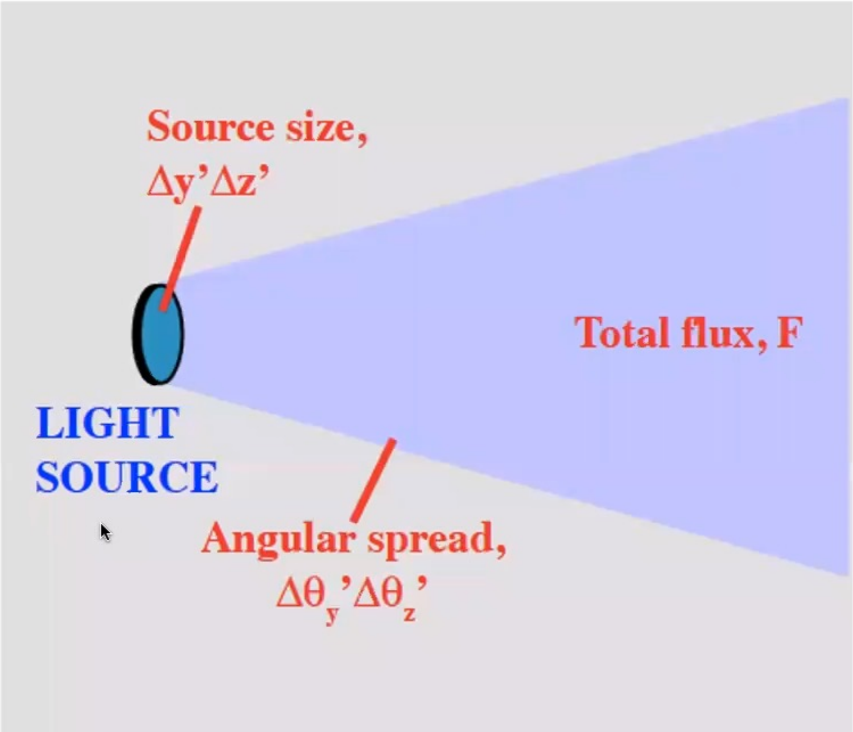


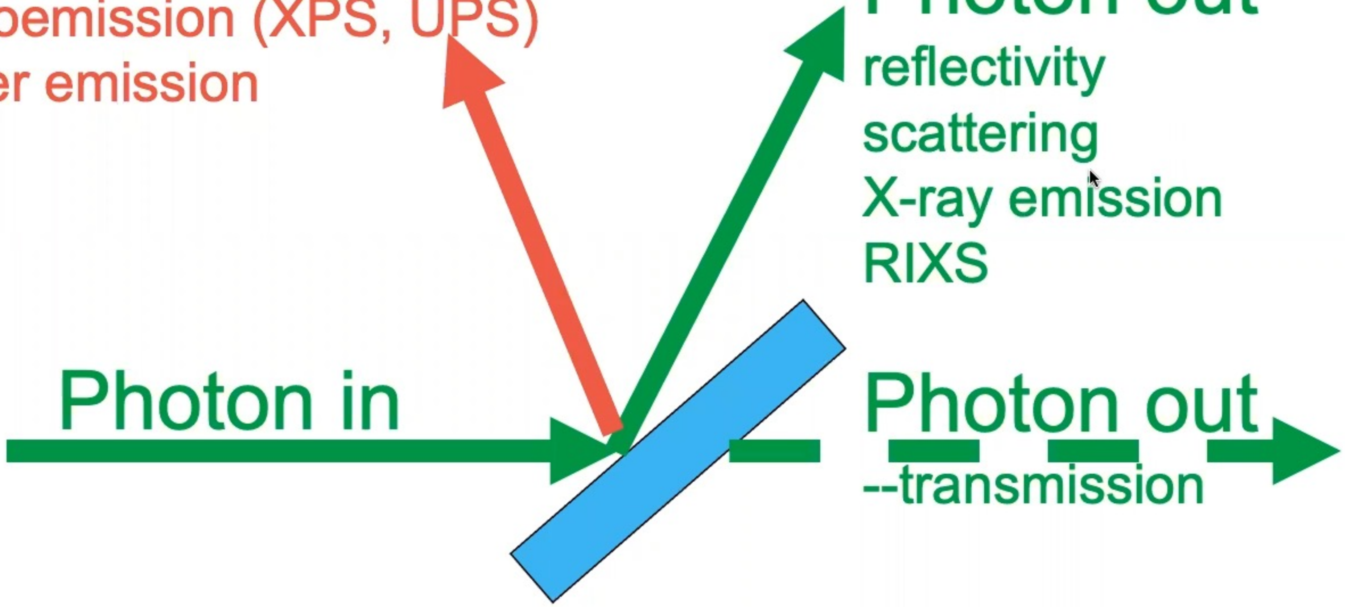
Fig. 8 - The source parameters which determine the brightness or brilliance.

Brightness

B = photons per
- source size
- angular spread
- energy interval
- time

The Brightness is conserved (Liouville Theorem)

Interactions of photons with matter



Electron out

electron yield
photoemission (XPS, UPS)
Auger emission

Photon out

reflectivity
scattering
X-ray emission
RIXS

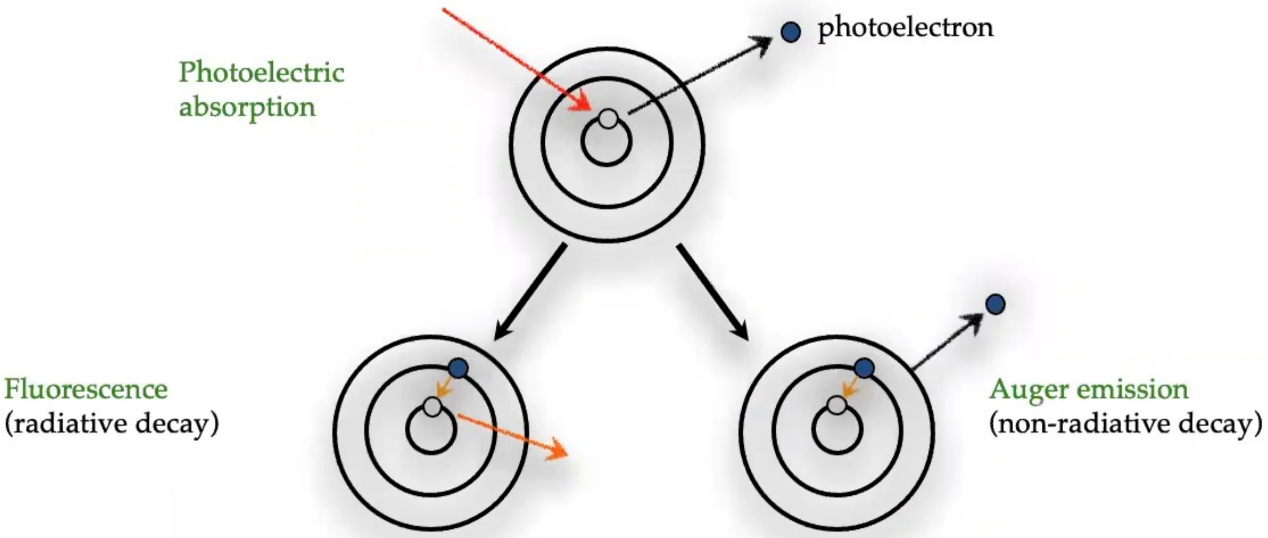
Photon in

Photon out

--transmission

Secondary Processes following the X-ray Absorption Process

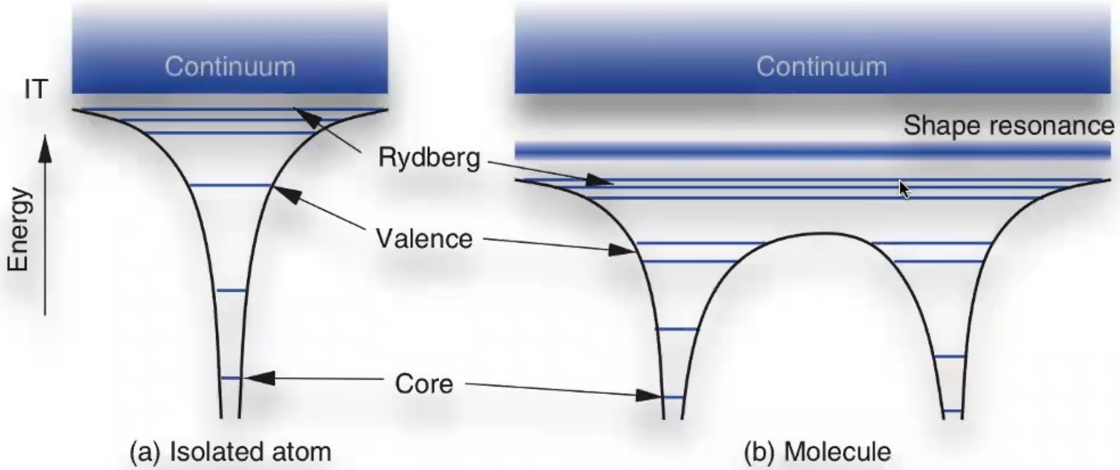
- X-rays are absorbed by matter through the photoelectric effect
- The incident X-ray photon promotes a core level electron to an unoccupied valence state level above the **ionization threshold**
- The electron ejected from the atom is called **photoelectron**
- The atom is left in an excited state with a core hole
- Two decay channels: **X-ray fluorescence** and **Auger emission**



Energy Level Schemes of atoms, molecules and solids

Atoms and Molecules

Chemical bonds primarily involve **valence electrons**:
charge redistribution, formation of bonding/antibonding states (molecular orbitals)



From: P. Willmott, *An Introduction to Synchrotron Radiation*, *Wiley* (2011)

Core levels: weakly affected by chemical bonds through so-called **chemical shifts**

- small BE changes due to differences in the distribution of valence electrons caused by chemical bonding

Shape resonances: quasi-bound electron states physically close to the molecule in the ionization continuum

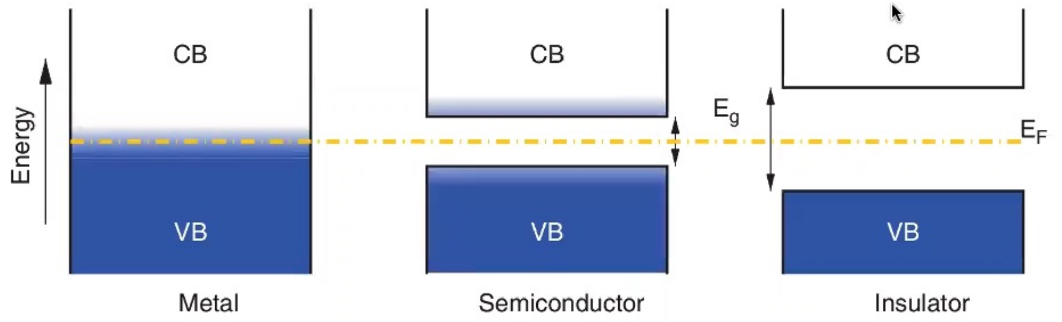
- they still 'feel' the influence of the electrostatic field of the molecule

Energy Level Schemes of solids

Solids

When a large number of atoms (N) is brought together into a solid, the number of orbitals that are formed is $2N$ and the energy differences among successive electron states become exceedingly small → **quasi-continuous bands of electron states**

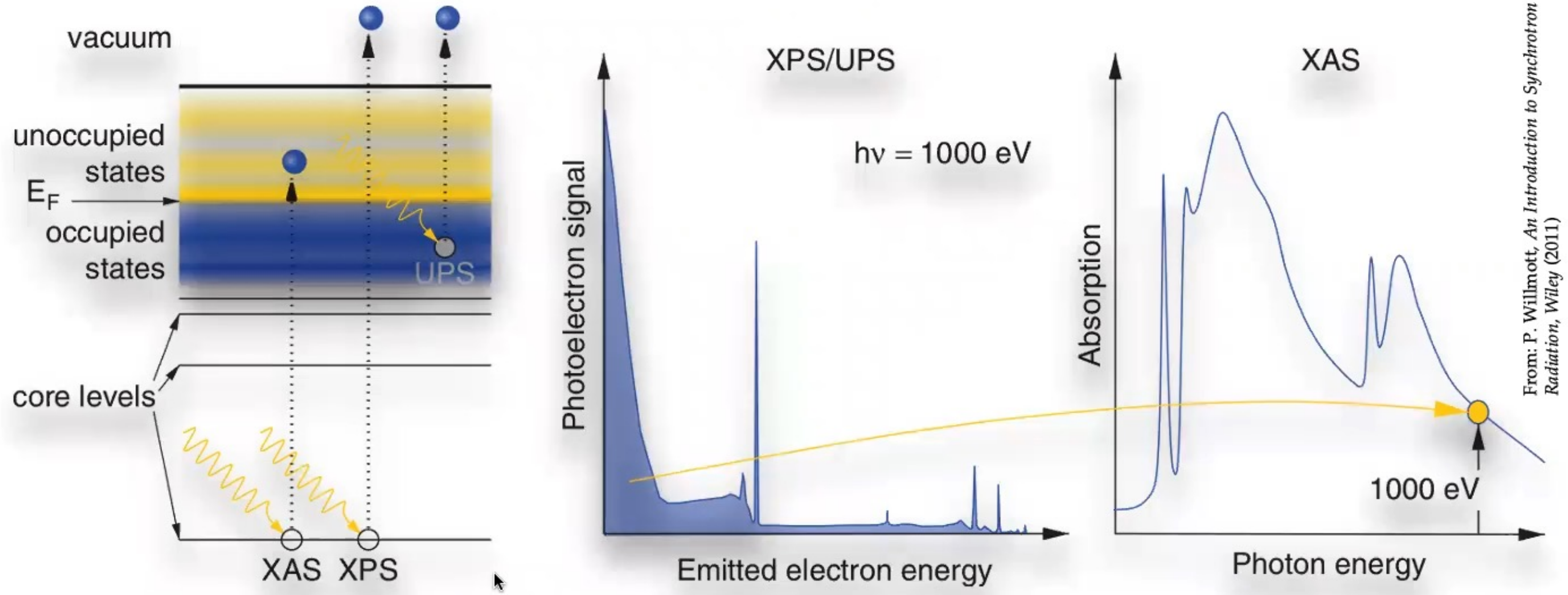
Simplified diagram of the electronic band structure of different solids:



From: P. Willmott, *An Introduction to Synchrotron Radiation*, *Wiley* (2011)

Metals:	highest occupied band is partly empty and partly filled regardless of temperature → gas of delocalized and nearly free valence electrons
Semiconductors:	narrow energy gap (<3 eV), a small fraction of valence electrons can be thermally promoted into the conduction band
Insulators:	wide gap, melting (or decomposition) takes place before a detectable fraction of valence electrons is promoted into the conduction band

X-ray absorption and photoemission



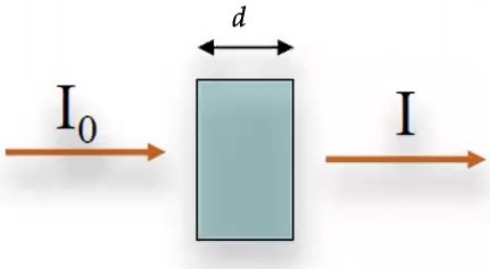
From: P. Willmott, *An Introduction to Synchrotron Radiation*, *Wiley* (2011)

- promotes core-level electrons to unoccupied valence-state levels and thereby probes these upper states by varying the incident photon energy

→ requirement: energy tunability + monochromatic radiation

Description of the X-ray Absorption Process

- Absorbing power of a material expressed through the **linear absorption coefficient μ**, which depends on the photon energy E = ħω



Beer-Lambert equation

$$\boxed{I(z) = I_0 e^{-\mu d}}$$

μ - attenuation/absorption coefficient

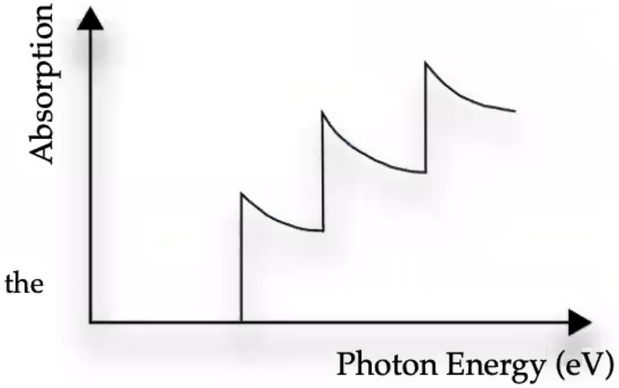
μ describes the probability that an X-ray beam travelling a distance *d* in a medium is absorbed

$\mu(E)$: element-specific and strongly dependent on the atomic number Z

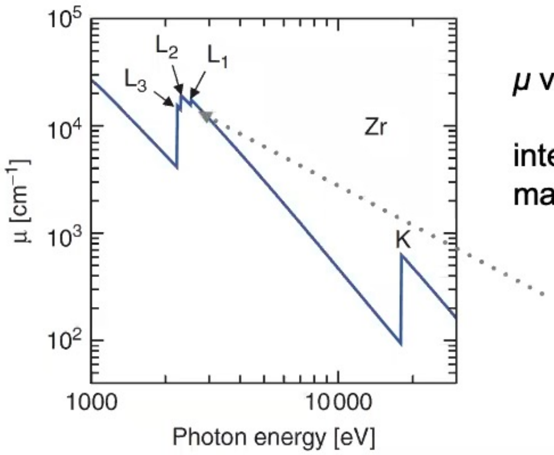
$$\boxed{\mu(E) \propto Z^4/E^3}$$

discontinuous jumps of $\mu(E)$ → absorption edges

⟶ photon energy equals the minimum energy needed to ionize the atom by ejection of an electron from a given energy level



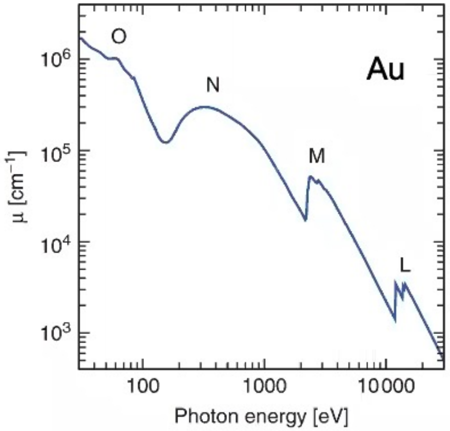
Absorption features and spectral regions



μ varies appr. as the inverse third power of the photon energy

interrupted by steplike increases in absorption as the photon energy matches the ionization potential of an occupied electron state in a atom

L-edge has three components, corresponding to ionization from the $2s$, $2p_{1/2}$ and $2p_{3/2}$ levels



From: P. Willmott, *An Introduction to Synchrotron Radiation*, *Wiley* (2011)

The shape of the absorption edges depends on the initial state excited in the transition

→ states with l = 0 or l = 1: sharp rising edges
→ states with larger l values: broader appearance "delayed onset" (by some tens of eV)

(l - angular-momentum quantum number)

Quantum states with high principal quantum number tend to remain away from the nucleus - classically, one would expect them to have a large circular orbit

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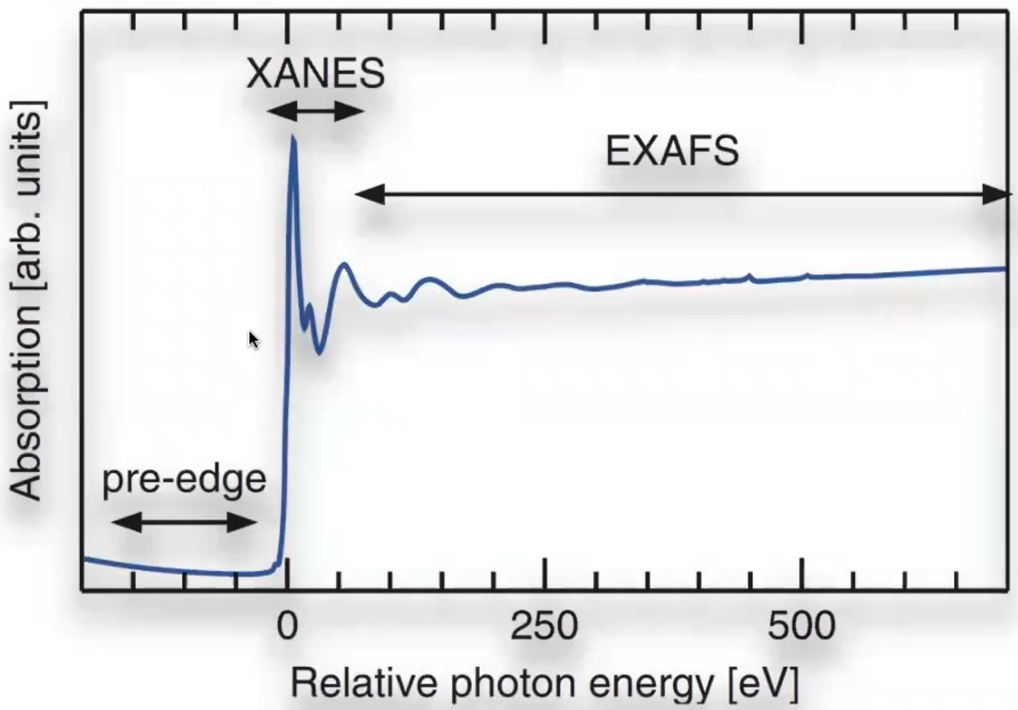
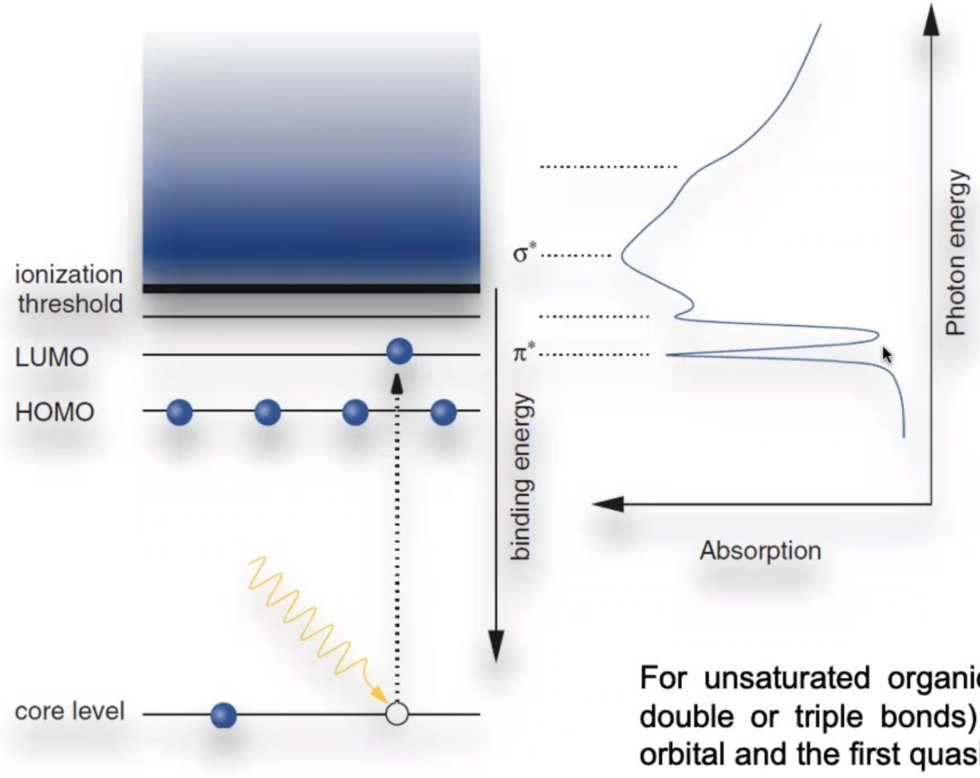
Absorption features and spectral regions



1. XANES (= X-ray Absorption Near-Edge Structure) or NEXAFS (= Near-Edge X-ray Absorption Fine Structure)*
2. EXAFS (= Extended X-ray Absorption Fine Structure)**

NEXAFS: application to molecular adsorbates in surface scienc

Interactions with the substrates are often "weak", in the sense that the excited electronic states immediately above the highest occupied state are found to display to a large degree a structure very similar to the one they display in the isolated molecules



From: P. Willmott, *An Introduction to Synchrotron Radiation*, *Wiley* (2011)

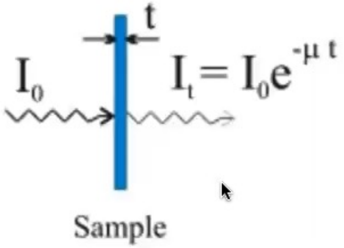
HOMO = highest occupied molecular orbital

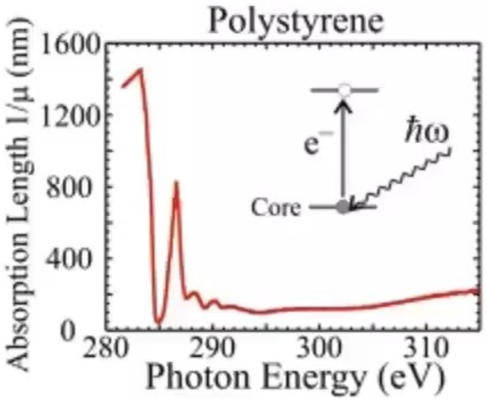
LUMO = lowest unoccupied molecular orbital

For unsaturated organic compounds (i.e., those with double or triple bonds) the LUMO is invariably a π* orbital and the first quasi-unbound state above IT a σ*

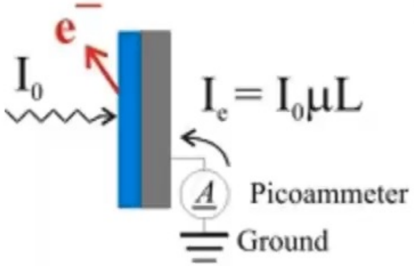
X-Ray Absorption Spectroscopy

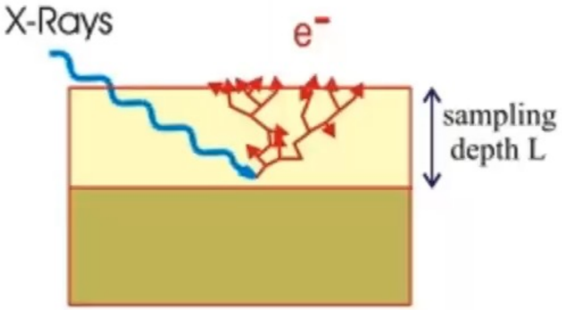
Transmission

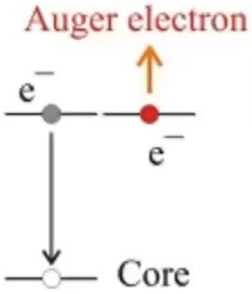




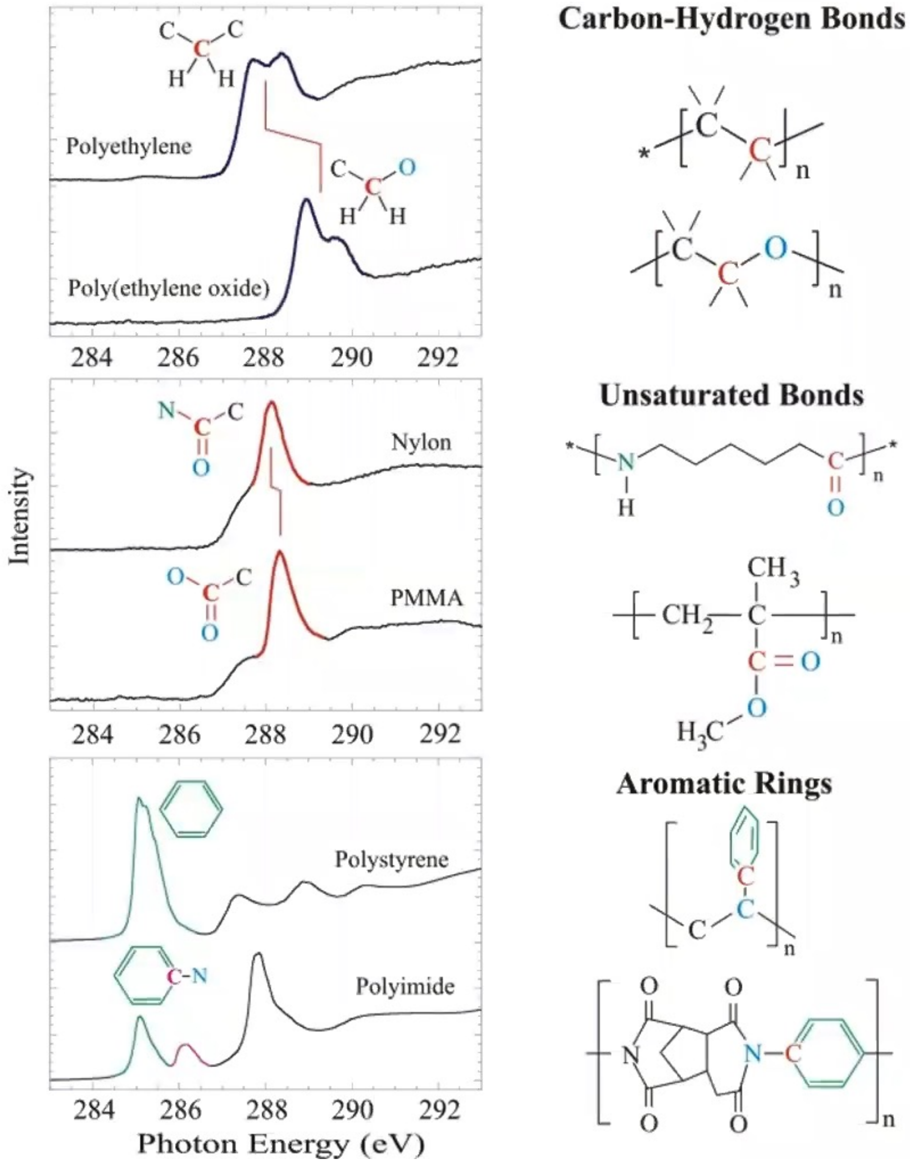
Electron Yield





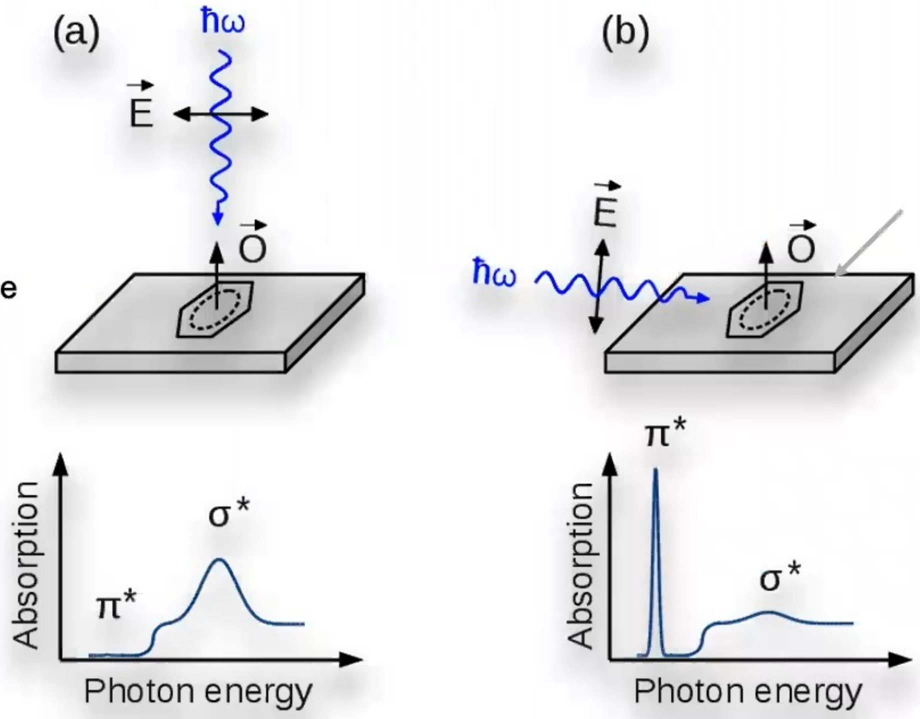


Basic Building Blocks of Polymers



Polarization-dependent NEXAFS

from the change in intensity of the NEXAFS resonances when varying the angle between the electric field and the substrate directions one gets information on the **orientation of molecules** with respect to the surface (tilt angles)



normal incidence

↓

π* quenched

grazing incidence

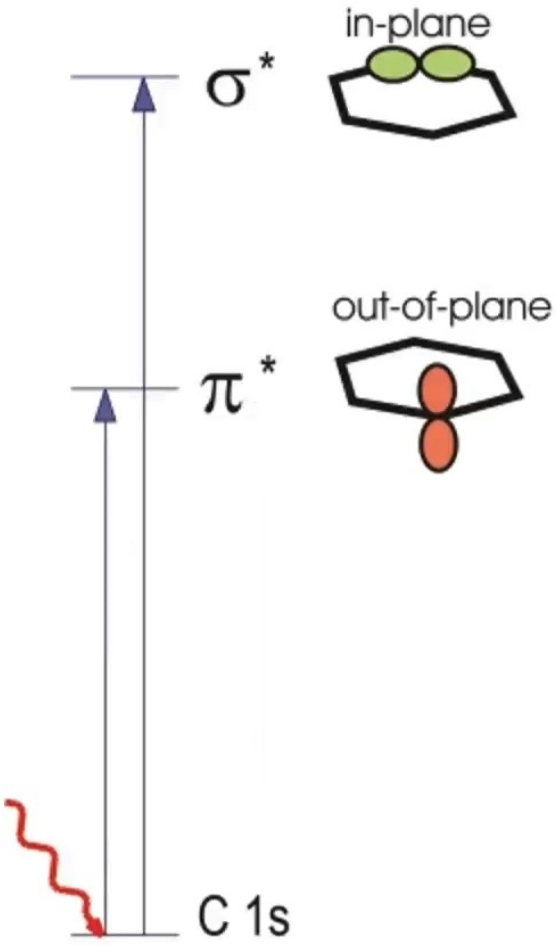
↓

π* maximized

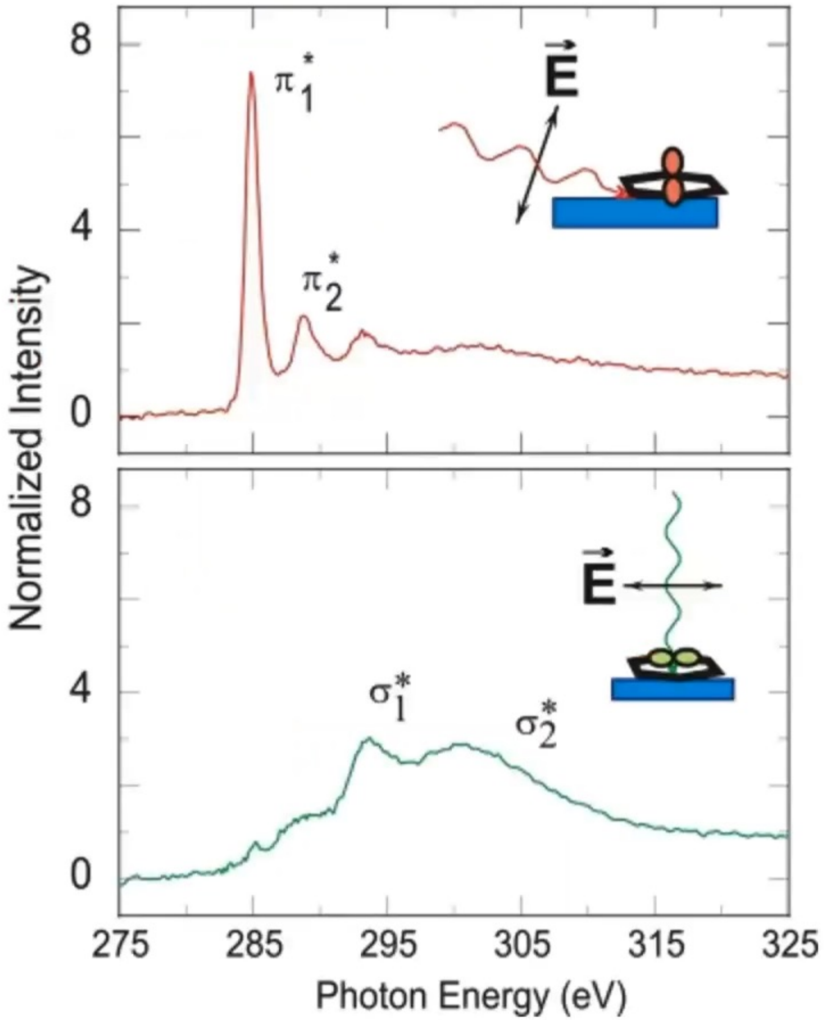
→ molecular orientation, orientation of functional groups

The Search Light Effect

Benzene Molecular Orbitals



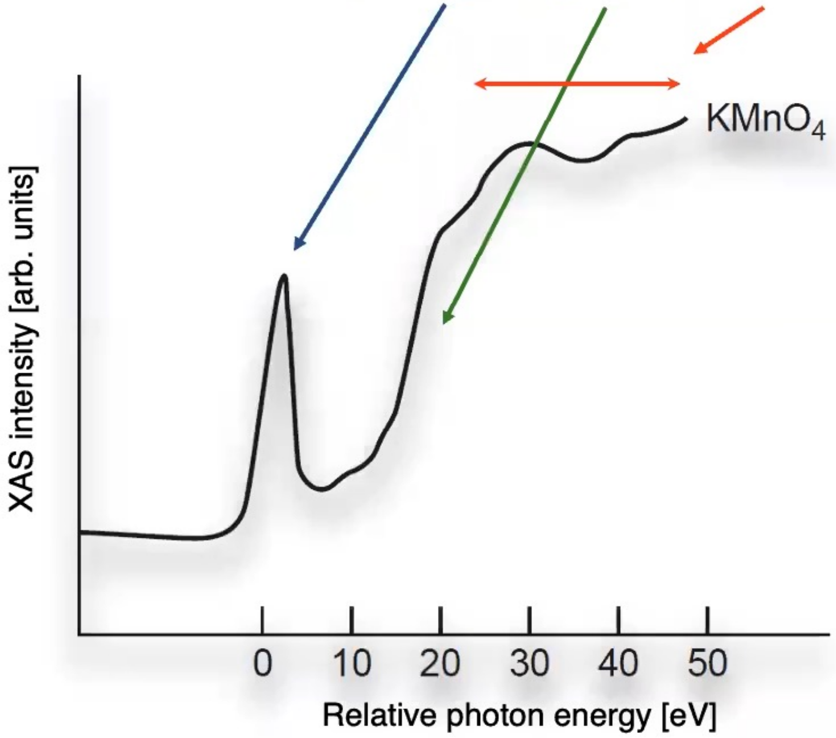
Lying-down benzene on Ag (110)



X-ray Absorption Near-Edge Structure (XANES or NEXAFS) of sol

What is XANES?

XANES = pre-edge + edge + XANES



XANES is very sensitive to the chemistry of the absorbing atom:

→ formal oxidation state

→ coordination environment

XANES

The intensity of transitions to bound-state unoccupied orbitals depends not only on the dipole selection rules (and the symmetry) but also on the **unoccupied DOS**

Re: [Xe] $6s^2\ 4f^{14}\ 5d^5$

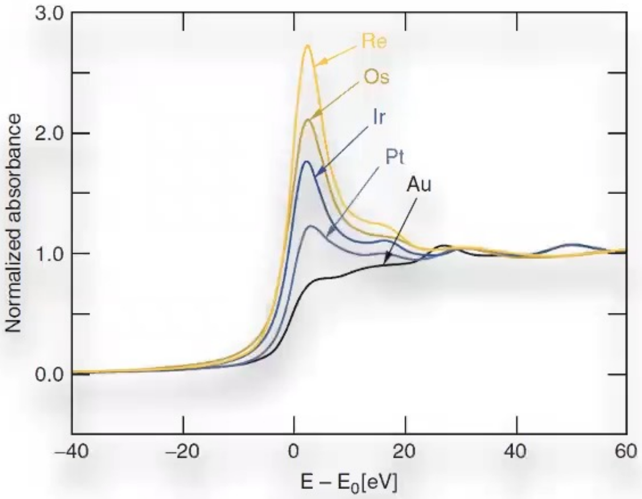
⋮

Ir: [Xe] $6s^2\ 4f^{14}\ 5d^7$

⋮

Au: [Xe] $6s^1\ 4f^{14}\ 5d^{10}$

L_3 absorption edges of five 5*d*-metals



G. Meitzner *et al.*, J. Phys. Chem. **96**, 4960-4964 (1992)

- from Re to Pt: strong white lines* of bound unoccupied 5*d*-states below IT
- Au has no such states, excitation is directly into the unbound *continuum*

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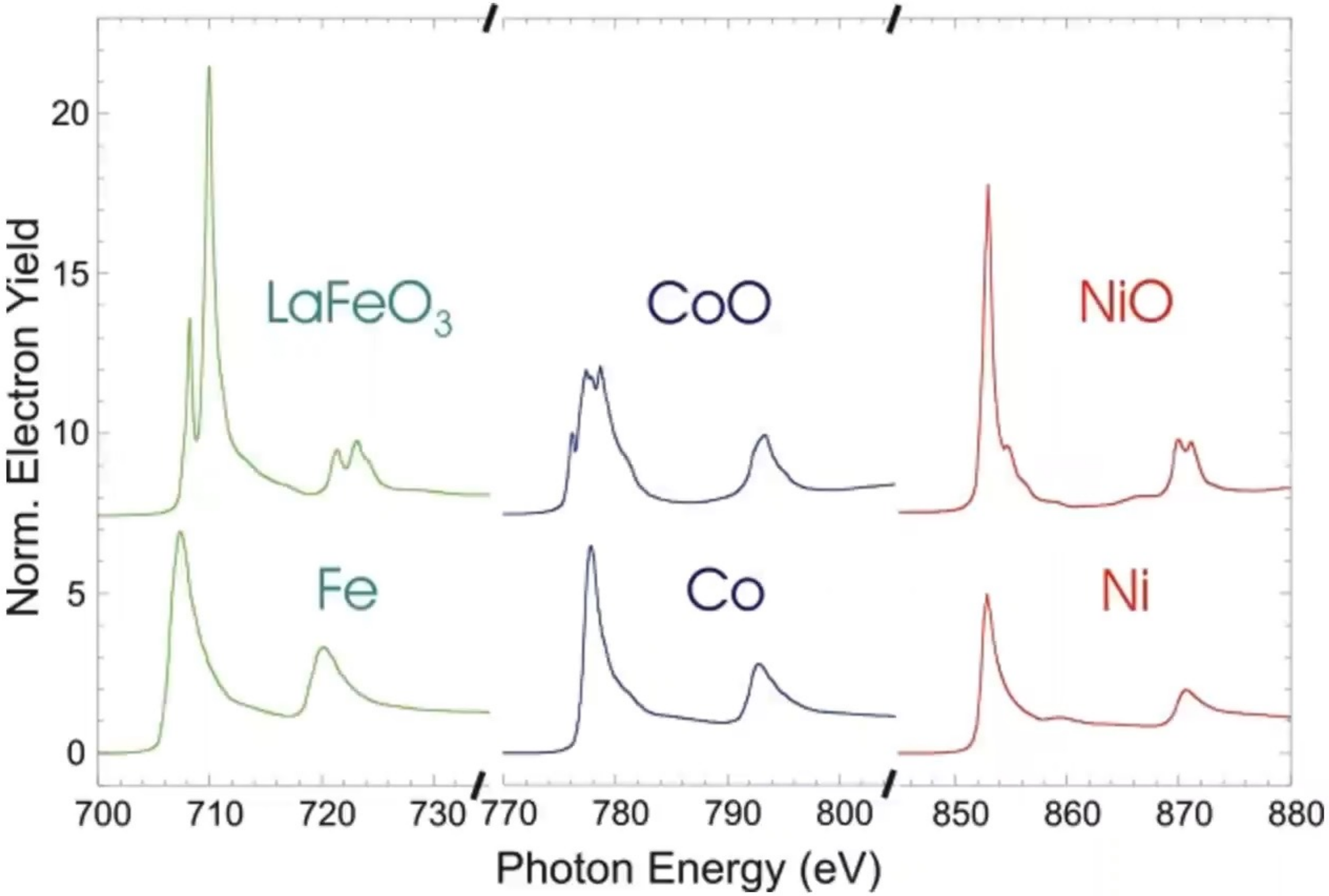
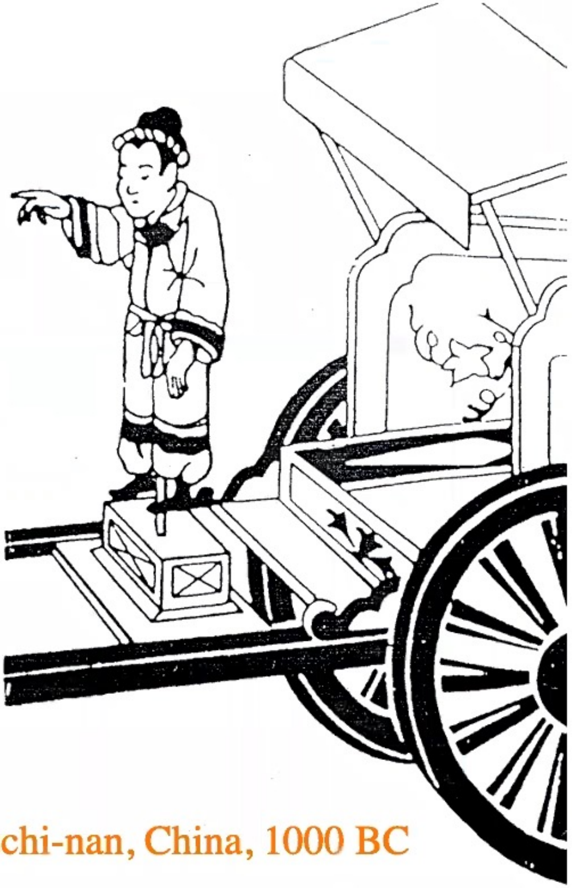

LaFeO$_3$
CoO
NiO
Fe
Co
Ni
Norm. Electron Yield
0
5
10
15
20
700
710
720
730
770
780
790
800
850
860
870
880
Photon Energy (eV)

Magnetism and Magnetic Materials in the Light of Synchrotron Radiation

W. Eberhardt BESSY

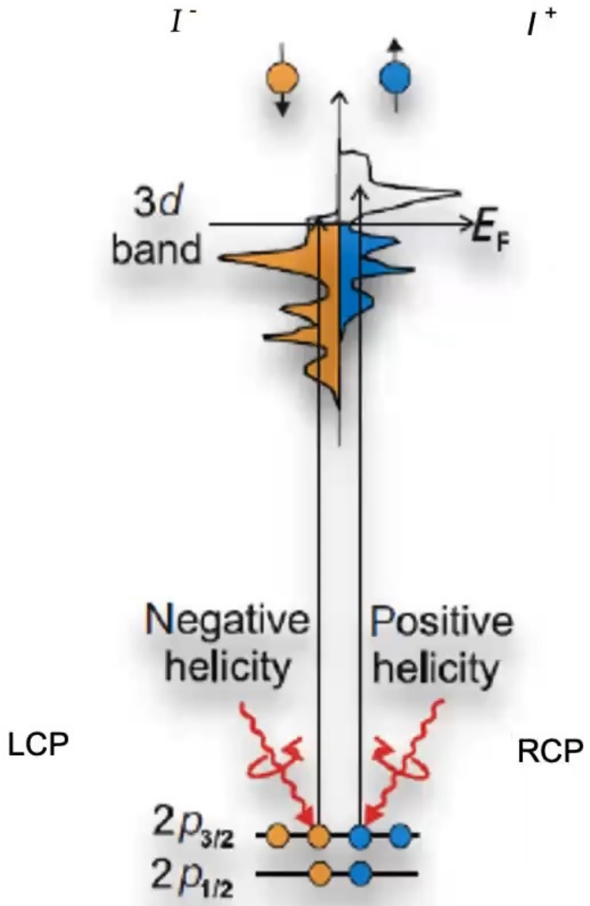


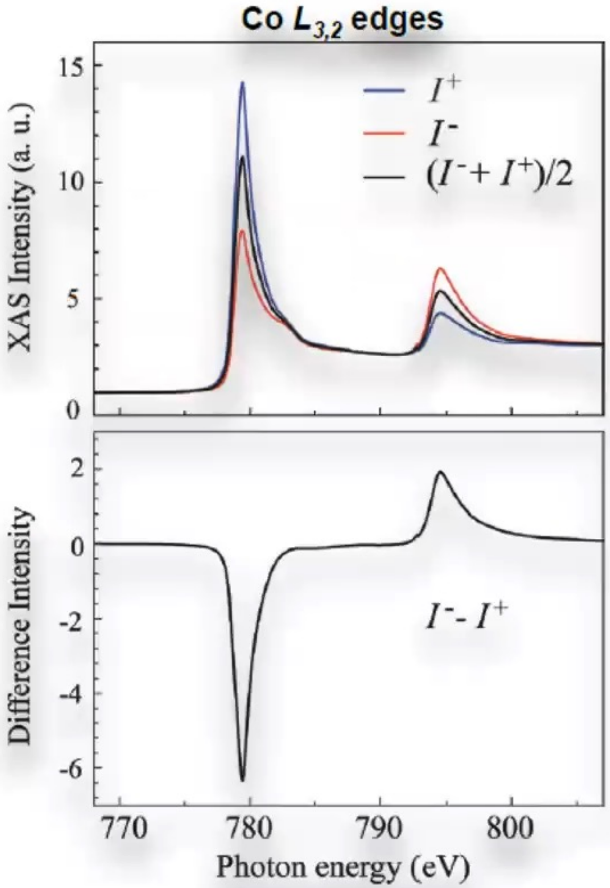
Tschi-nan, China, 1000 BC

It is not possible to understand
the magnetic effects of materials
in any honest way from the point
of view of classical physics.
Magnetic phenomena are completely a
quantum mechanical phenomenon.

R.P. Feynman
The Feynman Lectures Vol.II, 34-2

Principle of XMCD (X-Ray Magnetic Circular Dichroism)



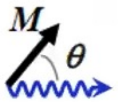


Quantitative analysis of XMCD spectra: sum rules

I_{XMCD} α $\boldsymbol{M\cos\theta}$

- The size of the dichroism effect scales as cos θ

  θ = angle between photon spin and magnetization direction



- Sum rules: relate A, B, I_{L_3}, I_{L_2} with the spin & orbital magnetic moments of the probed atom

1st sum rule: $I_{L_3} + I_{L_2}$ is $\propto$ to the number of 3*d* holes

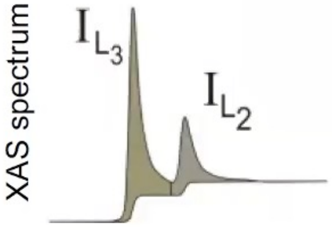
2nd sum rule: the spin magnetic moment is related to [2B-A]

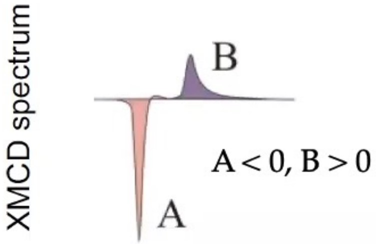
3rd sum rule: the orbital magnetic moment is $\propto$ to -[A+B]

See, e.g.: J. Stöhr, Journal of Magnetism and Magnetic Materials **200**, 470-497 (1999)

↓

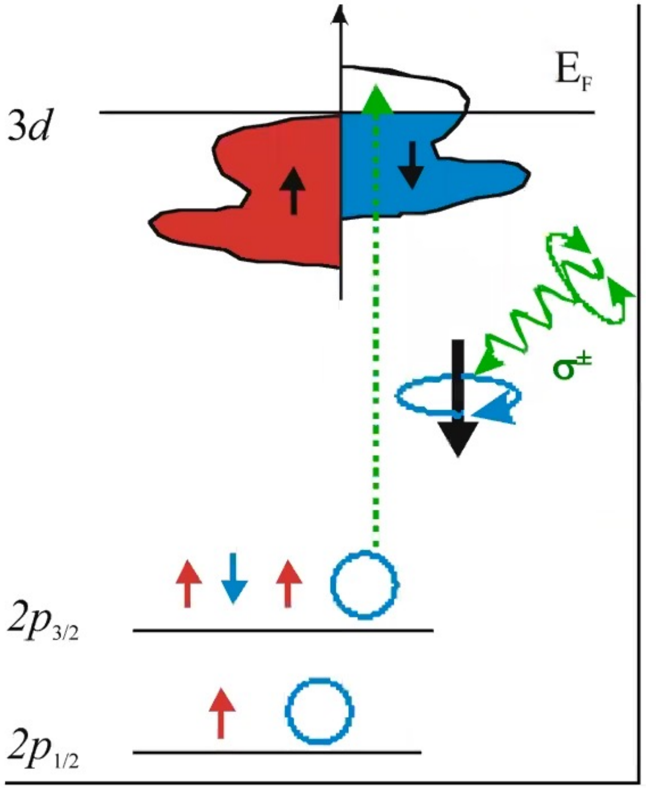
quantitative determination of the spin & orbital magnetic moments with element specificity

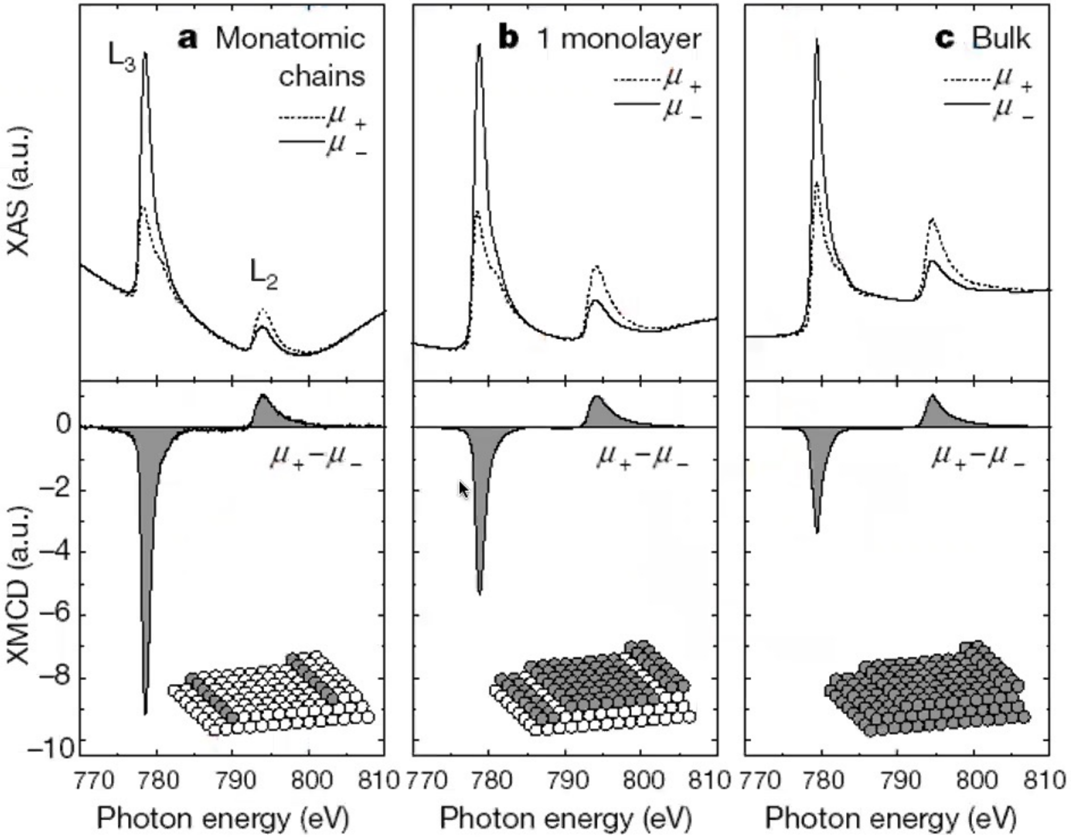




measurements: by reversing (1) photon's helicity or (2) the direction of the magnetization

Magnetic Systems → CMXD



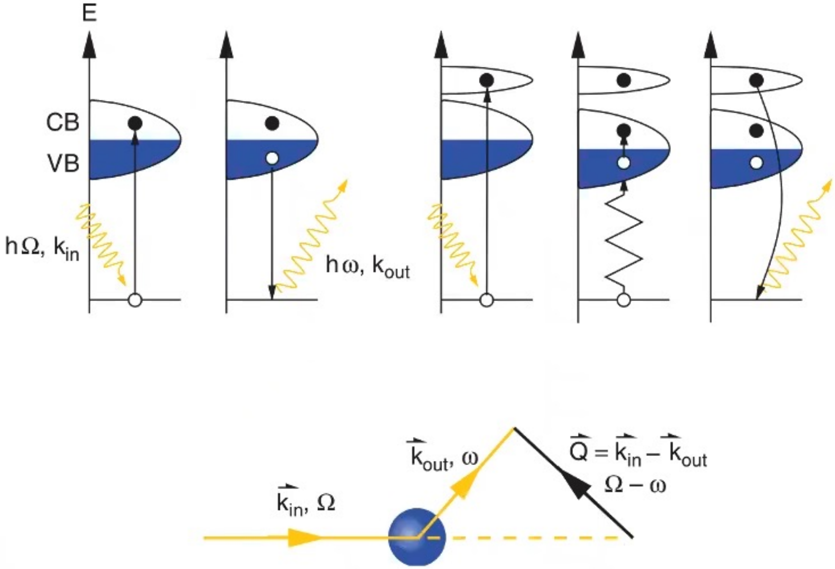


P. Gambardella, A. Dallmeyer, K. Maiti, M. C. Malagoli, W. Eberhardt, K. Kern, C. Carbone, **Nature 416**, 301 (2002)

Soft X-Ray Emission

Resonant Inelastic X-ray scattering (RIXS)

- Photons resonant with electronic transitions are inelastically scattered from matter
- measures both the energy and momentum change of the scattered photon (cf. ARPES)
- energy of the incident photon is chosen such that it coincides with one of the atomic X-ray absorption edges of the system in order to enhance the inelastic scattering cross section
- RIXS is both bulk sensitive and site (i. e., chemically) selective
- one can apply external electric or magnetic fields

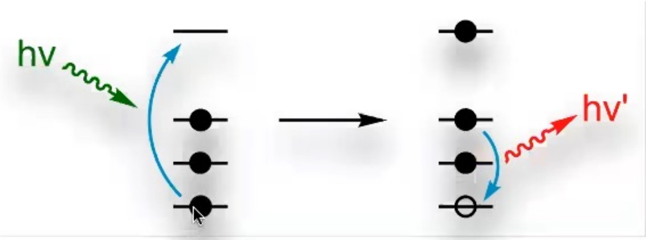


From: P. Willmott, *An Introduction to Synchrotron Radiation*, *Wiley* (2011)

X-Ray Fluorescence Spectroscopy

photon-in — photon-out technique

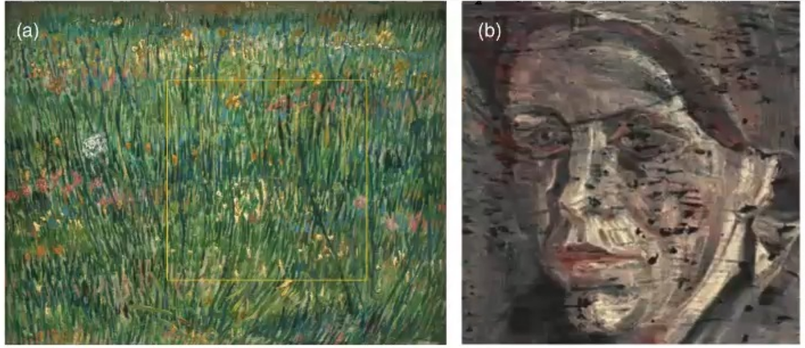
→ can be used also for isolating samples as well as under ambient or in-vivo environments



X-ray fluorescence (XRF)

- emission of characteristic "secondary" (or fluorescent) X-rays from a material that has been excited by being bombarded with high-energy X-rays
- widely used for elemental analysis and chemical analysis
- non-destructive analytical technique

Visualization of a Lost Painting by Vincent van Gogh



J. Dik et al, Anal. Chem. **80**, 6436 (2008)

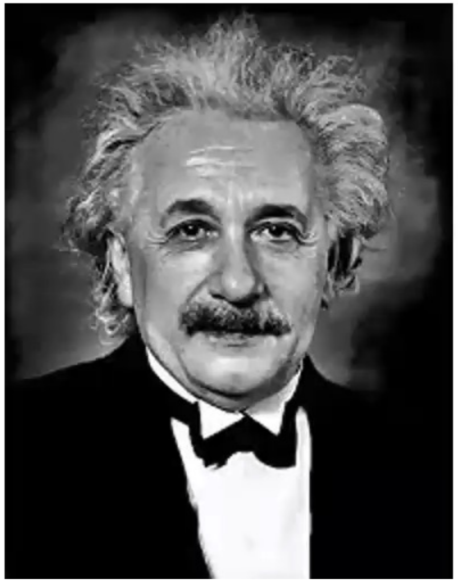
Energy Conservation in Photoemission (Einstein)

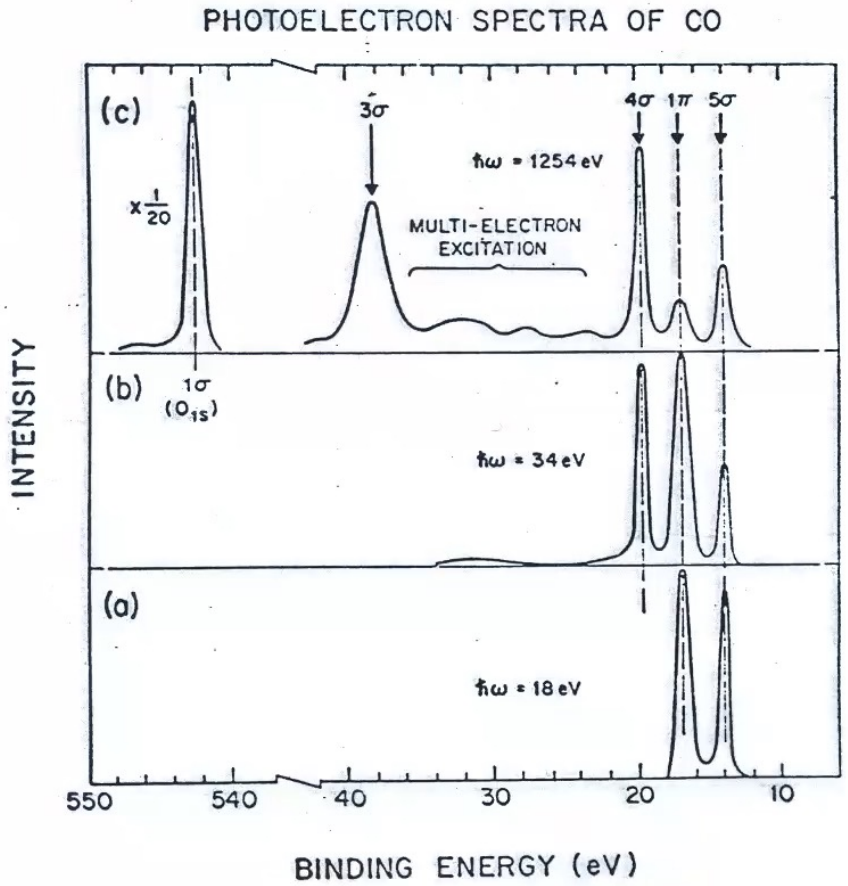
$$\boxed{E_{kin} = h\nu - E_B}$$

kinetic energy

photon energy

binding energy





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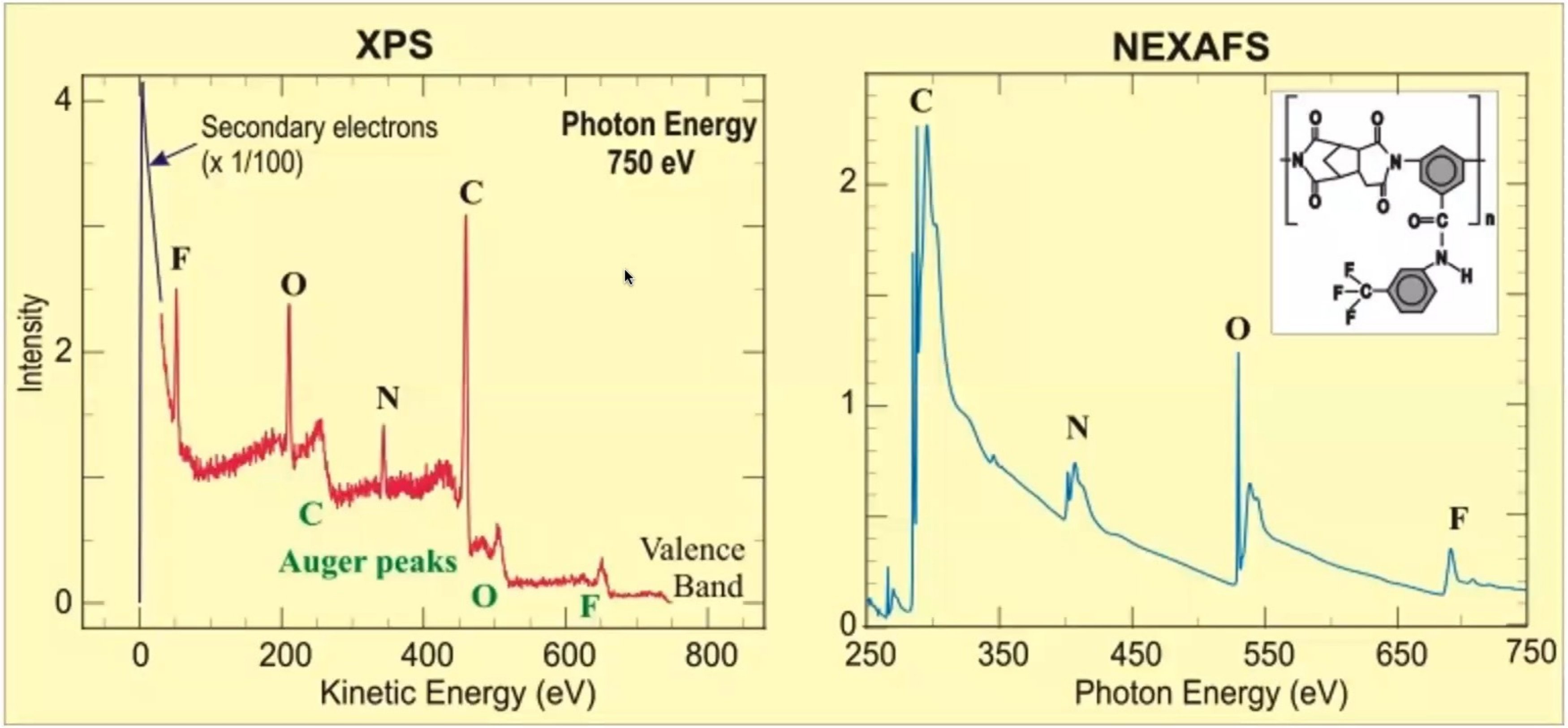
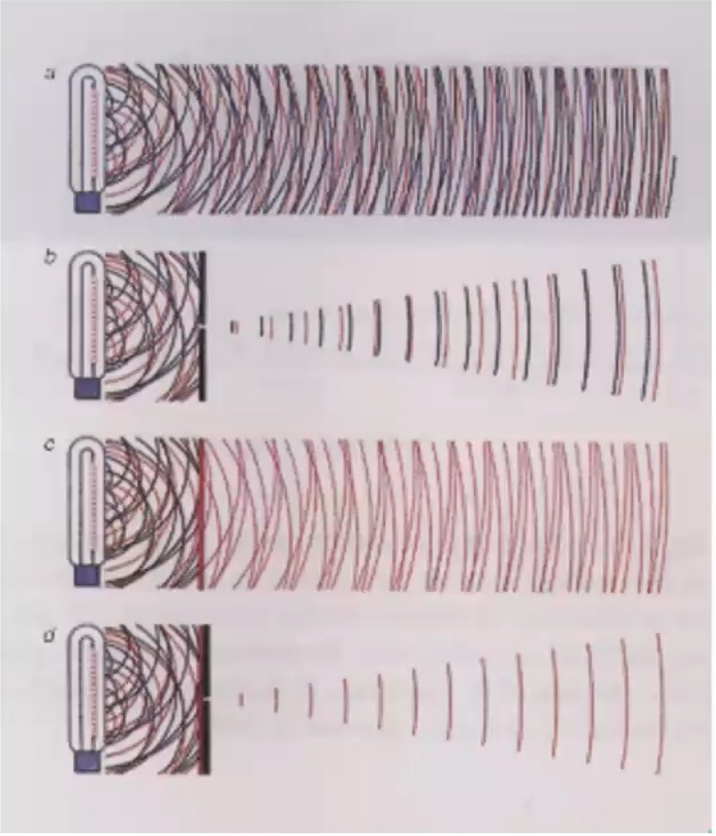

XPS
Secondary electrons
(x 1/100)
Photon Energy
750 eV
F
O
N
C
C
Auger peaks
O
F
Valence
Band
Intensity
0
2
4
0
200
400
600
800
Kinetic Energy (eV)
NEXAFS
C
N
O
F
0
1
2
250
350
450
550
650
750
Photon Energy (eV)
O
N
O
O
O
N
O=C
N
H
F
F-C
F
n

HESEB

Coherent Light Scattering



A. Schawlow, Sci. Am. **219**, 120 (Sept 1968)

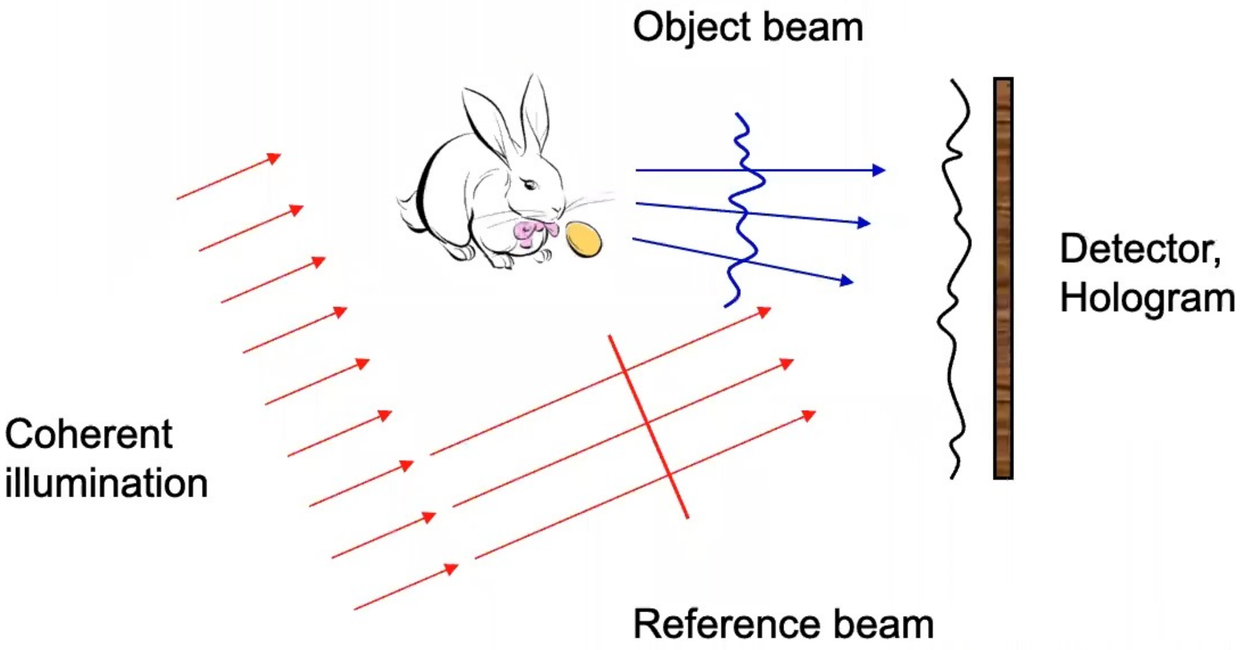
incoherent source

spatial filtering

spectral filtering

spatial & spectral filtering

Holography Principle
--- in-line holografy



Coherence --- a New Tool in X-Ray Science

Sensitive to the individual configuration

beyond statistical information

Spatial Domain

Reconstruction with nm feature resolution
chemical sensitivity

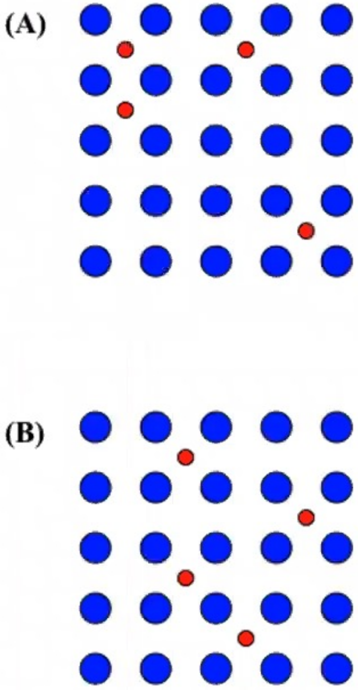
Temporal Domain

- Fingerprinting fluctuations -> Dynamics

→XPCS

General Features

resonant → element specific
photon-in photon-out
combines spectroscopy and scattering
chemical and structural information

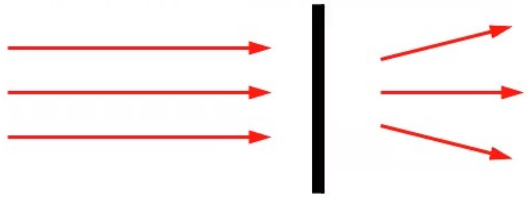


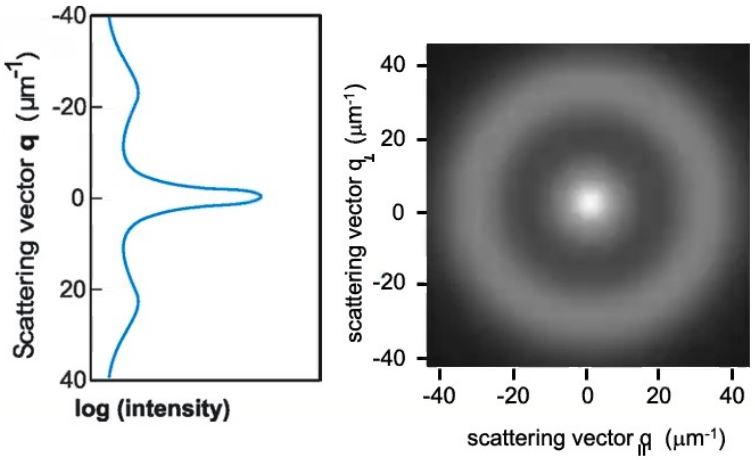
Identical periodic lattice
Identical mean deviation
But different individual configuration

Incoherent vs. *Coherent* X-Ray Scattering

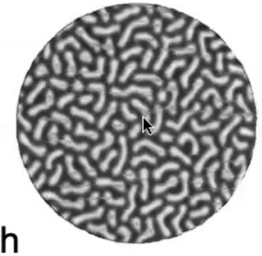
Small Angle Scattering

Incoherent scattering



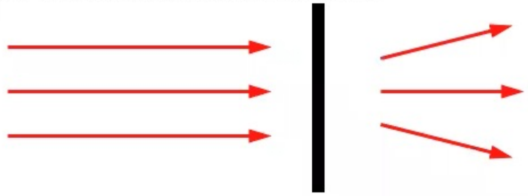


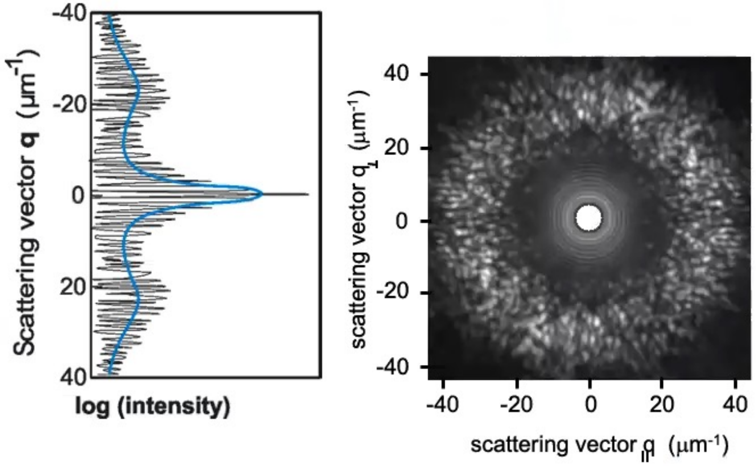
information about domain statistics



Speckle

Coherence length larger than illuminated area

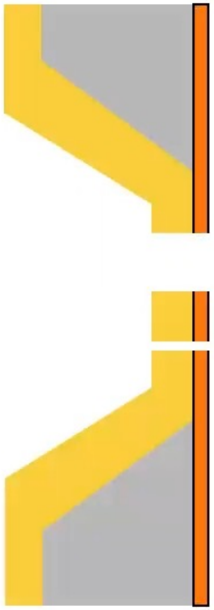




information about individual domain structure

HESEB

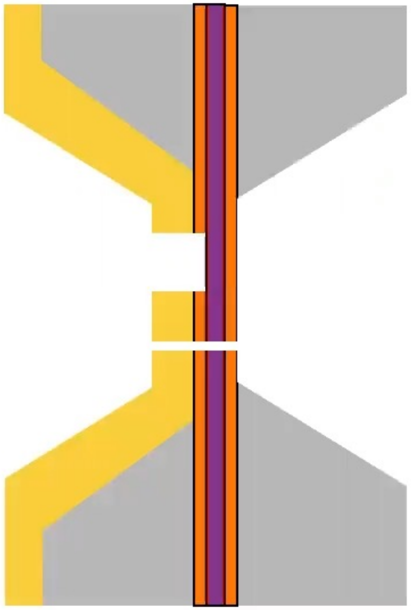
Fourier Transform Holography at λ=1.6 nm



Co $2p_{3/2}$ XMCD:
778 eV
1.59 nm

HESEB

Fourier Transform Holography at λ=1.6 nm



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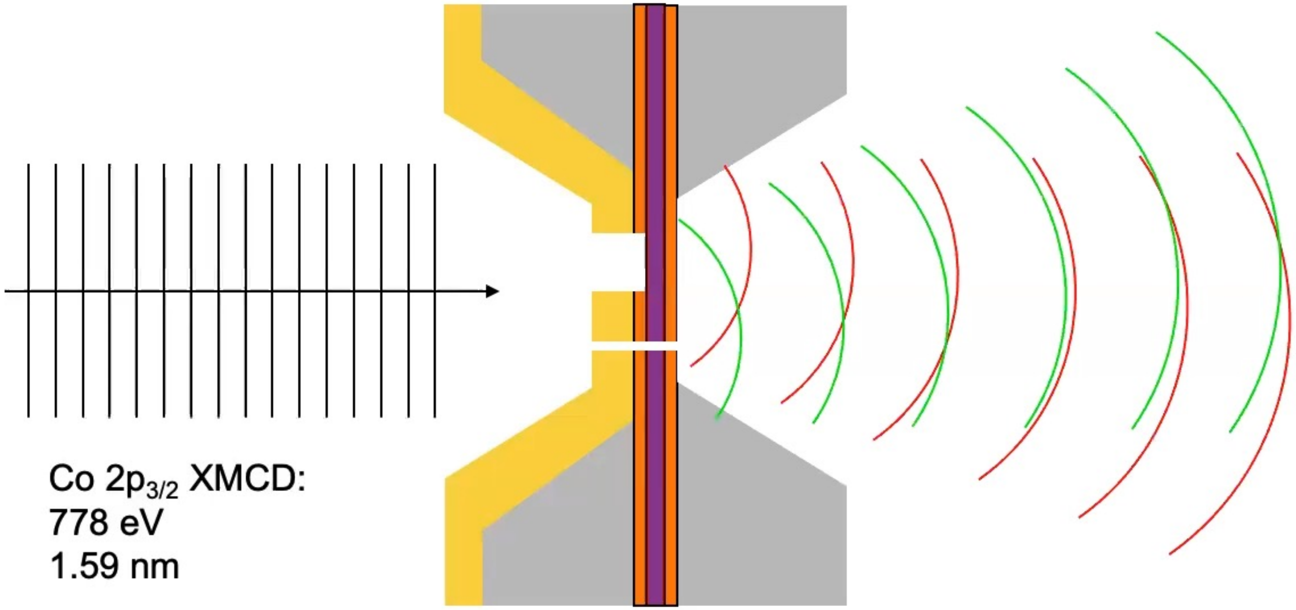
778 eV
1.59 nm

HESEB

Fourier Transform Holography at λ=1.6 nm



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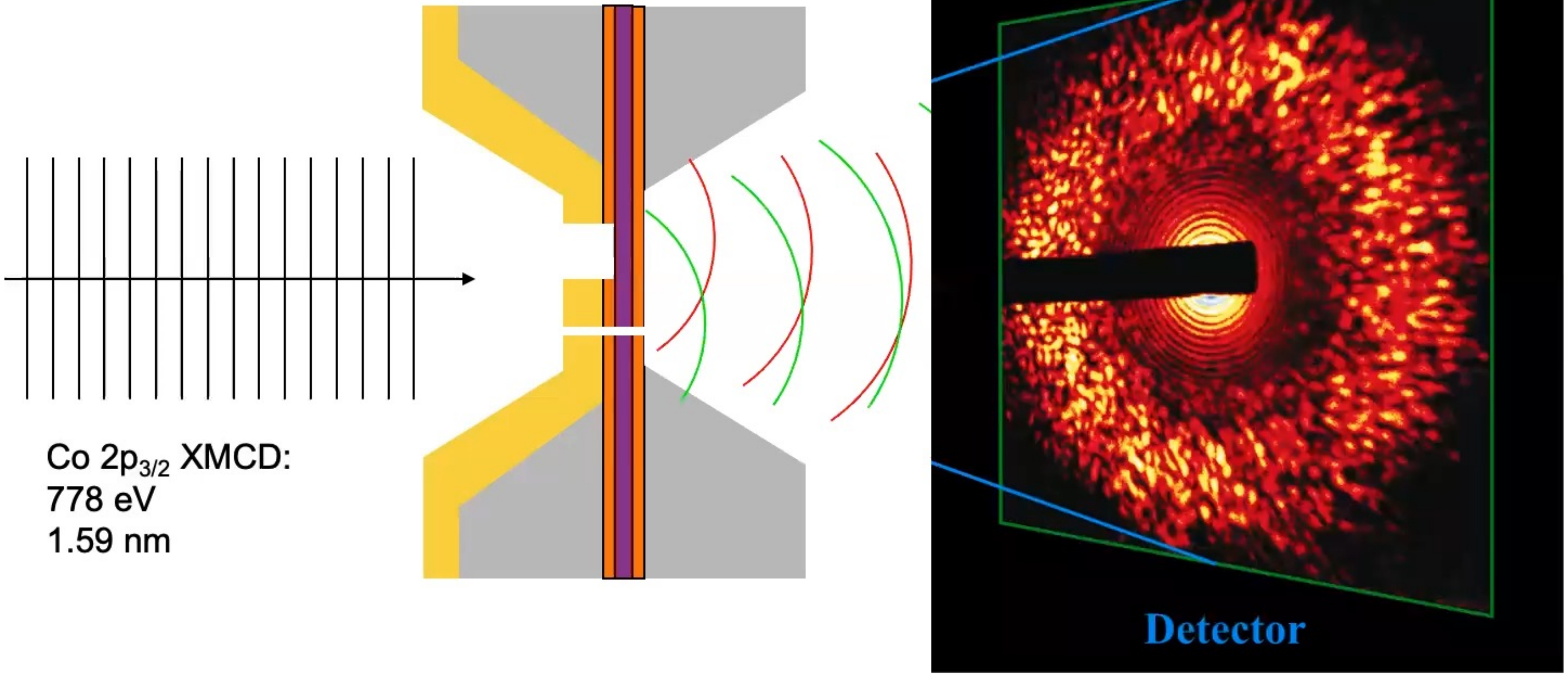
Fourier Transform Holography at λ=1.6 nm

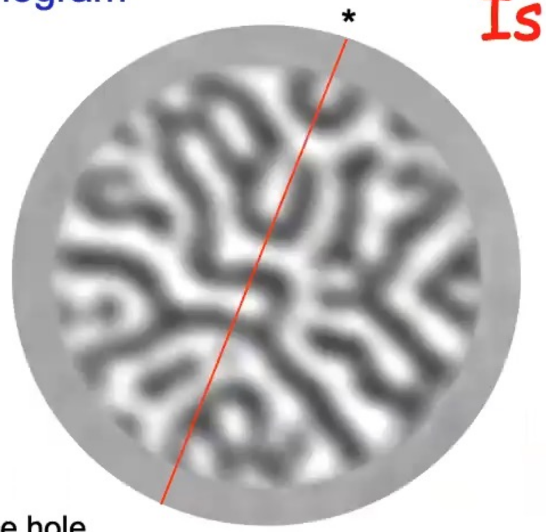


Co $2p_{3/2}$ XMCD:
778 eV
1.59 nm

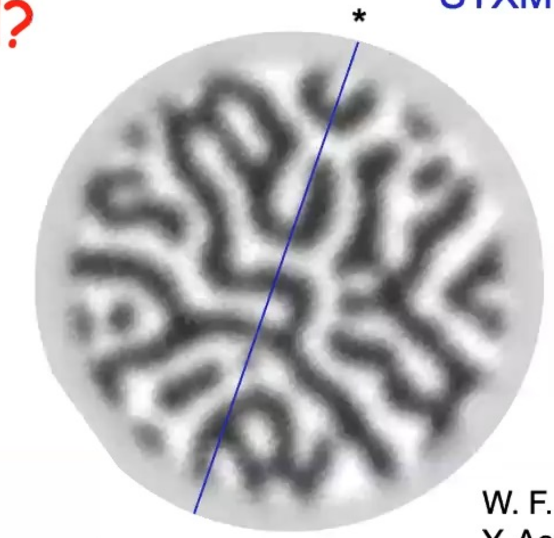
Is it real?

Is it good?

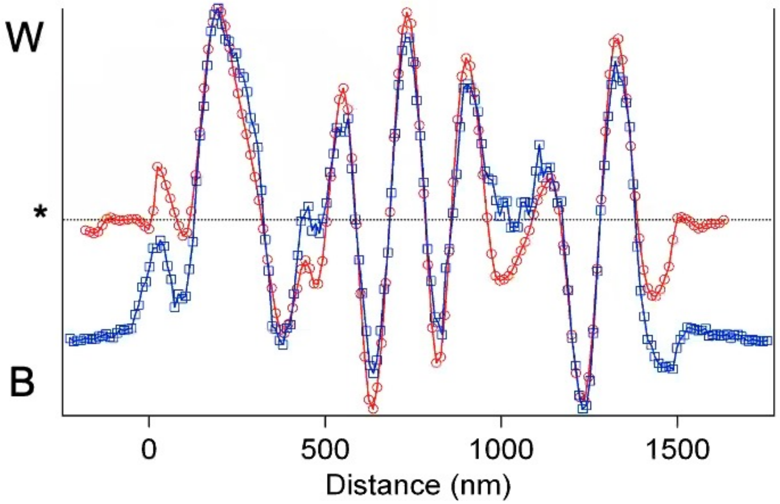
FT Hologram



STXM



Reference hole
∅ 100 nm

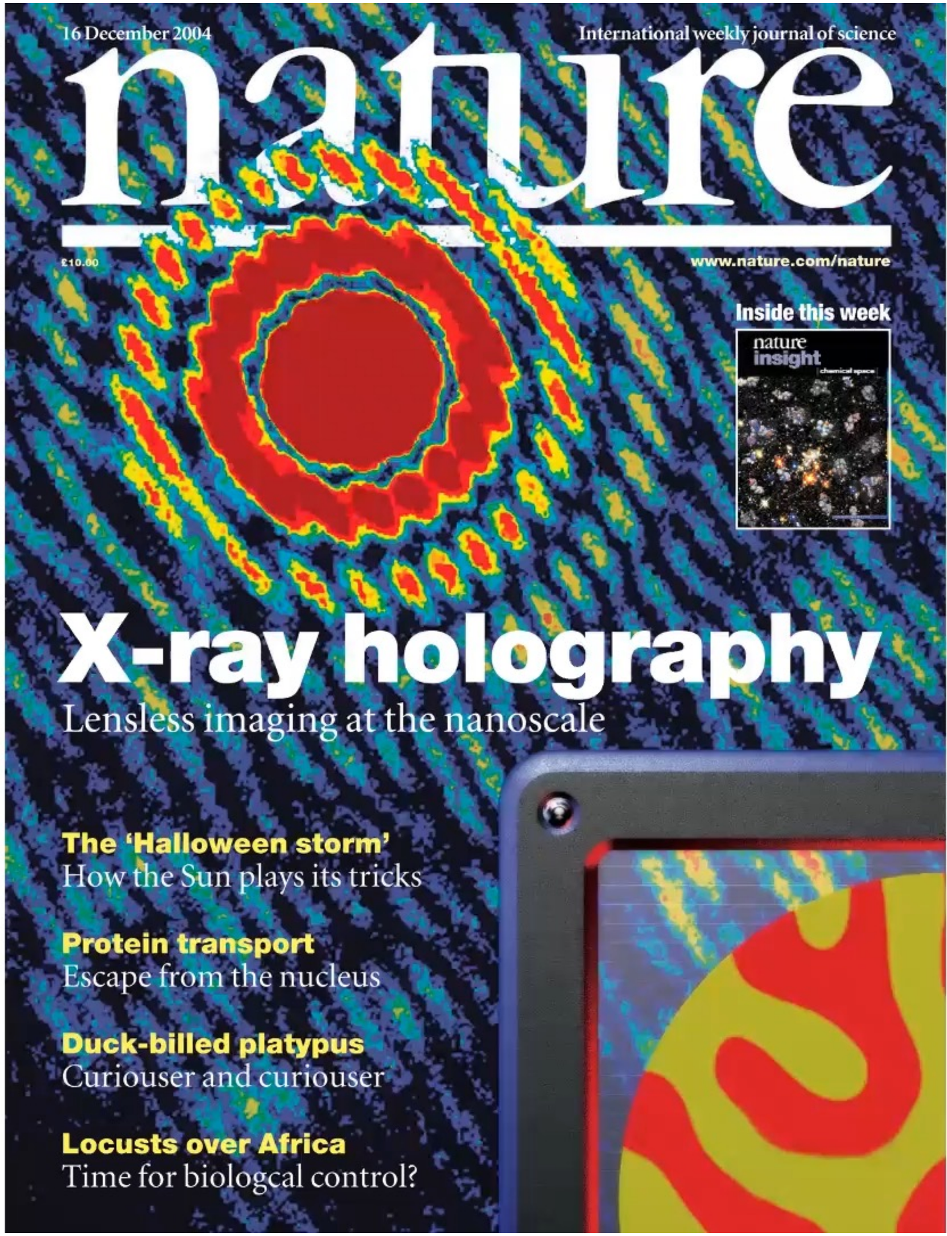


W. F. Schlotter
Y. Acremann

Resolution
30 - 40 nm

S. Eisebitt
J. Lüning
W.F. Schlotter
M. Lörgen
O. Hellwig
W. Eberhardt
J. Stöhr

NATURE **432**, 885 (2004)



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How the Sun plays its tricks

Protein transport
Escape from the nucleus

Duck-billed platypus
Curiouser and curiouser

Locusts over Africa
Time for biologcal control?

BESSY

Leland Stanford Junior University Organized 1891

SSRL

IBM
Almaden Research Center

HESEB

Summary

HESEB soft x-ray beamline

HESEB Helmholtz-SESAME Soft X-Ray Beamline for SESAME

- HESEB project is progressing well; BL has been installed in Jan 2022 (undulator in April 2022)
- First beam on June 8, 2022
- Alignment, Characterization and Commissioning
- User community building activities will increase – also in synergy with BEATS