Moderní experimentální metody
Rentgenová a elektronová spektroskopie I

Spektroskopie absorpční hrany rtg záření

- Principy, experimentální realizace
- Metody: XANES, EXAFS
- Postupy vyhodnocení dat, příklady
- Magnetismus – XMCD
- RIXS

Moderní experimentální metody
Rentgenová a elektronová spektroskopie II

Anomální rtg difrakce
- Kramersovy-Kronigovy relace
- Anomální difrakce – principy, použití
- DAFS

Flurescenční spektroskopie
- Spektroskopie charakteristického záření (XRF, EDS, WDS)
- Kvalitativní a kvantitativní analýza
- TRXRF
- Fluorescence ve stojaté vlně (SW-XRF) – rtg reflexe, difrakce

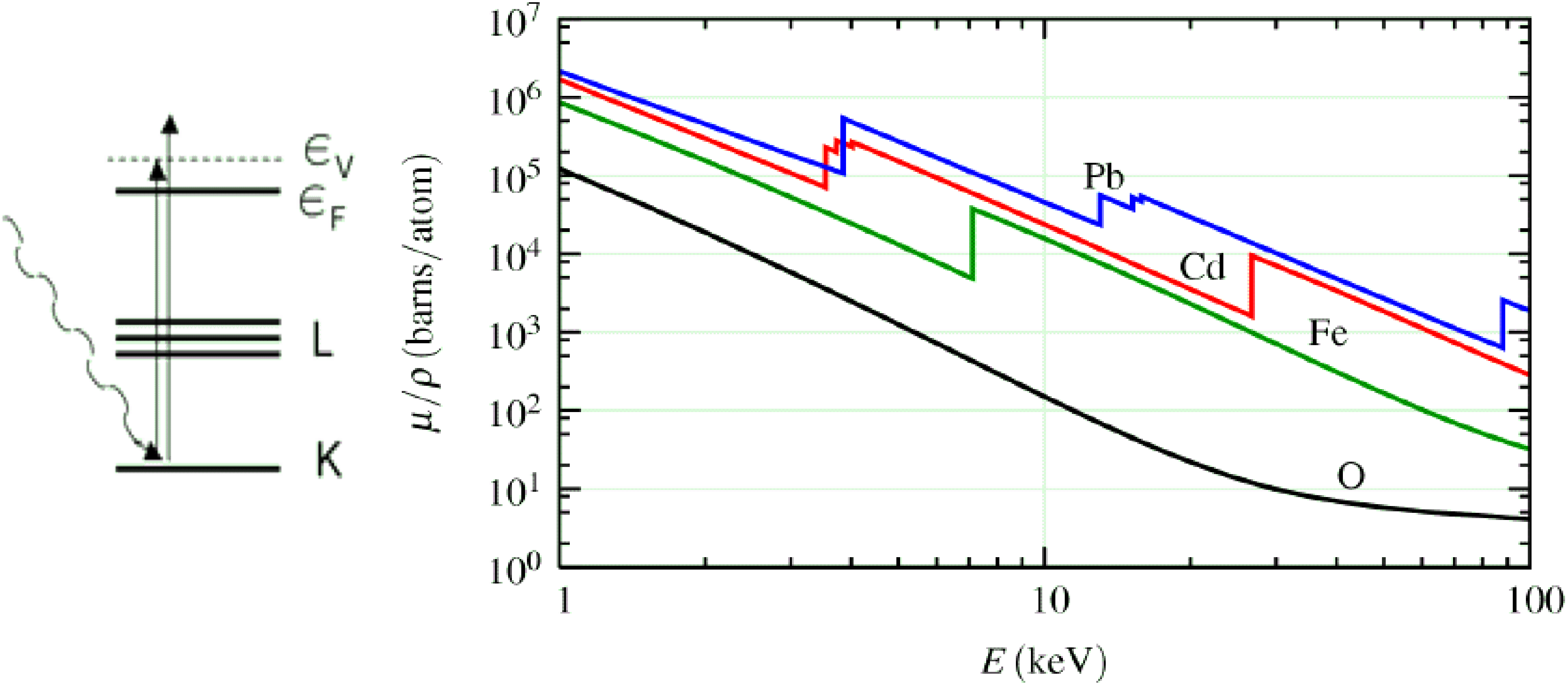
Moderní experimentální metody
Rentgenová a elektronová spektroskopie III

Fotoelektronová spektroskopie

- Fotoelektronová spektroskopie (XPS) a spektroskopie Augerových elektronů (AES)
- Úhlově rozlišená fotoelektronová spektroskopie (ARPES)
- Experimentální aspekty
- Zdroje: ARPES, ARUPS
- Detektory
- Příprava vzorků

Absorpce rtg záření

Ionizace hluboké elektronové hladiny – absorpční hrana.



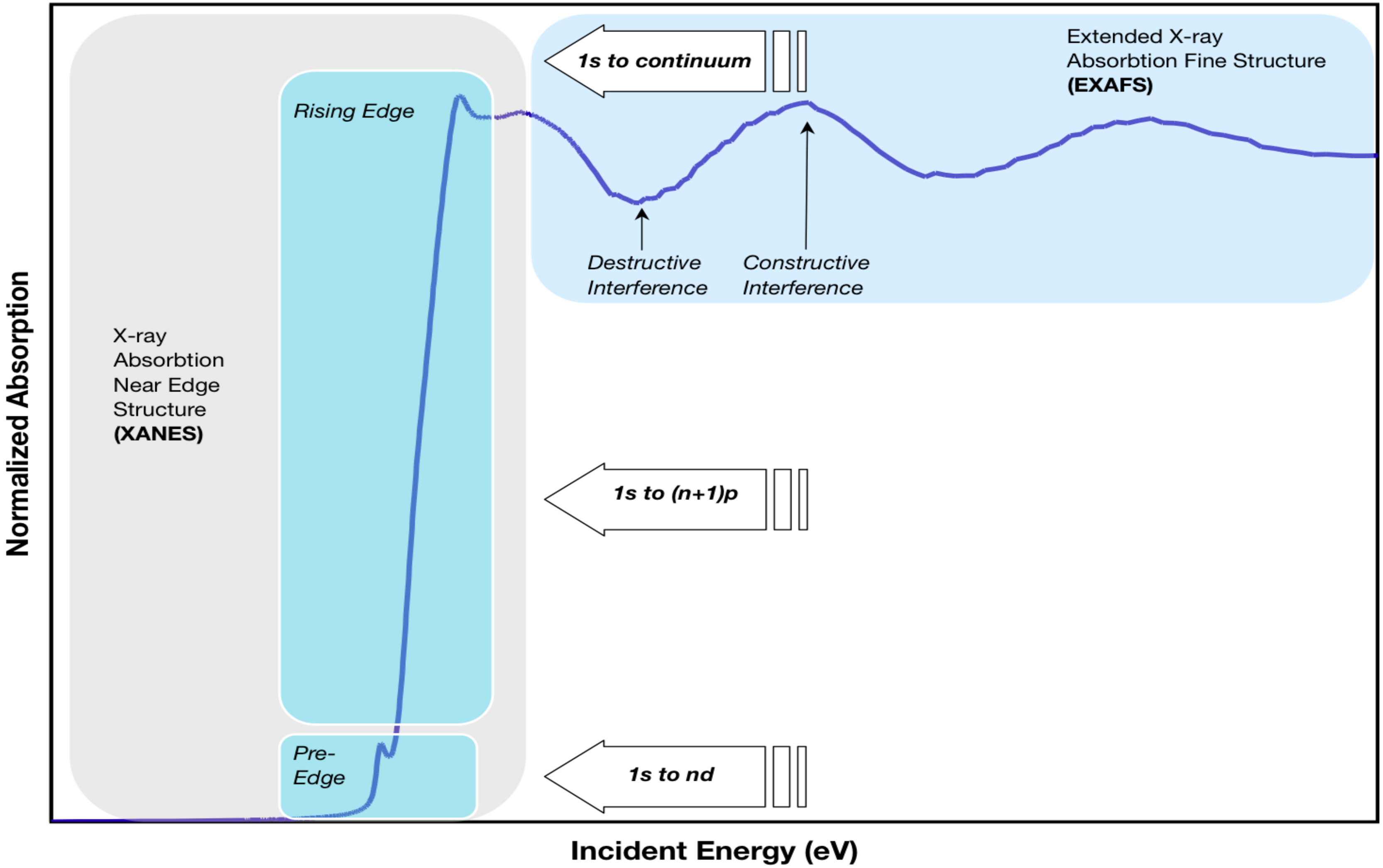
Závislost absorpce na vlnové délce pro olovo (Z=82).

Empirická závislost absorpce na energii mimo absorpční hranu:

$$\boxed{\alpha(\epsilon) = \frac{a}{\epsilon^3} + \frac{b}{\epsilon^4}\ ,}$$

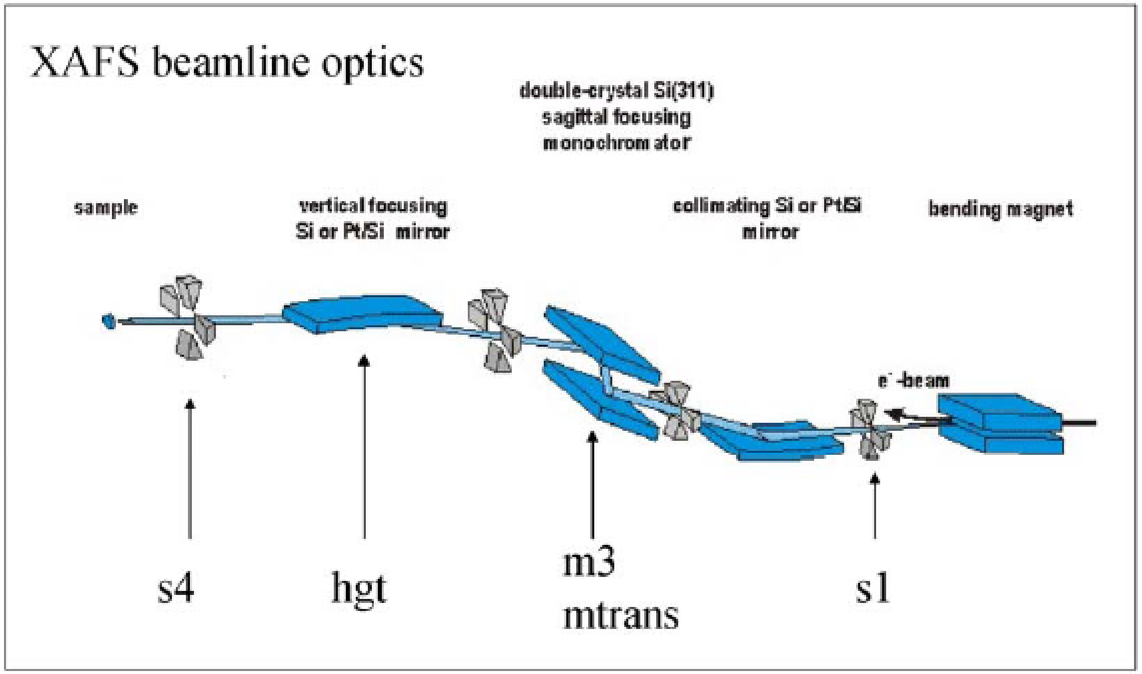
XAFS

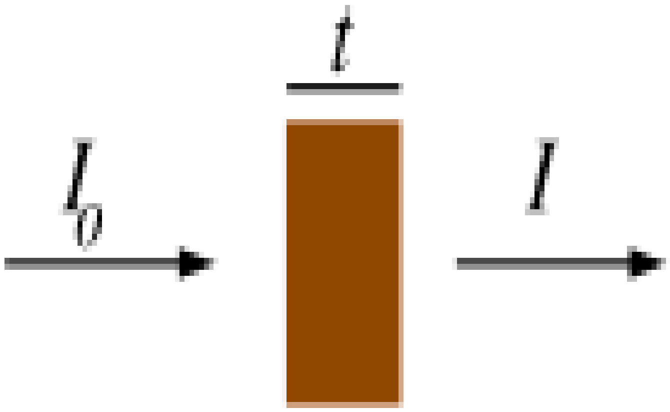
Rentgenová absorpční spektroskopie jemné struktury
X-ray absorption fine structure – XAFS
Extended x-ray absorption fine structure – EXAFS
Near-edge x-ray absorption fine structure – NEXAFS
X-ray absorption near-edge structure – XANES

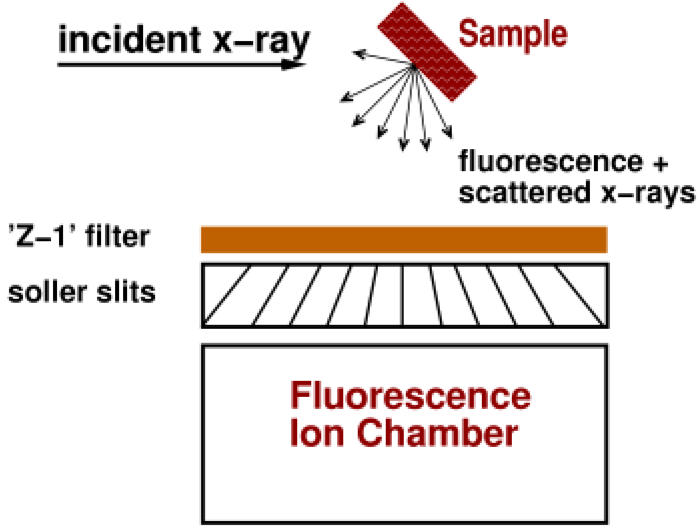


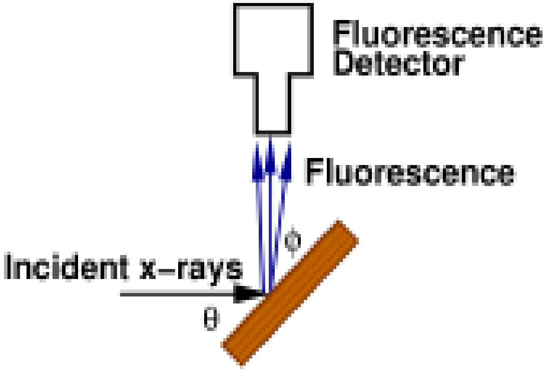
XAFS

Rentgenová absorpční spektroskopie jemné struktury
Uspořádání experimentu ESRF BM26A



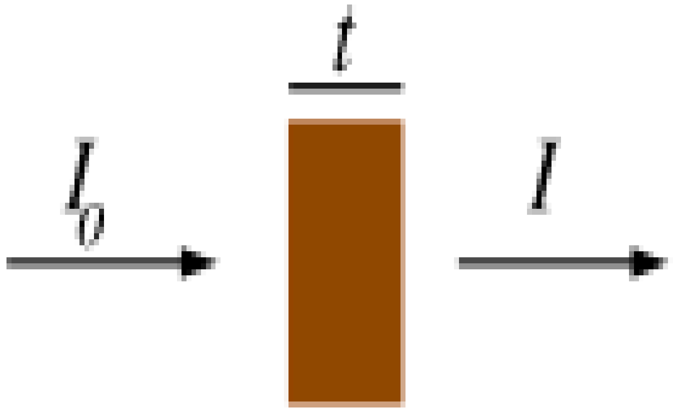


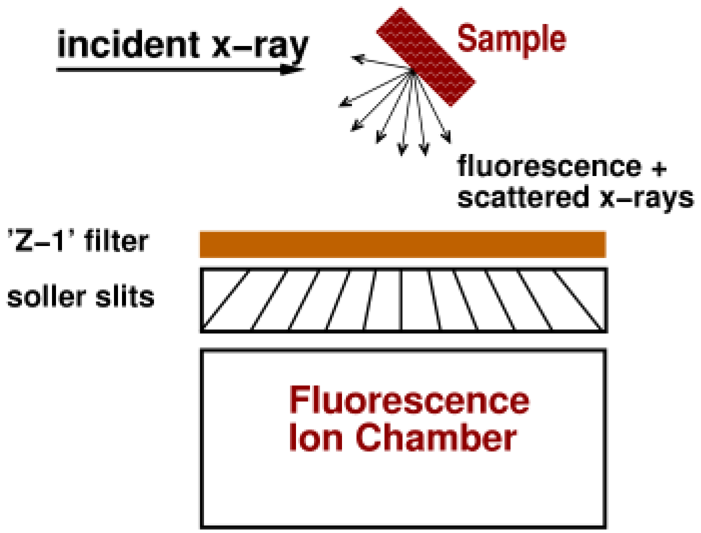




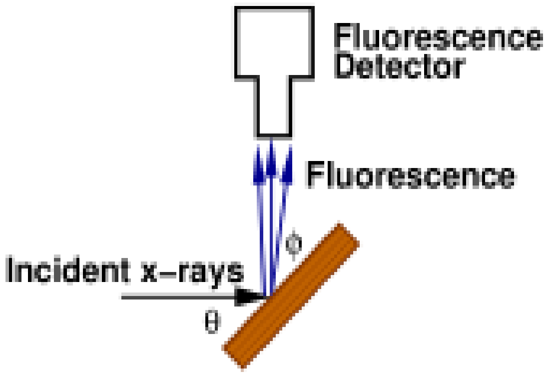
XAFS

Rentgenová absorpční spektroskopie jemné struktury
Uspořádání experimentu



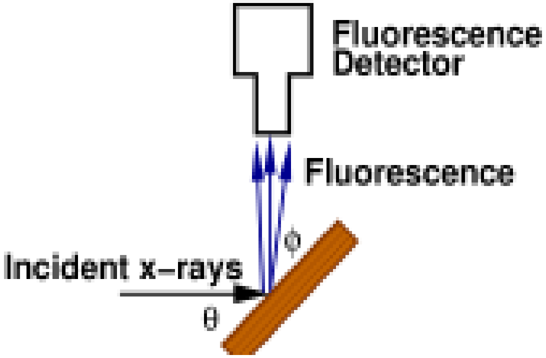


Electron yield measurement



XAFS

Rentgenová absorpční spektroskopie jemné struktury



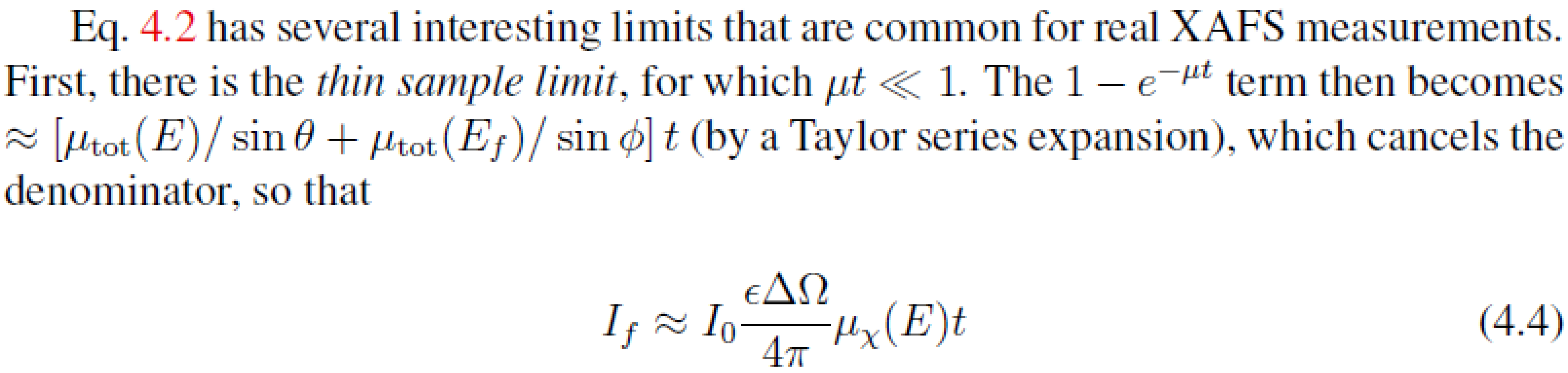
$$\mu(E) \propto I_f / I_0.$$

$$I_f = I_0 \frac{\epsilon \Delta\Omega}{4\pi} \frac{\mu_\chi(E)\left\{1 - e^{-[\mu_{\mathrm{tot}}(E)/\sin\theta + \mu_{\mathrm{tot}}(E_f)/\sin\phi]t}\right\}}{\mu_{\mathrm{tot}}(E)/\sin\theta + \mu_{\mathrm{tot}}(E_f)/\sin\phi}$$

$$\mu_{\mathrm{tot}}(E) = \mu_\chi(E) + \mu_{\mathrm{other}}(E)$$

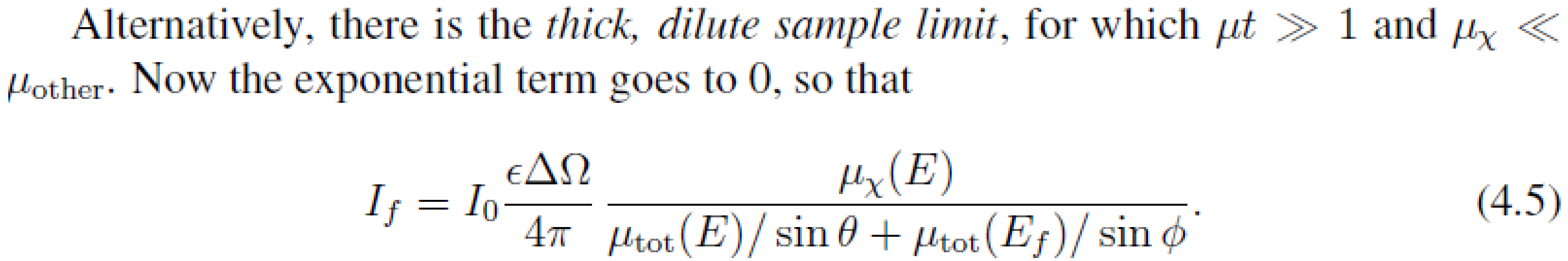
XAFS

Rentgenová absorpční spektroskopie jemné struktury



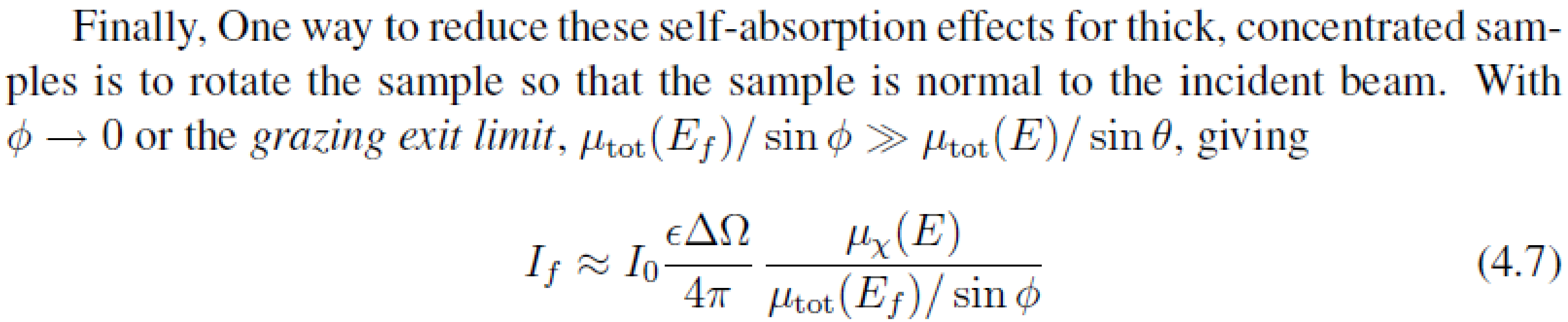
Eq. 4.2 has several interesting limits that are common for real XAFS measurements. First, there is the *thin sample limit*, for which $\mu t \ll 1$. The $1 - e^{-\mu t}$ term then becomes $\approx [\mu_{\text{tot}}(E)/\sin\theta + \mu_{\text{tot}}(E_f)/\sin\phi]\, t$ (by a Taylor series expansion), which cancels the denominator, so that

$$I_f \approx I_0 \frac{\epsilon \Delta\Omega}{4\pi} \mu_\chi(E) t \tag{4.4}$$



Alternatively, there is the *thick, dilute sample limit*, for which $\mu t \gg 1$ and $\mu_\chi \ll \mu_{\text{other}}$. Now the exponential term goes to 0, so that

$$I_f = I_0 \frac{\epsilon \Delta\Omega}{4\pi} \frac{\mu_\chi(E)}{\mu_{\text{tot}}(E)/\sin\theta + \mu_{\text{tot}}(E_f)/\sin\phi}. \tag{4.5}$$



Finally, One way to reduce these self-absorption effects for thick, concentrated samples is to rotate the sample so that the sample is normal to the incident beam. With $\phi \to 0$ or the *grazing exit limit*, $\mu_{\text{tot}}(E_f)/\sin\phi \gg \mu_{\text{tot}}(E)/\sin\theta$, giving

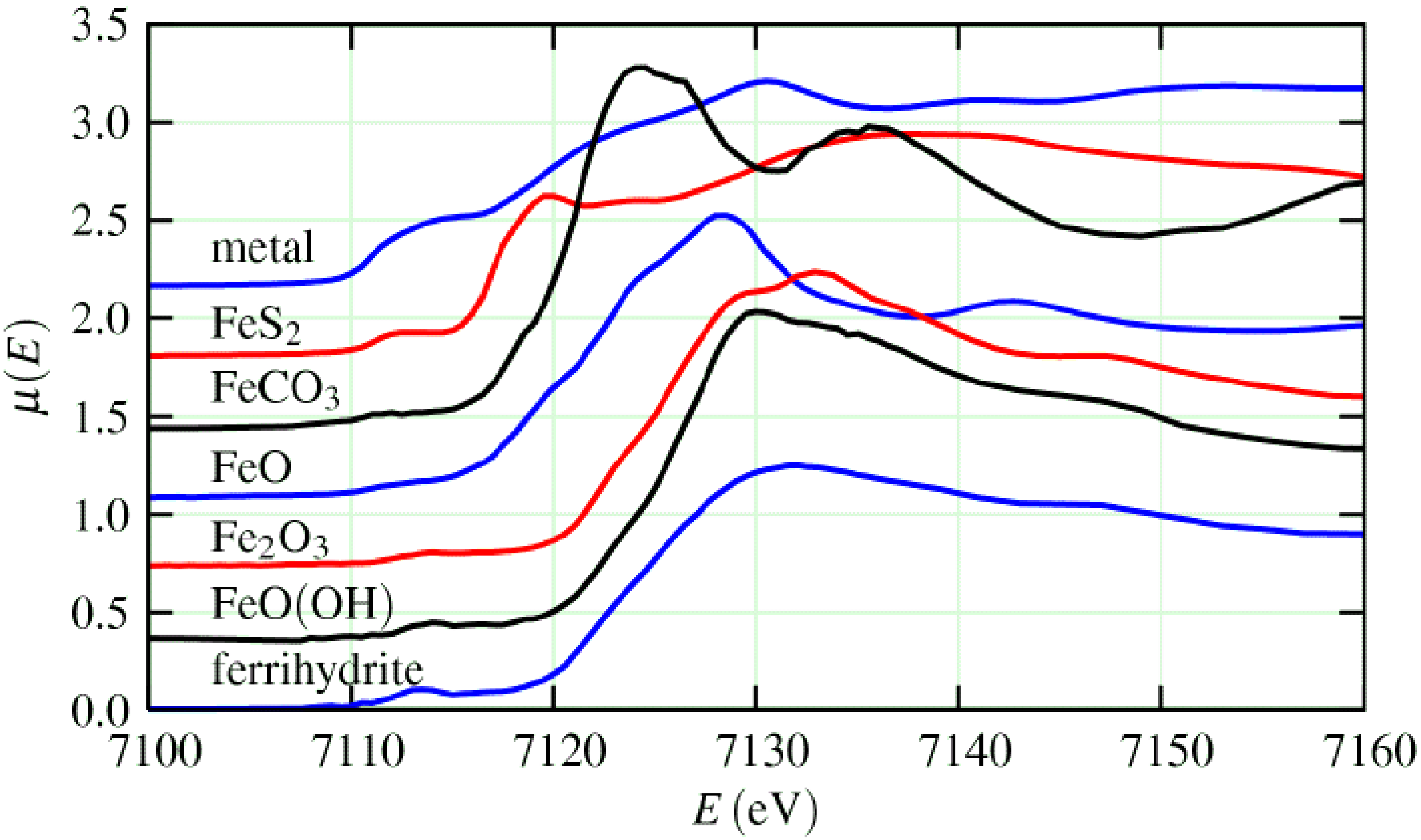
$$I_f \approx I_0 \frac{\epsilon \Delta\Omega}{4\pi} \frac{\mu_\chi(E)}{\mu_{\text{tot}}(E_f)/\sin\phi} \tag{4.7}$$

XANES

Profil absorpční hrany závisí na chemickém stavu atomu. Nutný kvantově-mechanický výpočet.

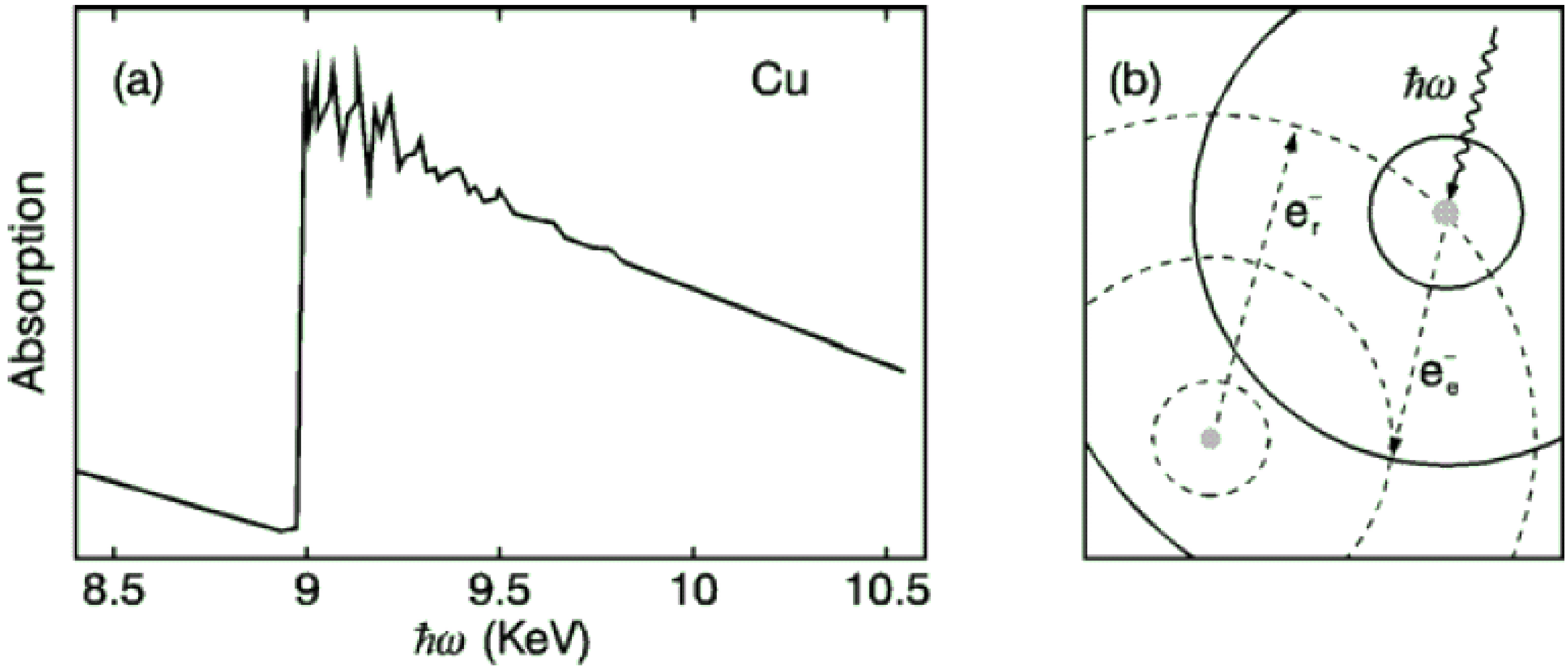
Přechod z hluboké hladiny do volných stavů nad Fermiho mezí.

Příklad pro železo v různých chemických stavech.



EXAFS

Jemná struktura okolí absorpční hrany – určení poloh nejbližších atomů.



Propustnost

$$T(\epsilon) = \mathrm{e}^{-\mu(\epsilon)t}$$

Normovaná absorpce

$$\chi(\epsilon) = \frac{\mu(\epsilon) - \mu_0}{\Delta\mu_{\mathrm{edge}}}$$

EXAFS

Vlnový vektor
excitovaného elektronu

$$k_e^2 = \frac{2m_e}{\hbar^2}(\epsilon - \epsilon_0)$$

Příspěvek jednoho atomu ve vzdálenosti *R*

$$\chi(k) = \frac{f(k)}{kR^2}\sin[2kR + \delta(k)]$$

Celková amplitude středovaná přes polohy a typ sousedů

Závislost úměrná R^{-2} – citlivé maximálně na třetí nejbližší sousedy.

EXAFS

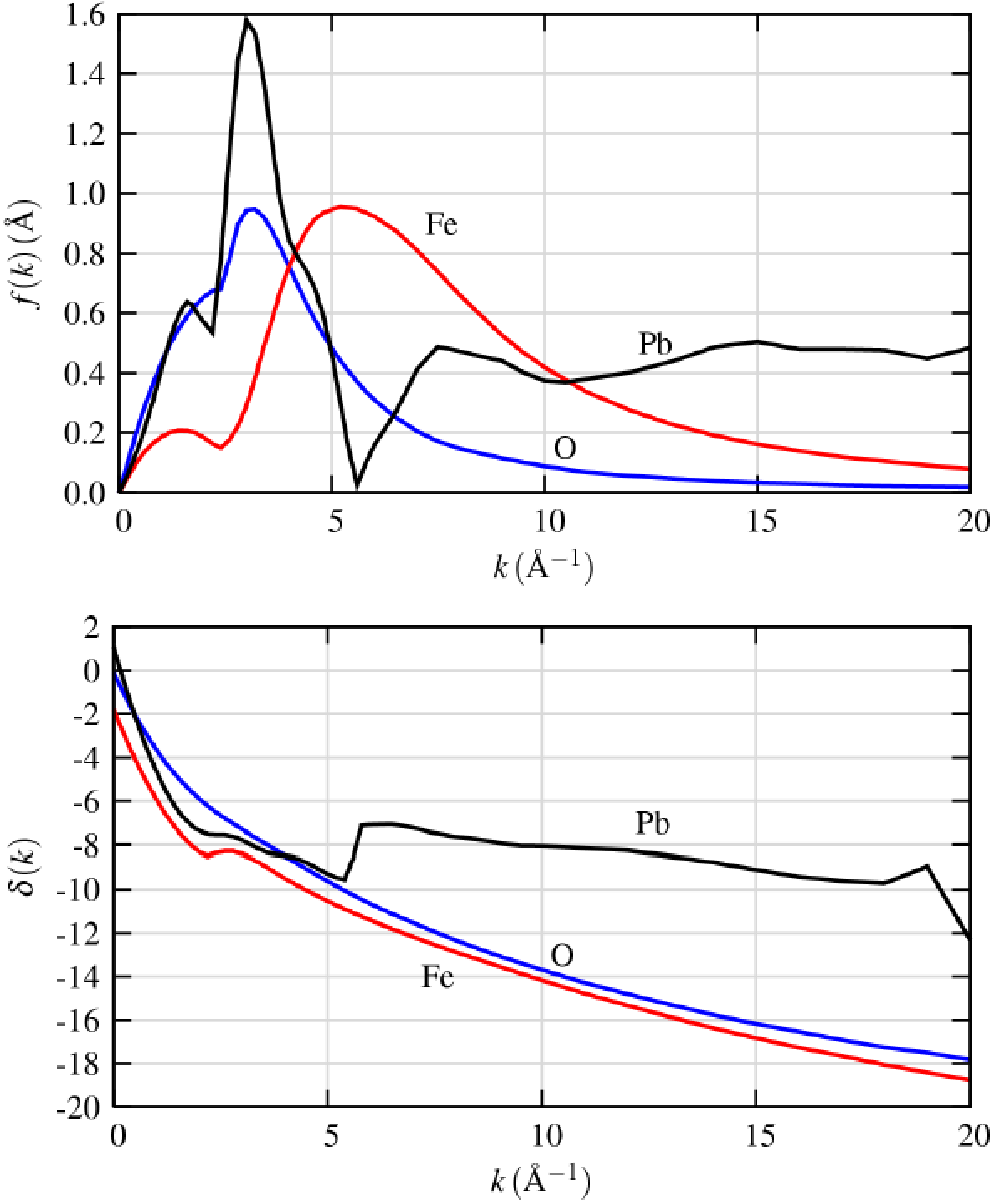
Příspěvek jednoho atomu ve vzdálenosti *R*

$$\chi(k) = \sum_j \frac{N_j e^{-2k^2\sigma_j^2} e^{-2R_j/\lambda(k)} f_j(k)}{kR_j^2} \sin[2kR_j + \delta_j(k)]$$

Celková amplitude středovaná přes polohy a typ sousedů

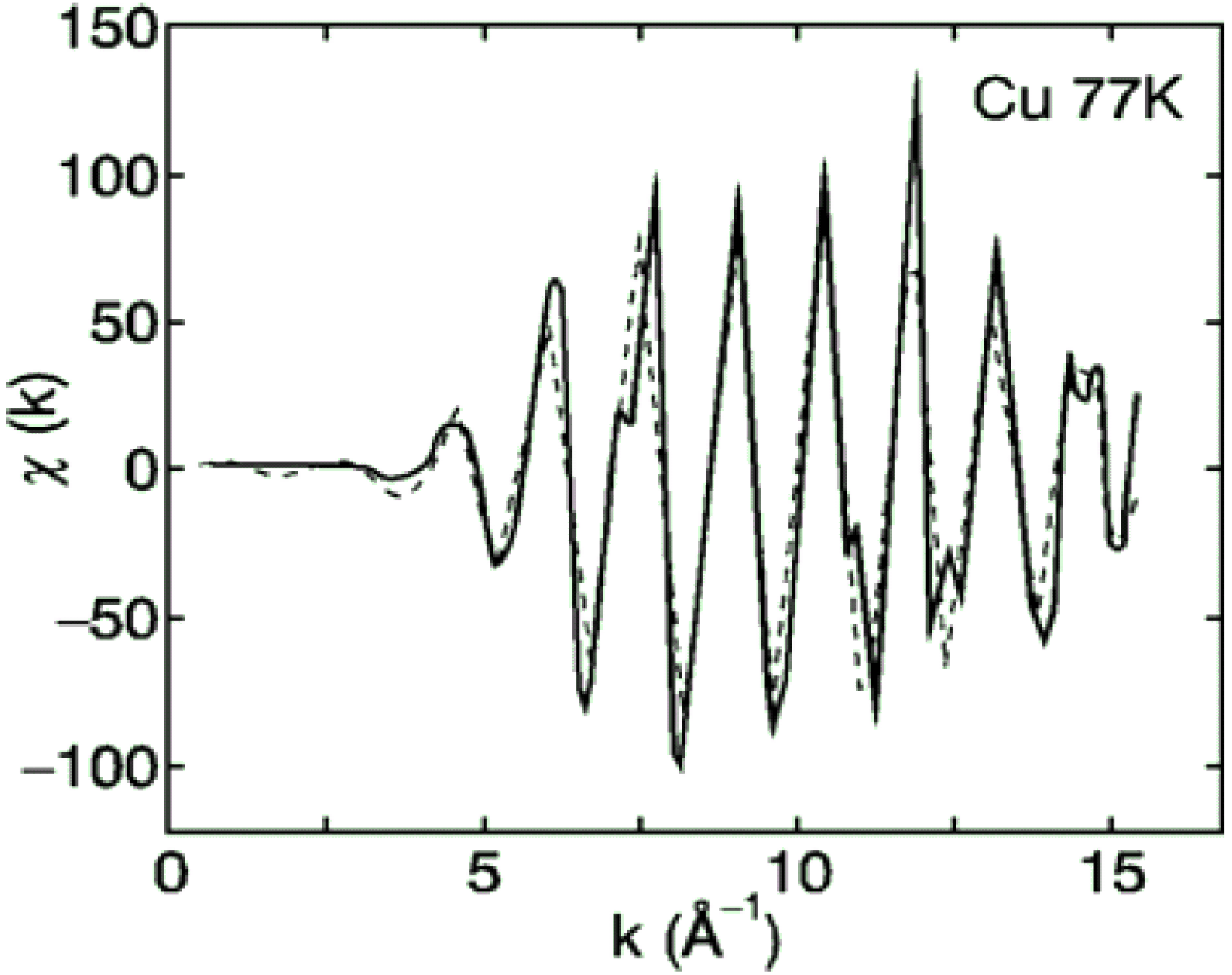
Závislost úměrná R^{-2} – citlivé maximálně na třetí nejbližší sousedy.

EXAFS


1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$f(k)$ (Å)
Fe
Pb
O
0
5
10
15
20
k (Å^{-1})
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
$\delta(k)$
Pb
O
Fe
0
5
10
15
20
k (Å^{-1})

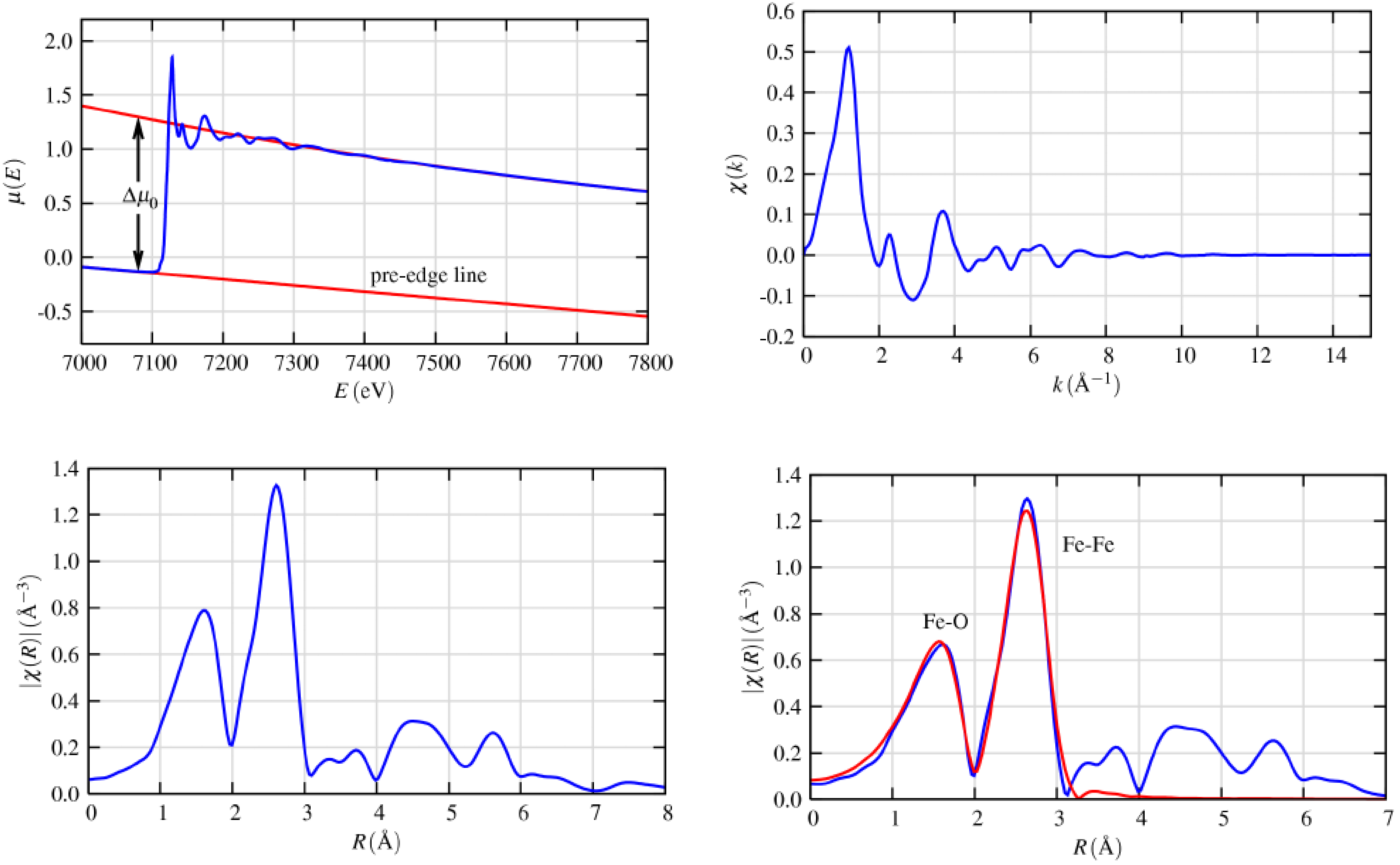
EXAFS

Normovaný koeficient absorpce pro měď.
Měření čárkovaně, simulace plnou čarou.



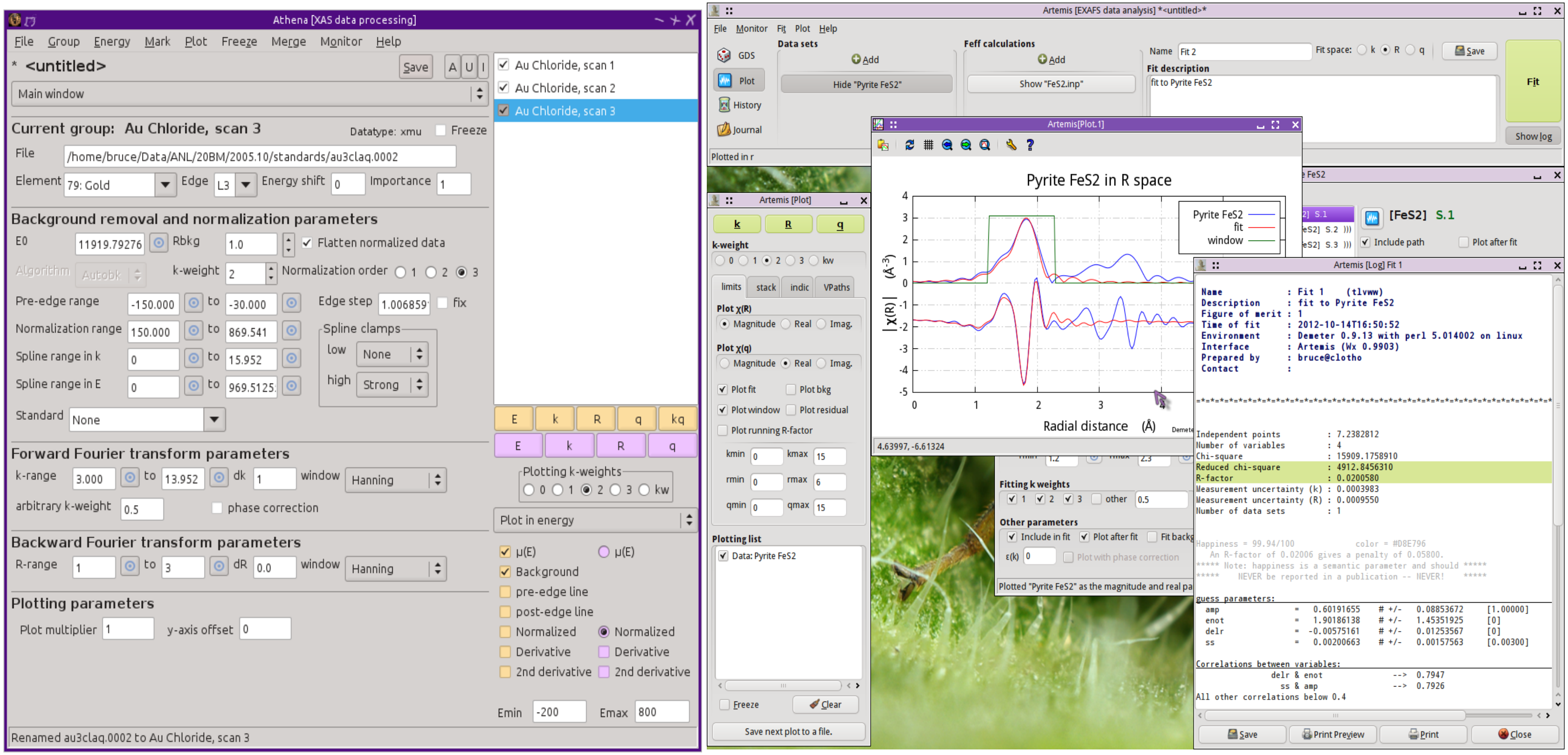
EXAFS

Fe-O data



EXAFS + XANES analytický software

- FEFF
- FDMNES
- Demeter (Bruce Ravel):
    - Athena
    - Artemis
    - Hephaestus



* <untitled>

Current group: Au Chloride, scan 3

Datatype: xmu

File: /home/bruce/Data/ANL/20BM/2005.10/standards/au3claq.0002

Element: 79: Gold — Edge: L3 — Energy shift: 0 — Importance: 1

Background removal and normalization parameters

E0: 11919.79276 — Rbkg: 1.0 — ☑ Flatten normalized data

k-weight: 2 — Normalization order: ○ 1 ○ 2 ● 3

Pre-edge range: -150.000 to -30.000 — Edge step: 1.006859 ☐ fix

Normalization range: 150.000 to 869.541

Spline range in k: 0 to 15.952

Spline range in E: 0 to 969.5125

Spline clamps: low None, high Strong

Standard: None

Forward Fourier transform parameters

k-range: 3.000 to 13.952 — dk: 1 — window: Hanning

arbitrary k-weight: 0.5 — ☐ phase correction

Backward Fourier transform parameters

R-range: 1 to 3 — dR: 0.0 — window: Hanning

Plotting parameters

Plot multiplier: 1 — y-axis offset: 0

☑ Au Chloride, scan 1

☑ Au Chloride, scan 2

☑ Au Chloride, scan 3

Plotting k-weights: ○ 0 ○ 1 ● 2 ○ 3 ○ kw

Plot in energy

☑ μ(E) ○ μ(E)

☑ Background

☐ pre-edge line

☐ post-edge line

☐ Normalized ● Normalized

☐ Derivative ☐ Derivative

☐ 2nd derivative ☐ 2nd derivative

Emin: -200 — Emax: 800

Renamed au3claq.0002 to Au Chloride, scan 3

Name: Fit 2 — Fit space: ○ k ● R ○ q

Fit description: fit to Pyrite FeS2

Hide "Pyrite FeS2" — Show "FeS2.inp"

Plotted in r

k-weight: ○ 0 ○ 1 ● 2 ○ 3 ○ kw

Plot χ(R): ● Magnitude ○ Real ○ Imag.

Plot χ(q): ○ Magnitude ● Real ○ Imag.

☑ Plot fit ☐ Plot bkg

☑ Plot window ☐ Plot residual

☐ Plot running R-factor

kmin: 0 kmax: 15

rmin: 0 rmax: 6

qmin: 0 qmax: 15

Plotting list: ☑ Data: Pyrite FeS2

Save next plot to a file.

4.63997, -6.61324

[FeS2] S.1 — ☑ Include path — ☐ Plot after fit

Fitting k weights: ☑ 1 ☑ 2 ☑ 3 ☐ other 0.5

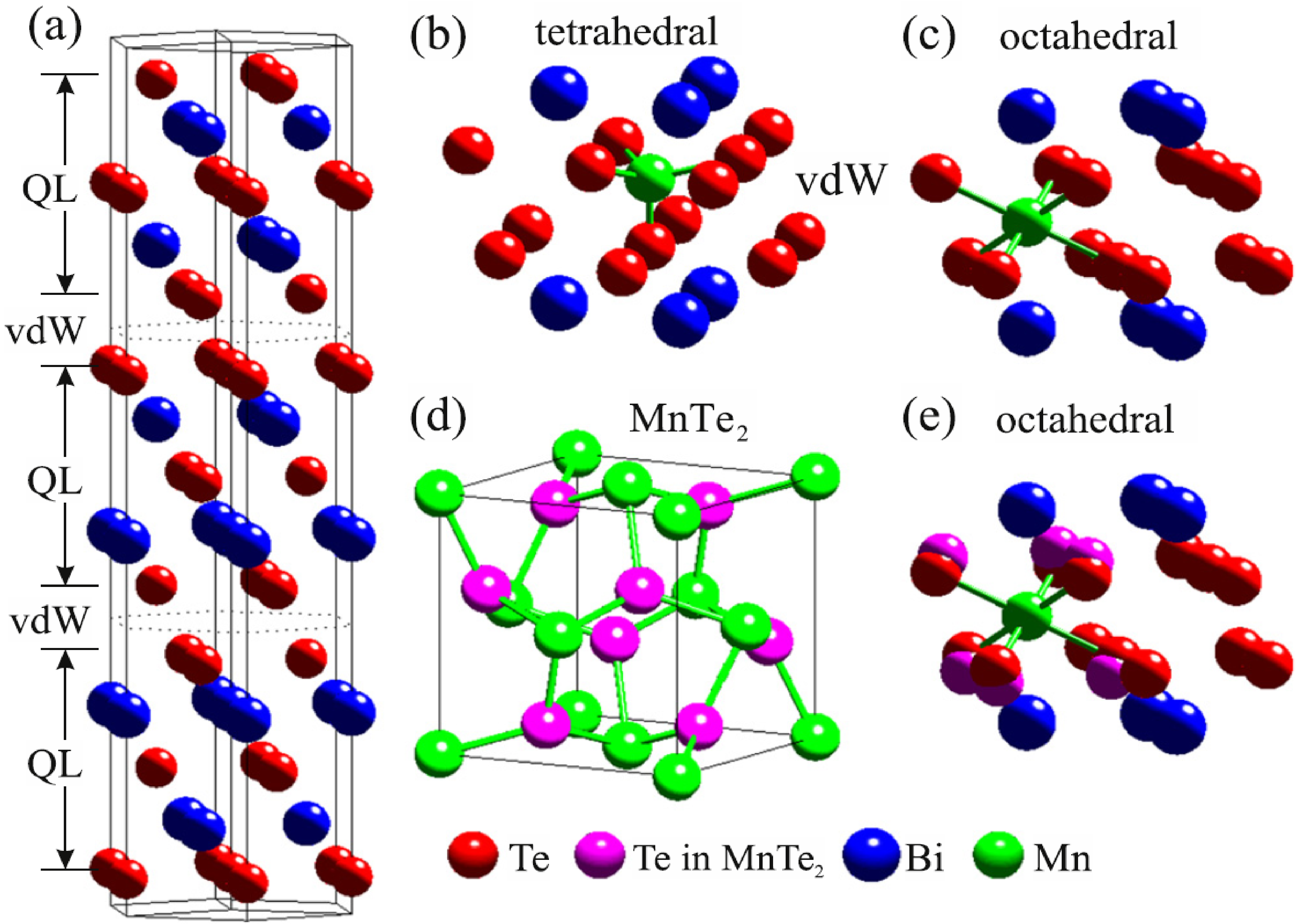
Other parameters: ☑ Include in fit ☑ Plot after fit

Plotted "Pyrite FeS2" as the magnitude and real pa

```
Name             : Fit 1    (tlvww)
Description      : fit to Pyrite FeS2
Figure of merit  : 1
Time of fit      : 2012-10-14T16:50:52
Environment      : Demeter 0.9.13 with perl 5.014002 on linux
Interface        : Artemis (Wx 0.9903)
Prepared by      : bruce@clotho
Contact          :

=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*=*

Independent points          : 7.2382812
Number of variables         : 4
Chi-square                  : 15909.1758910
Reduced chi-square          : 4912.8456310
R-factor                    : 0.0200580
Measurement uncertainty (k) : 0.0003983
Measurement uncertainty (R) : 0.0009550
Number of data sets         : 1


Happiness = 99.94/100           color = #D8E796
   An R-factor of 0.02006 gives a penalty of 0.05800.
***** Note: happiness is a semantic parameter and should *****
*****    NEVER be reported in a publication -- NEVER!    *****

guess parameters:
  amp            =   0.60191655    # +/-    0.08853672    [1.00000]
  enot           =   1.90186138    # +/-    1.45351925    [0]
  delr           =  -0.00575161    # +/-    0.01253567    [0]
  ss             =   0.00200663    # +/-    0.00157563    [0.00300]

Correlations between variables:
               delr & enot              -->  0.7947
                 ss & amp               -->  0.7926
All other correlations below 0.4
```

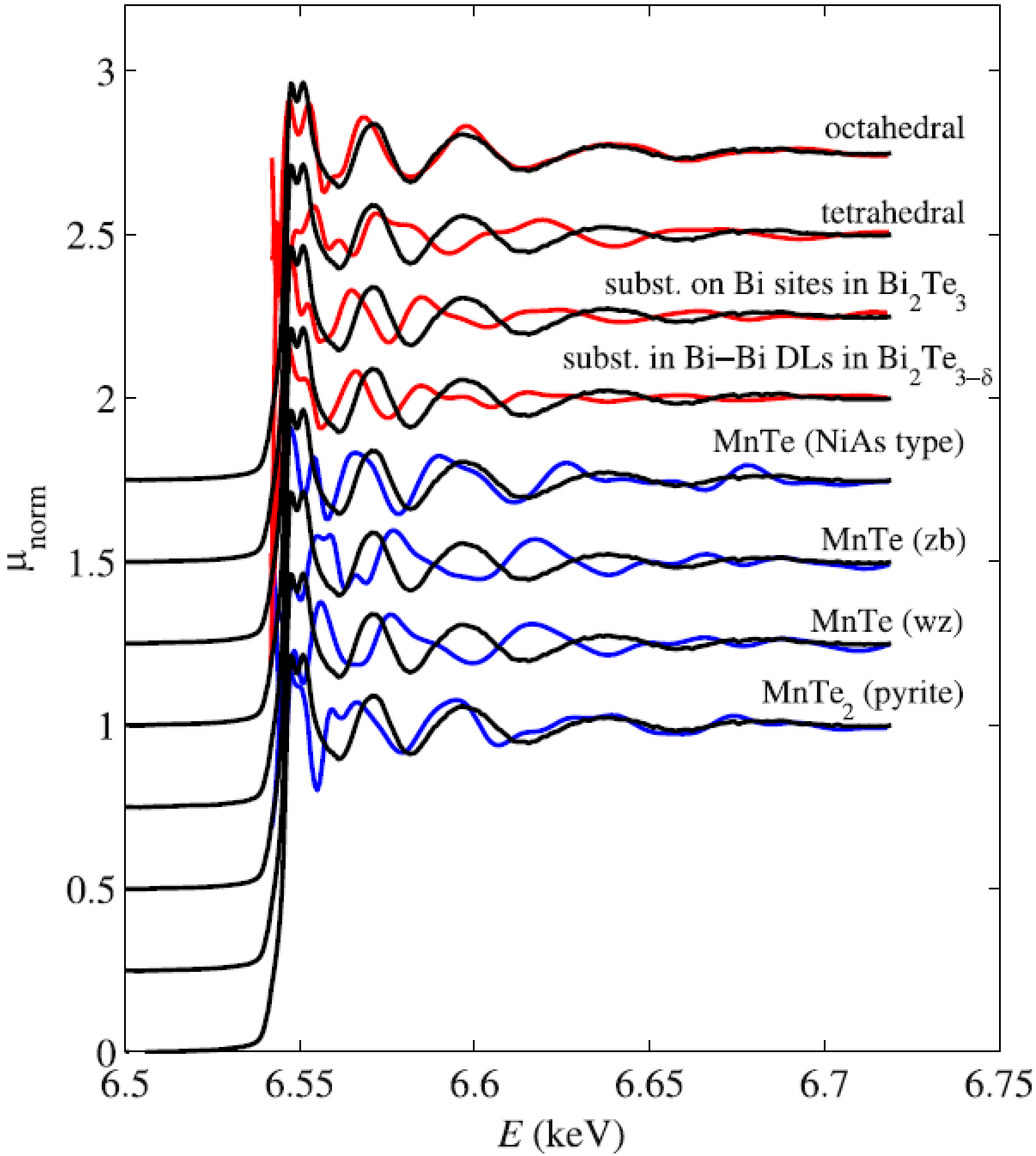
EXAFS

Mn in BiTe

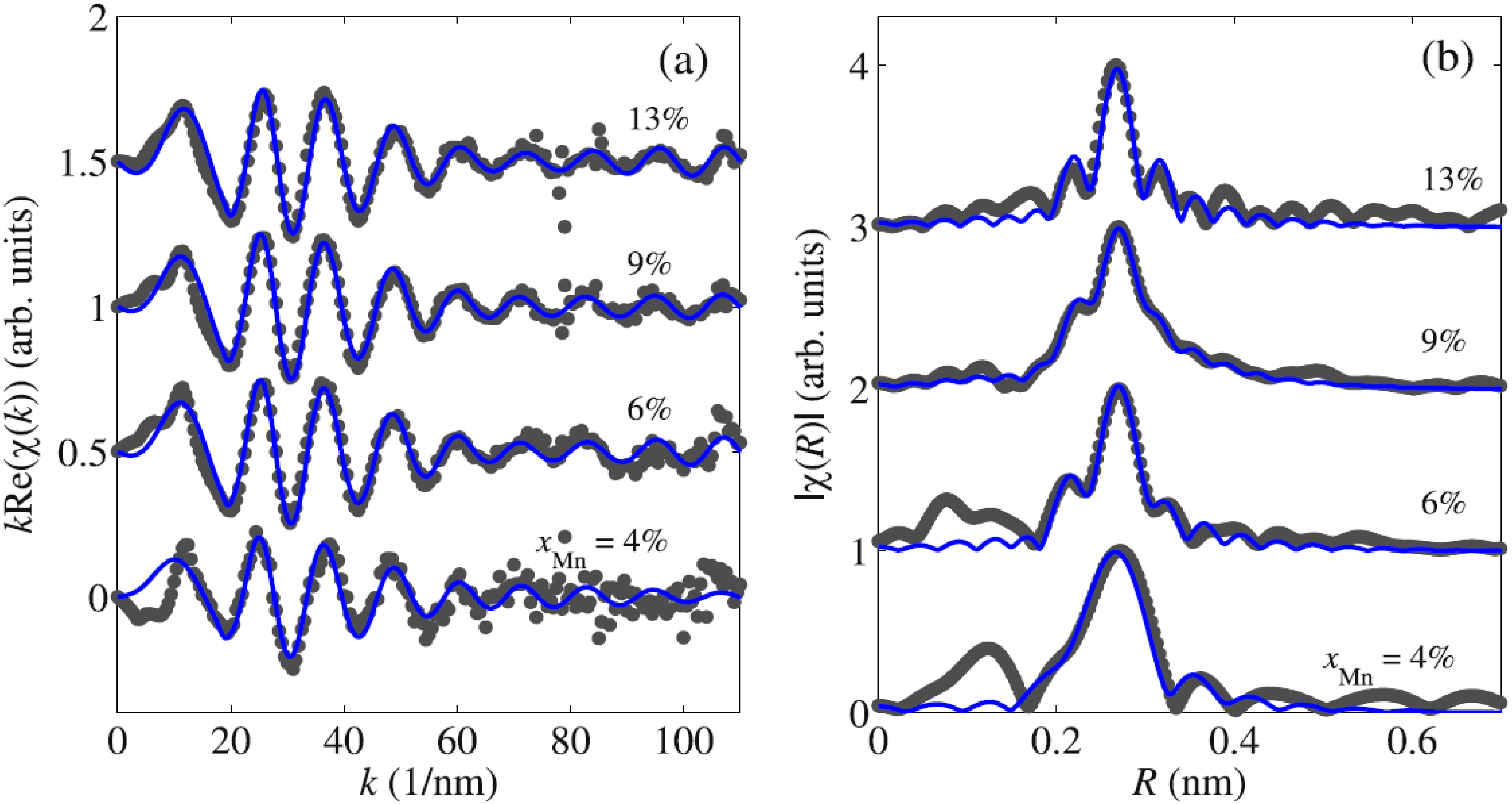


EXAFS

Mn in BiTe



EXAFS

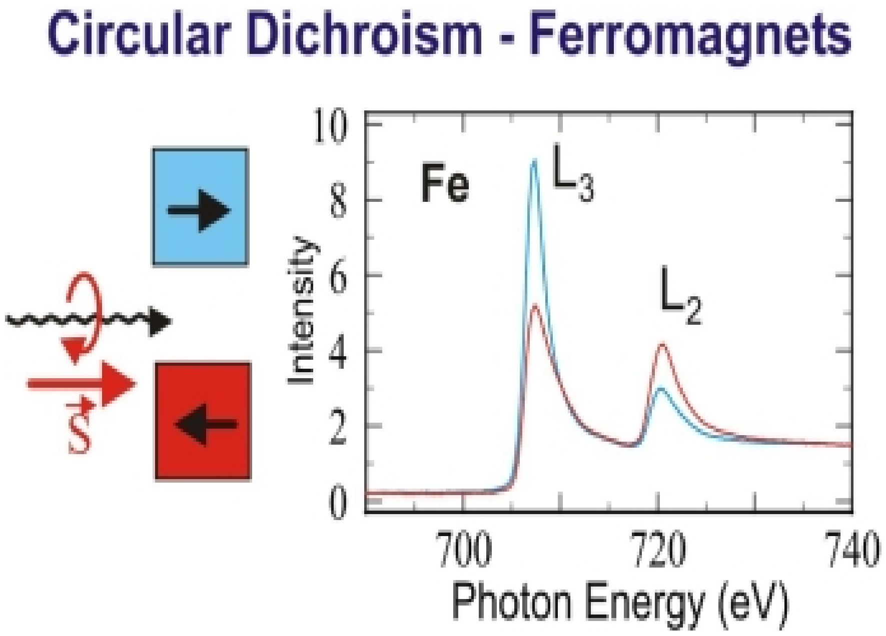


x_{Mn} (%)	d_{Mn-Te} (nm)	d_{Mn-Bi} (nm)
4	0.290 ± 0.009	—
6	0.292 ± 0.004	0.304 ± 0.010
9	0.292 ± 0.004	0.303 ± 0.010
13	0.291 ± 0.006	0.306 ± 0.014

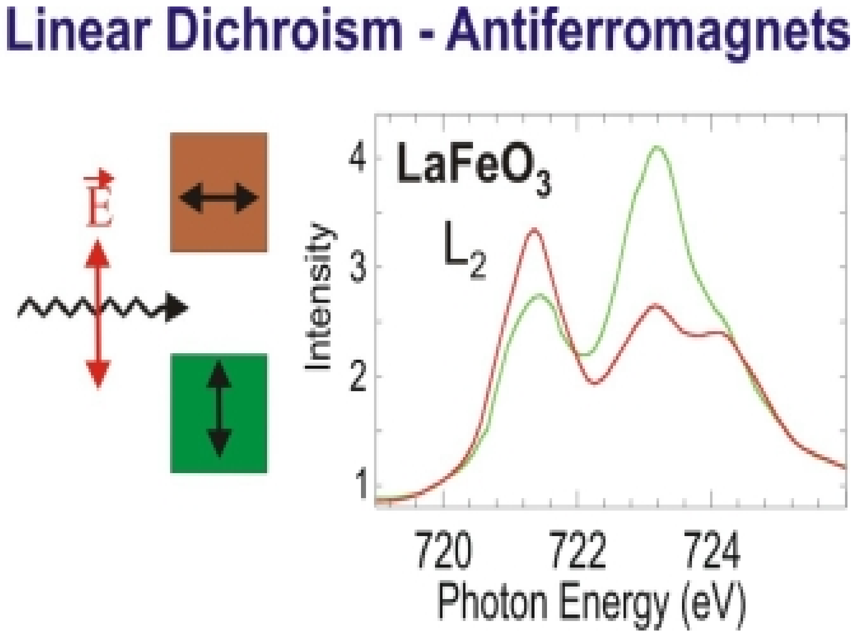
XMCD

Absorpce na hladinách s orbitálním momentem

Povrchově citlivé,
Prvkově citlivé



Circular Dichroism - Ferromagnets

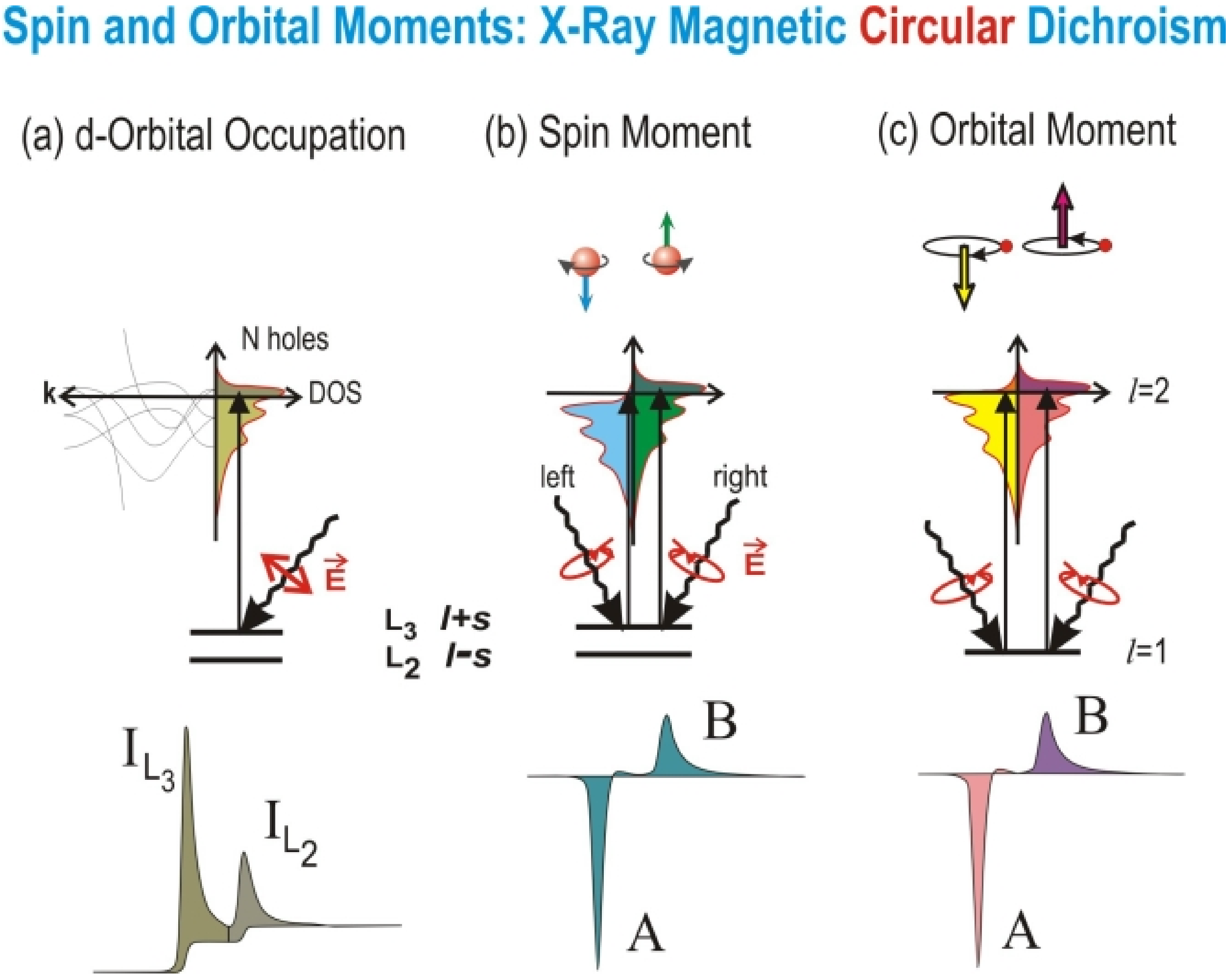


Linear Dichroism - Antiferromagnets

Asymmetry $A=(I_+-I_-)/(I_++I_-)$

XMCD

Absorpce na hladinách s nenulovým orbitálním momentem (vyšší než K)

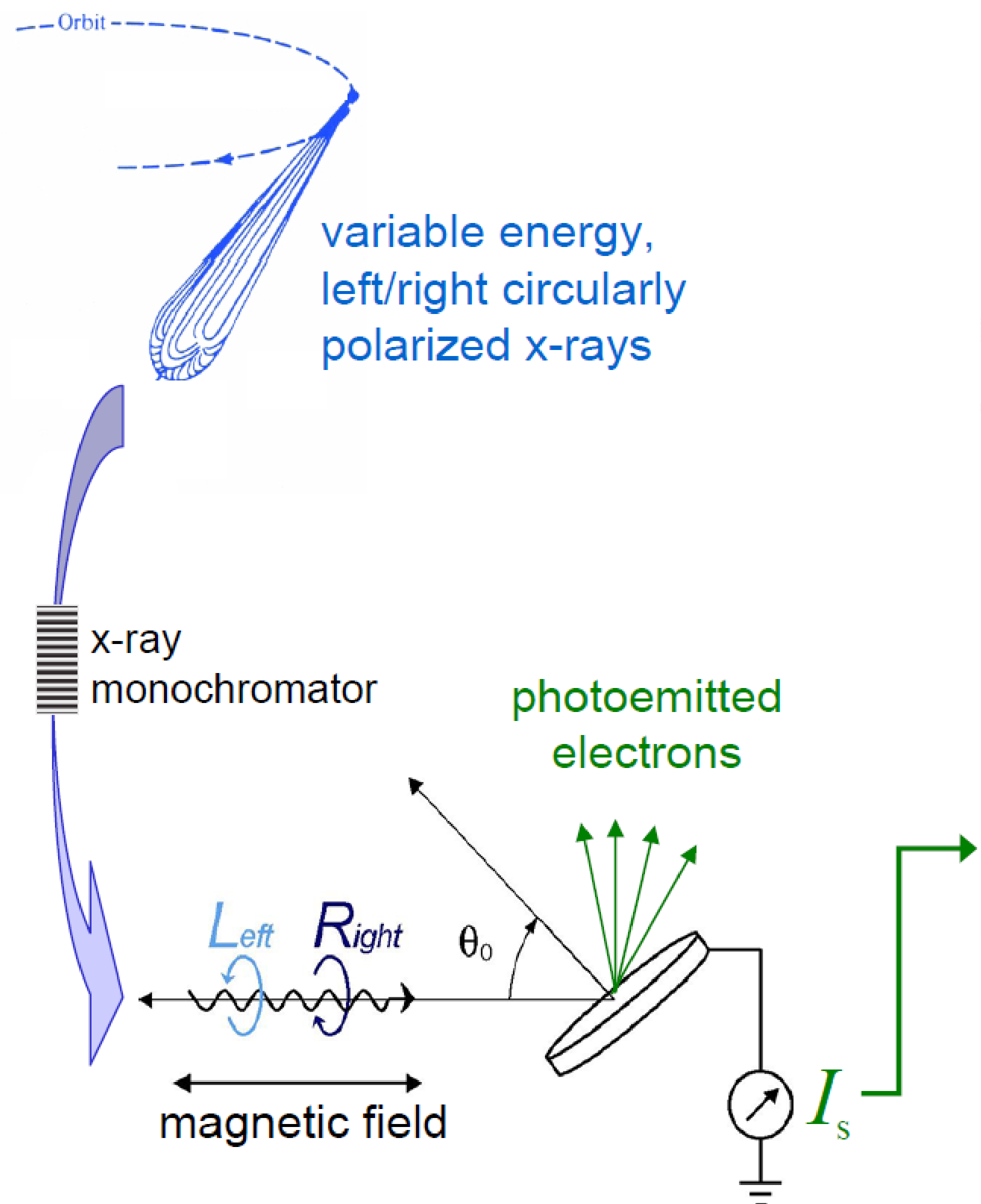


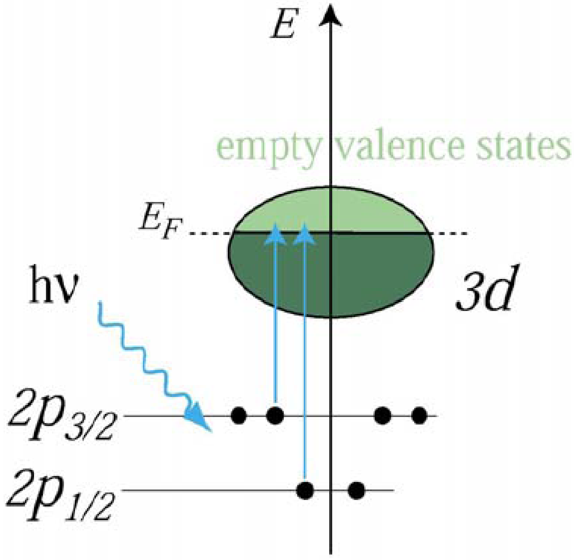
X-rays absorption and X-ray magnetic circular dichroism (XMCD)

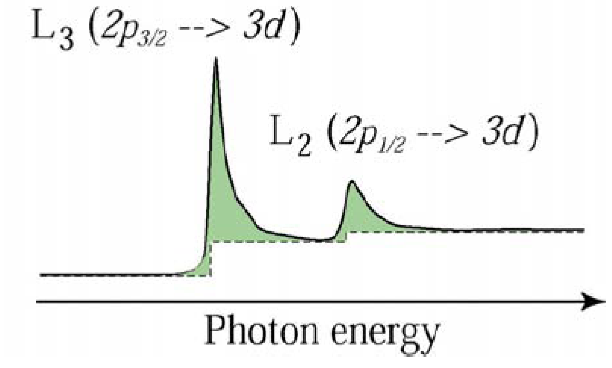
Two step model:

1) spin-polarized photoelectrons are created by using circularly polarized x-rays
2) these polarized photoelectrons are used to analyze the spin-split valence density of states, thus the valence band acts as a spin-sensitive detector.

synchrotron storage ring







$I_s \propto \mu$

x-ray absorption cross-section

XMCD theory: basic idea

Photon-electron interaction: dipole approximation $H_{\mathrm{int}}(0,t) \approx \underline{r}\cdot\underline{\varepsilon}_q\,[a_k \exp(-i\omega_k t) + \mathrm{c.c.}]$

The dipole operator $P_q^{1} = \underline{r}\cdot\underline{\varepsilon}_q$ can be written in terms of Racah's tensor operators (where $Y_{1,m}$ are the spherical harmonics)

$\underline{\varepsilon}_q$ is the polarization dependent electric vector

q = 0 -> linear polarization
q = +/- 1 -> circular polarization

$$P^{(1)}_{\pm 1} = \mp\frac{1}{\sqrt{2}}(x \pm iy) = rC^{(1)}_{\pm 1} = r\sqrt{\frac{4\pi}{3}}Y_{1,\pm 1}$$

$$P^{(1)}_{0} = z = rC^{(1)}_{0} = r\sqrt{\frac{4\pi}{3}}Y_{1,0}$$

The photon absorption generates a transition from an initial core level to a final level close to the Fermi level (note that the spin is not affected)

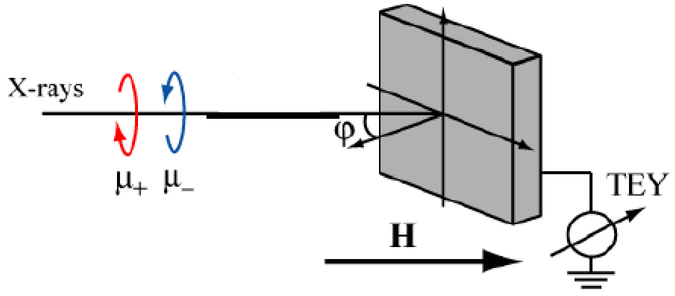
$$|i\rangle = R_i(r)\,|c, m_c; s = \frac{1}{2}, m_s\rangle \longrightarrow |f\rangle = R_f(r)\,|l, m_l; s = \frac{1}{2}, m_s\rangle$$

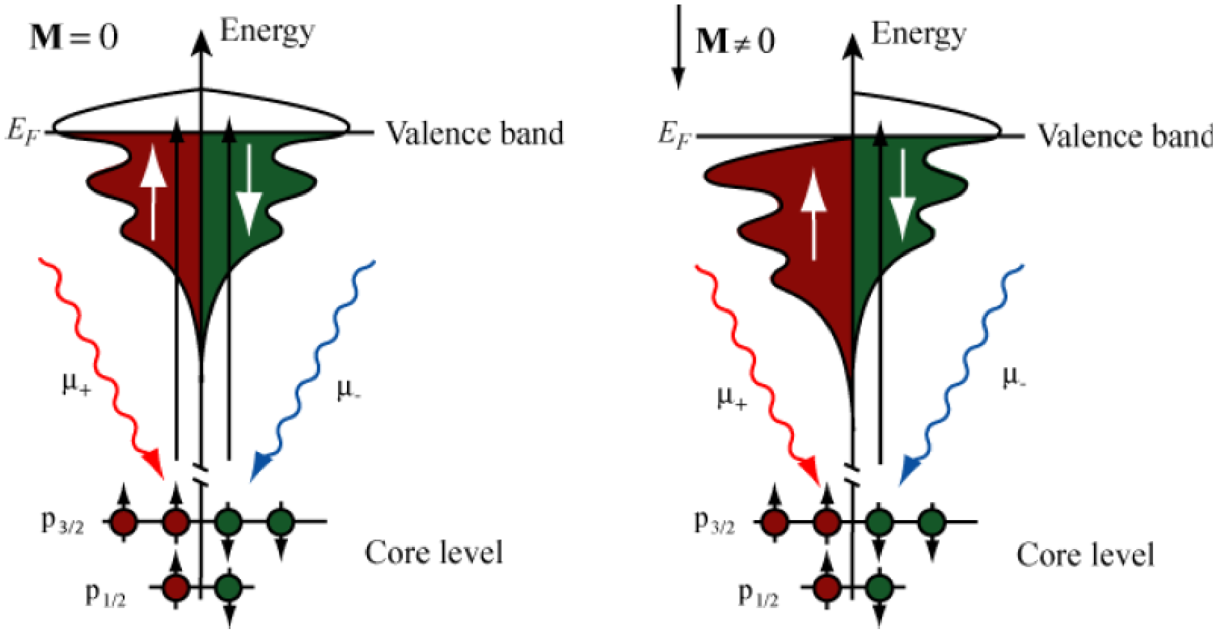
$\langle l,m\|C^{(1)}_{\pm 1}\|l-1,m\mp 1\rangle = \sqrt{\frac{(l\pm m)(l\pm m-1)}{2(2l-1)(2l+1)}}$	$\langle l,m\|C^{(1)}_{\pm 1}\|l+1,m\mp 1\rangle = -\sqrt{\frac{(l\mp m+2)(l\mp m+1)}{2(2l+3)(2l+1)}}$
$= \sqrt{\frac{l(l-1)\pm(2l-1)m+m^2}{2(2l-1)(2l+1)}}$	$= -\sqrt{\frac{l(l+3)\mp(2l+1)m+m^2}{2(2l+3)(2l+1)}}$
$\langle l,m\|C^{(1)}_{0}\|l-1,m\rangle = \sqrt{\frac{l^2-m^2}{(2l-1)(2l+1)}}$	$\langle l,m\|C^{(1)}_{0}\|l+1,m\rangle = \sqrt{\frac{(l+1)^2-m^2}{(2l+3)(2l+1)}}$

Table 1.3: Electric dipole matrix elements $\langle l, m_l|C_q^{(1)}|c, m_c\rangle$ in the one electron model. The matrix elements are non-vanishing when $c = l-1$ (left column) or $c = l+1$ (right column), and when $m_c + q = m_l$. q denotes the state of polarization of the photons which mix the states $|l, m_l\rangle$ and $|c, m_c\rangle$.

Remember: things become easily complicate. For example, if spin-orbit interaction is not negligible the (L, m_L, S, m_S) is not the good basis and you have to use the (L, S, J, m_J) basis

X-rays absorption and X-ray magnetic circular dichroism (XMCD)





μ in dipole approximation

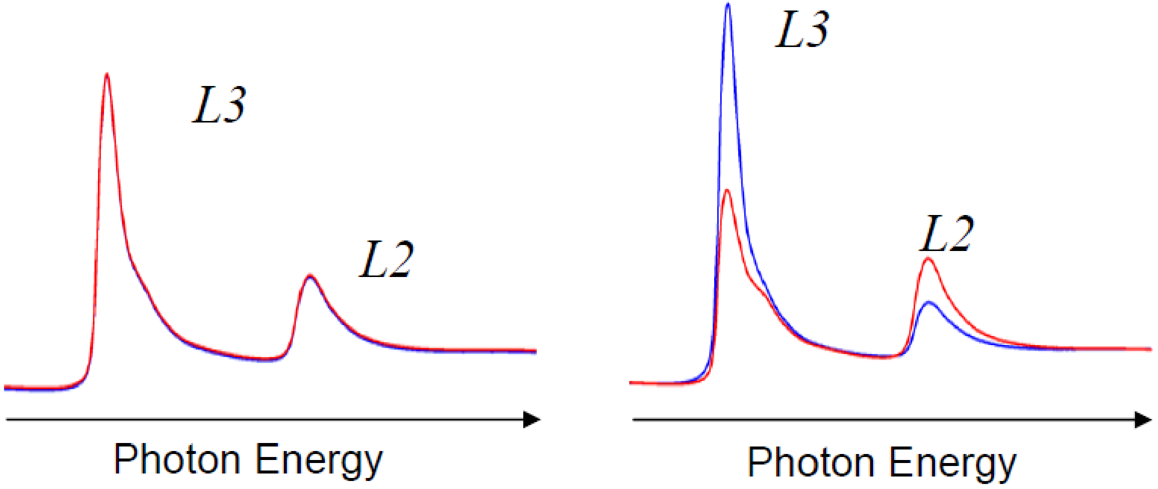
$$\mu \propto \left|\langle f|\varepsilon r|i\rangle\right|^2 \delta(\hbar\omega-(E_f-E_i))\rho(E_f)$$

Dipole selection rules

$\Delta l = \pm 1$, $\Delta s = 0$ 2p < 3d, 4s

$\Delta m_l = +1$ right circular

$\Delta m_l = -1$ left circular



X-rays absorption and X-ray magnetic circular dichroism (XMCD)

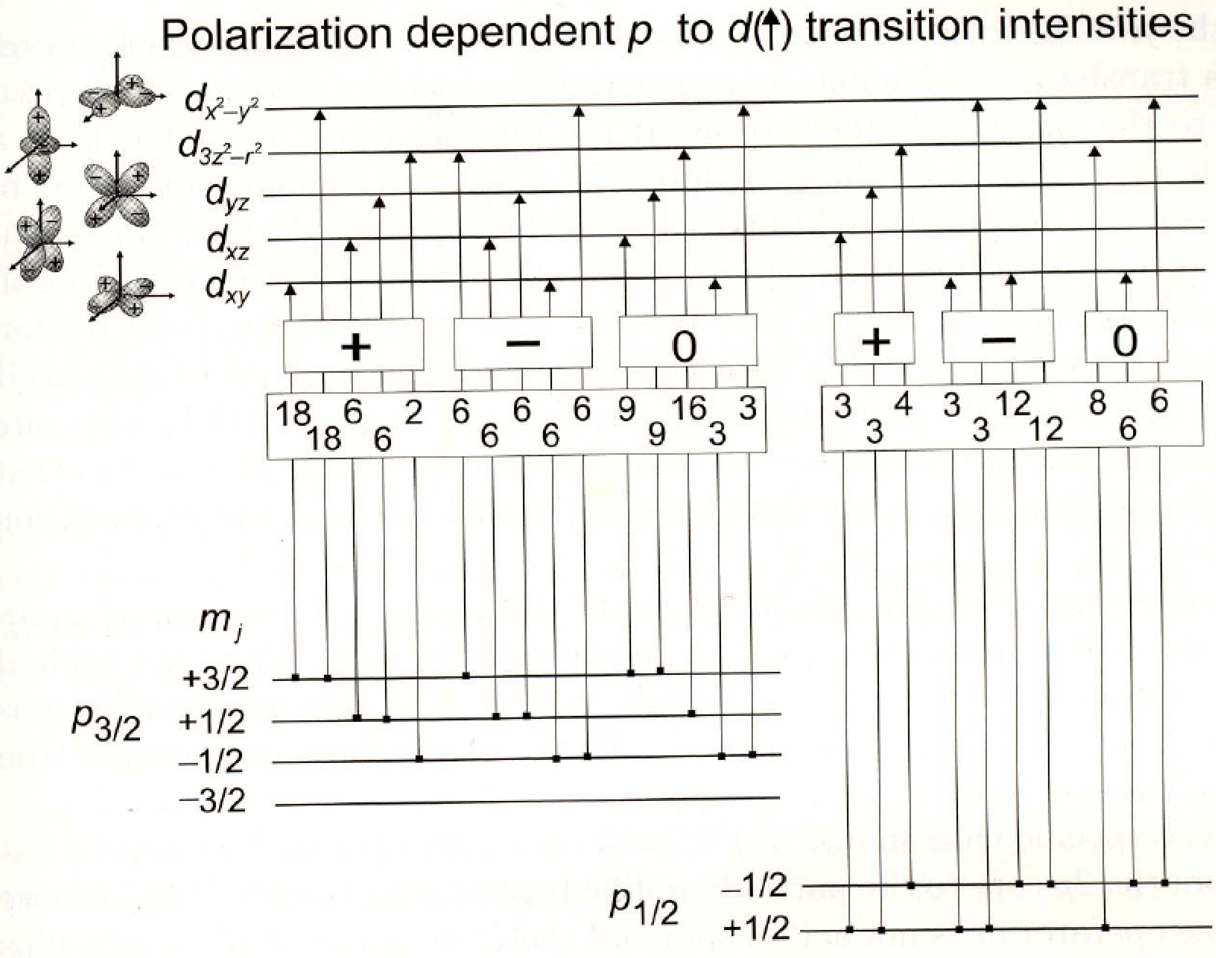
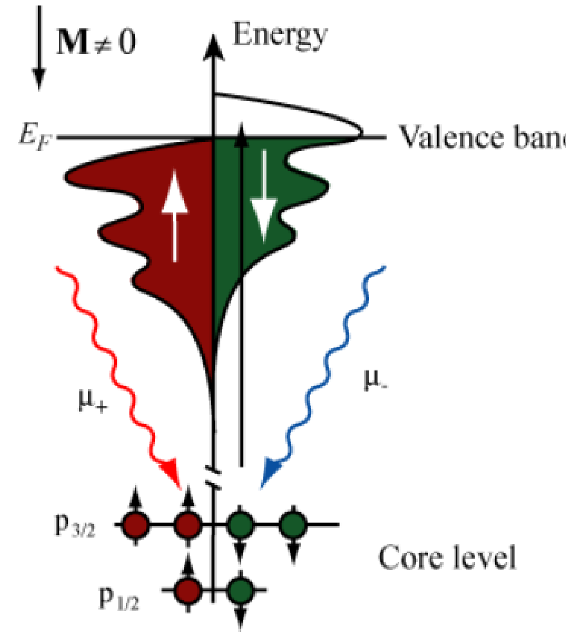
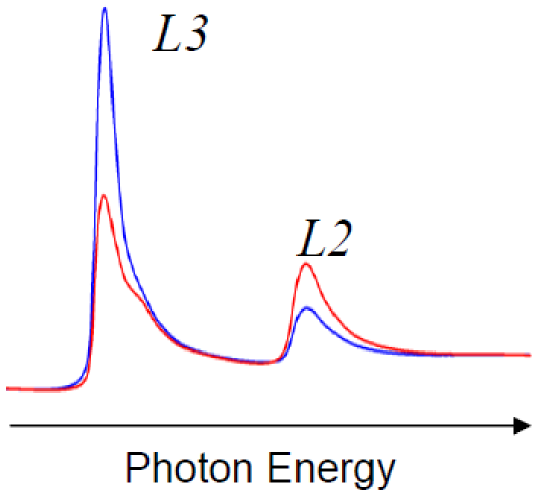


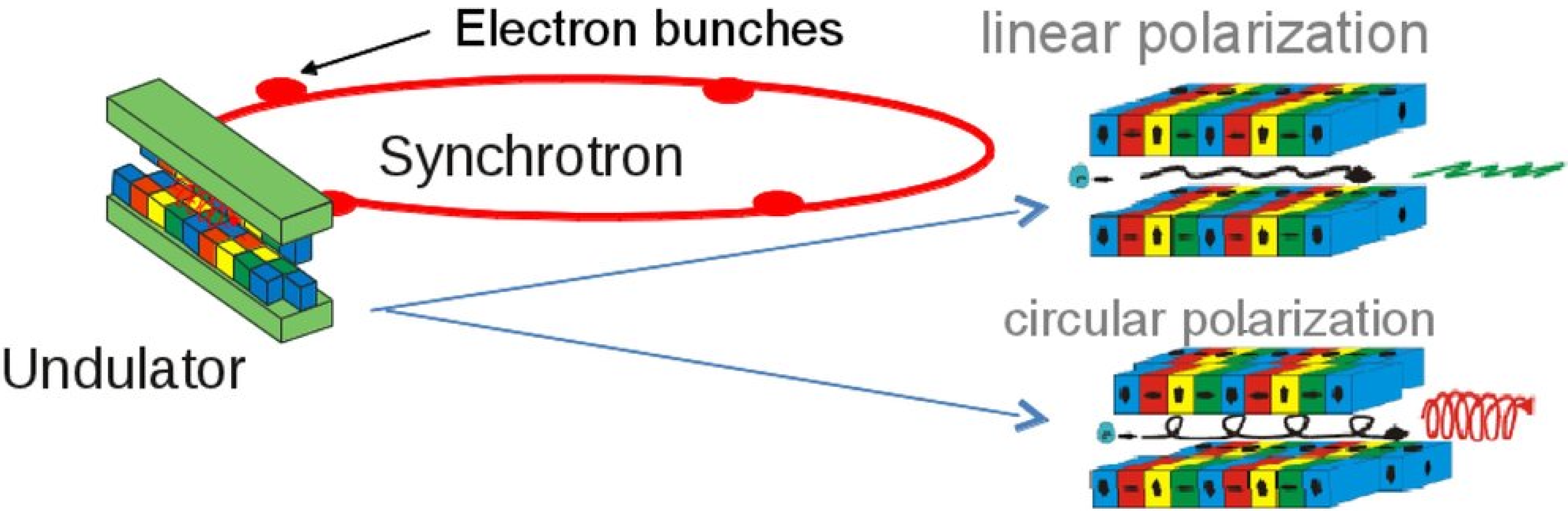
Fig. 9.14. Polarization dependent transition intensities in a one-electron model from spin–orbit and exchange split p core states $|j, m_j\rangle$ to *spin-up* ($m_s = +1/2$) d valence orbitals (Table A.2), assumed to be split by the exchange interaction. The listed intensities each need to be divided by 90 to get the proper absolute values in units of $\mathcal{A}\mathcal{R}^2$. We have chosen the z-axis as the spin quantization axis and the transition intensities are for circular polarization with $\boldsymbol{k} \parallel z$ and angular momenta $q = +1$ (labeled +) and $q = -1$ (labeled −) and for linear polarization with $\boldsymbol{E} \parallel z$ (labeled $q = 0$). We have assumed a splitting of the p states by the exchange interaction, lifting the degeneracy in m_j. Note that this causes an opposite order of m_j states for $p_{3/2}$, $l + s$ and $p_{1/2}$, $l - s$ because of the opposite sign of s





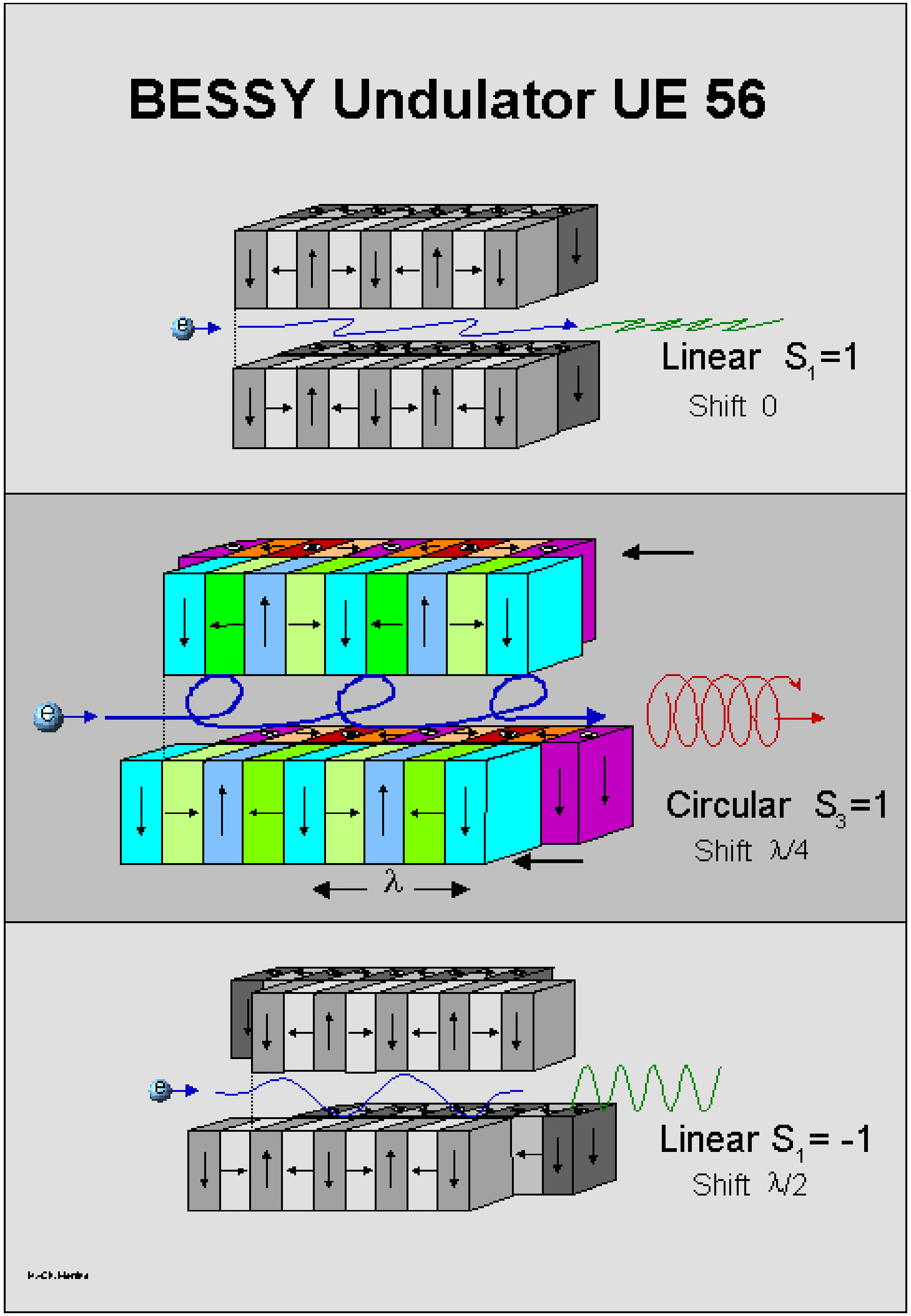
XMCD

Generace polarizovaného rtg záření



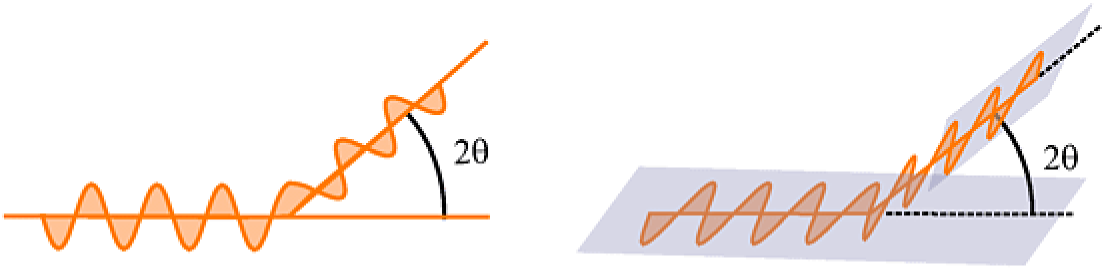
XMCD

Generace polarizovaného rtg záření



XMCD

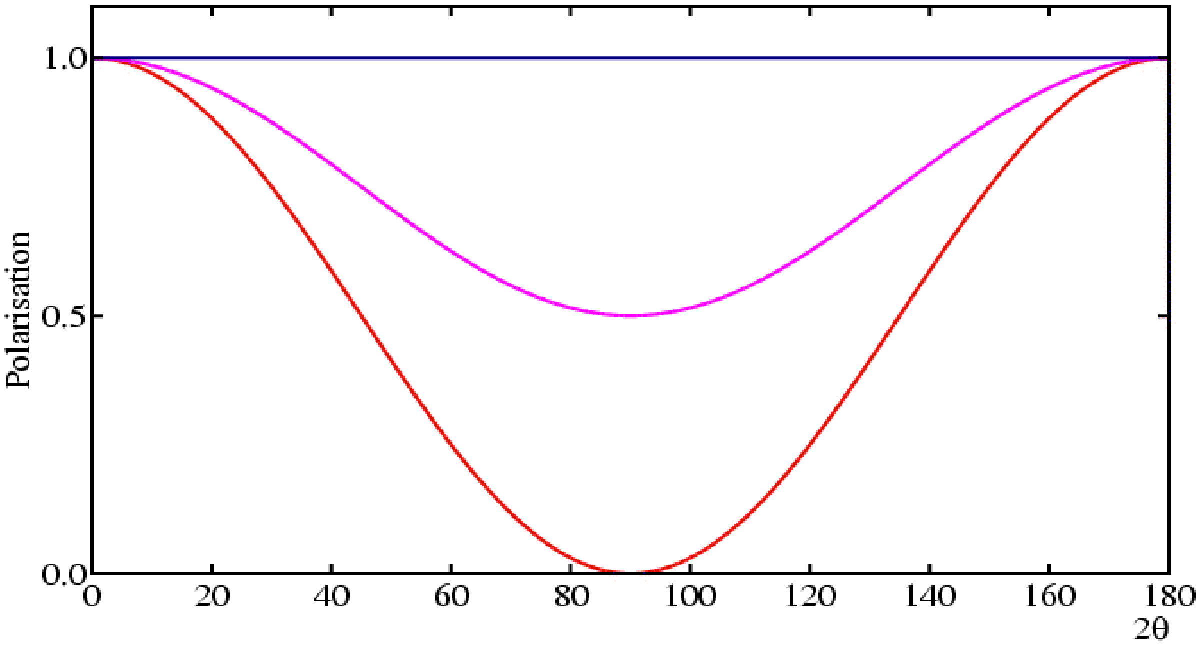
Lineární polarizátor pro rtg záření



Case (1): P-Polarisation in plane of scattering, $P = \cos^2 2\theta$

Case (2): S-Polarisation perpendicular to plane of scattering, $P = 1$

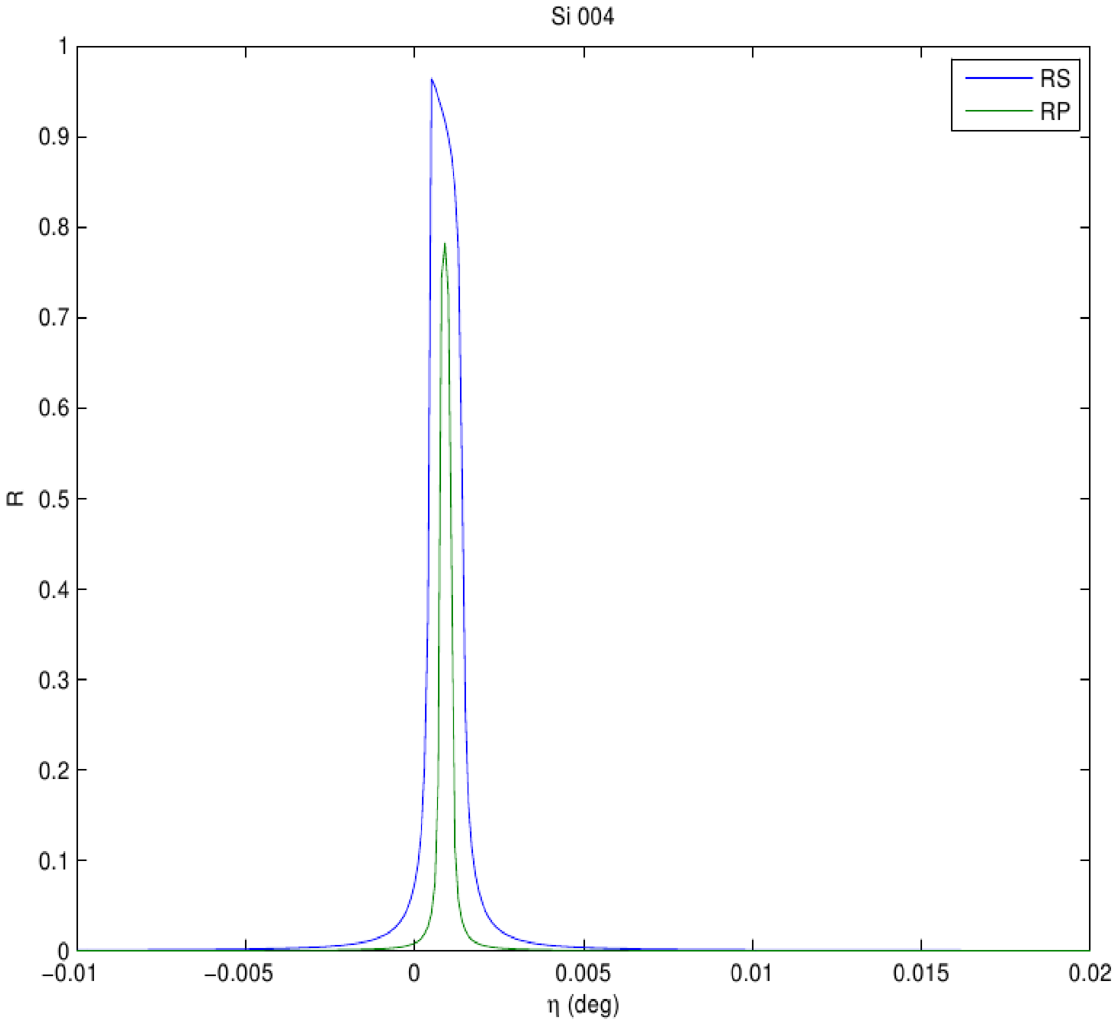
“Brewsterův úhel” = 45 stupňů



XMCD

Generace polarizovaného rtg záření

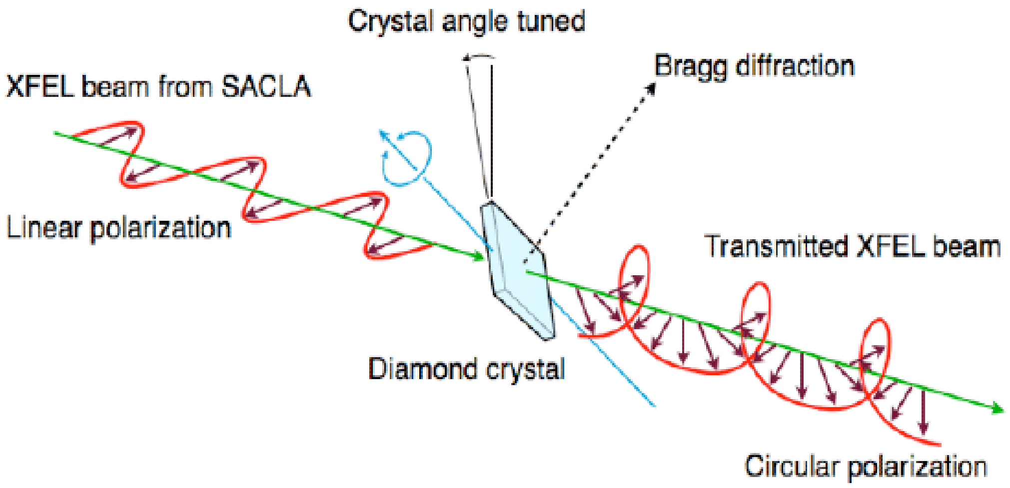
Difrakční křivka Si 004, Cu K alfa, 2theta=69.5 deg

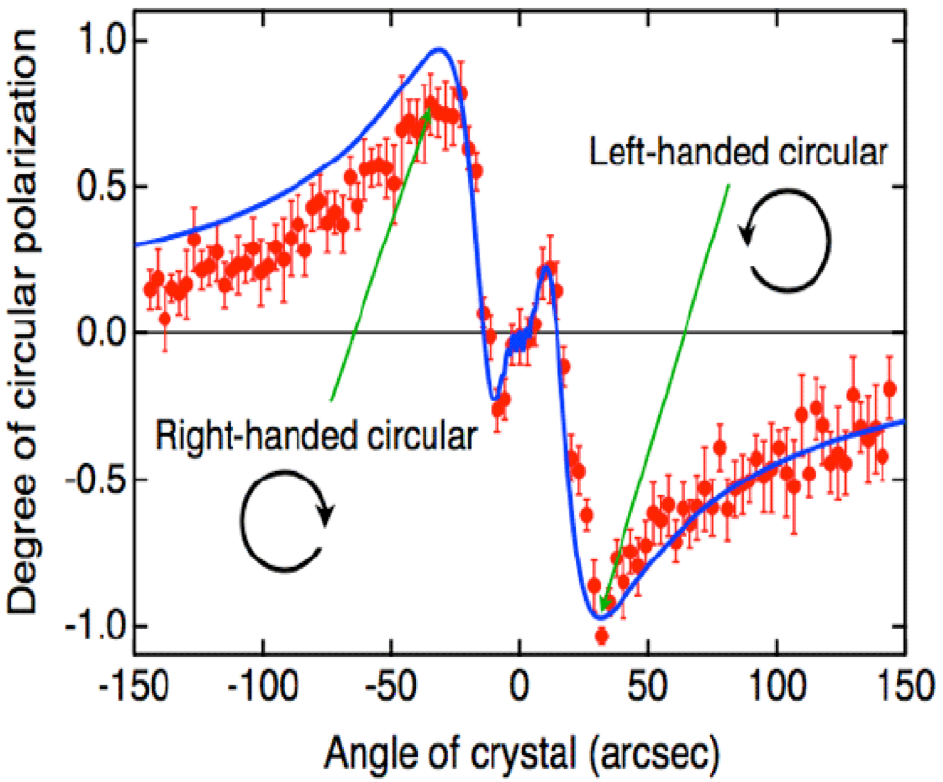


XMCD

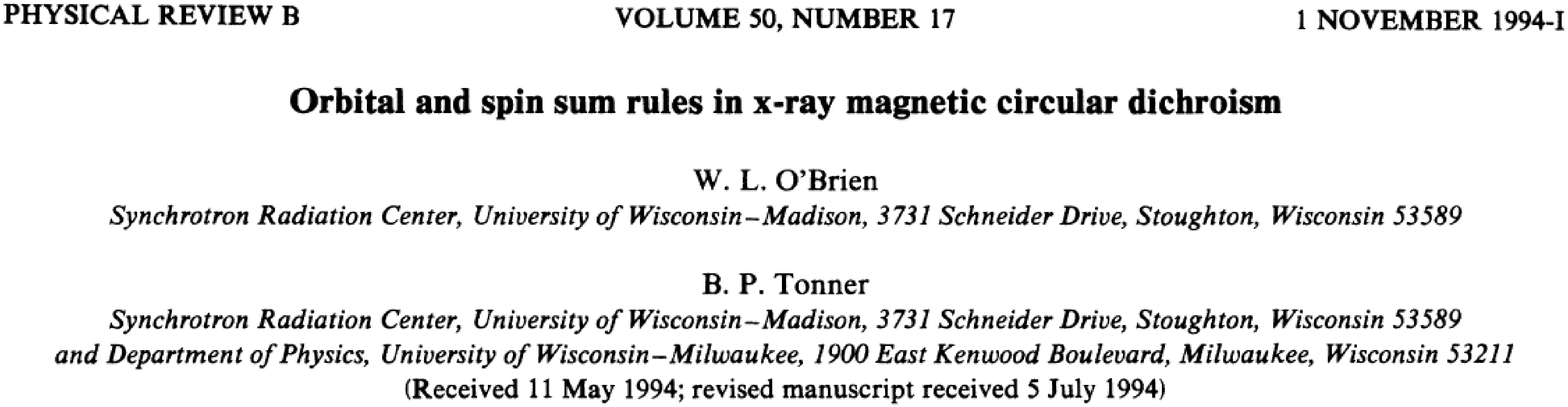
Generace polarizovaného rtg záření

“čtvrtvlnná destička”





XMCD



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Orbital and spin sum rules in x-ray magnetic circular dichroism

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Electron yield

$$Y_i(\hbar\omega) \propto \hbar\omega\sigma_i(\hbar\omega) \ ,$$

XMCD

$$\frac{\Delta A_{L_3}+\Delta A_{L_2}}{A_t}=\frac{\int_{L_3}\sigma_M(\hbar\omega)d\omega+\int_{L_2}\sigma_M(\hbar\omega)d\omega}{\int_{L_{2,3}}[\sigma_0(\hbar\omega)+\sigma_+(\hbar\omega)+\sigma_-(\hbar\omega)]d\omega}=\frac{\langle L_z\rangle}{2n_h} \tag{8}$$

$$\frac{\Delta A_{L_3}-2\Delta A_{L_2}}{A_t}=\frac{\int_{L_3}\sigma_M(\hbar\omega)d\omega-2\int_{L_2}\sigma_M(\hbar\omega)d\omega}{\int_{L_{2,3}}[\sigma_0(\hbar\omega)+\sigma_+(\hbar\omega)+\sigma_-(\hbar\omega)]d\omega}=\frac{2}{3n_h}\langle S_Z\rangle+\frac{7}{3n_h}\langle T_Z\rangle\ , \tag{9}$$

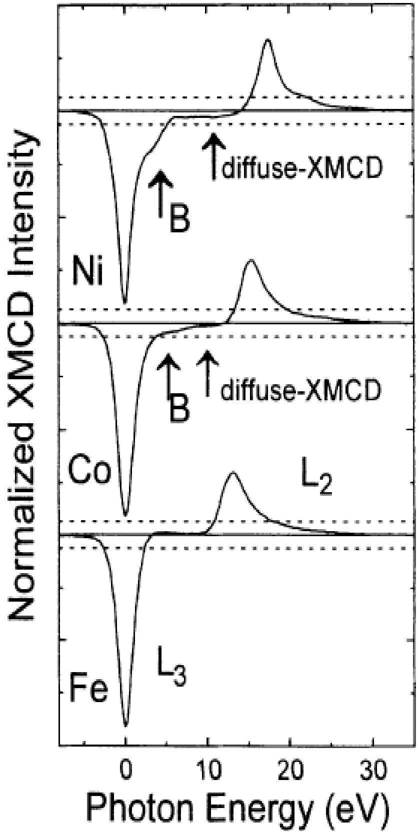


FIG. 6. Fe, Co, and Ni XMCD spectra shown normalized to constant L_3 peak height. The features labeled B are due to multiple initial-state configurations. The constant negative intensity between B and the L_2 peak in the Ni and Co spectra is due to diffuse magnetism.

XMCD

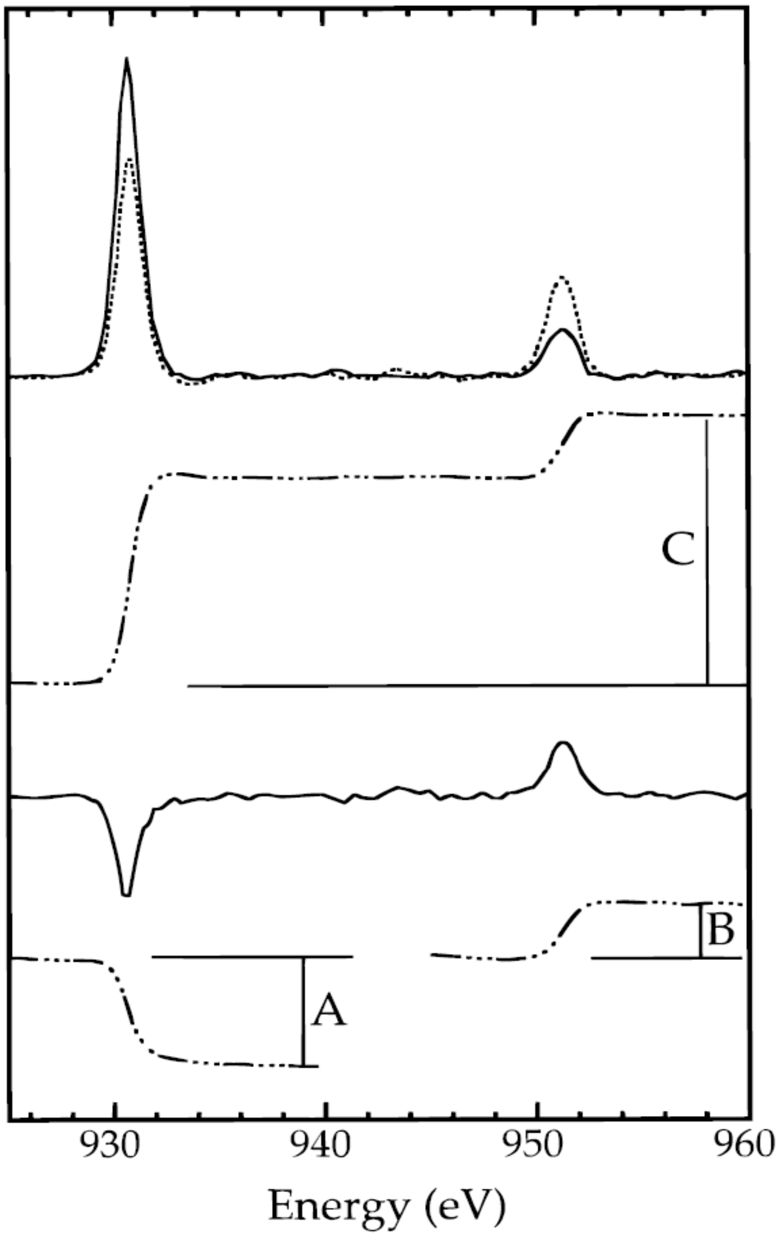
$$\langle L_z \rangle = -2n_{\mathrm{h}} \cdot \frac{\int_{\mathrm{L}_3+\mathrm{L}_2}[I^{\uparrow\uparrow} - I^{\uparrow\downarrow}]\mathrm{d}\omega}{\int_{\mathrm{L}_3+\mathrm{L}_2}[I^{\uparrow\uparrow} + I^{0} + I^{\uparrow\downarrow}]\mathrm{d}\omega}$$

$$\langle S_z \rangle = -\frac{3}{2} n_{\mathrm{h}} \cdot \frac{\int_{\mathrm{L}_3}[I^{\uparrow\uparrow} - I^{\uparrow\downarrow}]\mathrm{d}\omega - 2\int_{\mathrm{L}_2}[I^{\uparrow\uparrow} - I^{\uparrow\downarrow}]\mathrm{d}\omega}{\int_{\mathrm{L}_3+\mathrm{L}_2}[I^{\uparrow\uparrow} + I^{0} + I^{\uparrow\downarrow}]\mathrm{d}\omega}$$

The final spectrum is the sum of 20 individual (F/I_0) sets for each side, with the X-ray photon angular momentum either parallel ($I^{\uparrow\uparrow}$) or antiparallel, ($I^{\uparrow\downarrow}$) to that of the C(II) majority 3d spin. Each of the averaged spectra were first normalized to

Here n_{h} represents the number of 3d vacancies in the metal ion, ω is the X-ray frequency, and I^0 refers to the absorption for X-rays linearly polarized along the magnetization direction; as is customary, we approximate this by $(I^{\uparrow\uparrow} + I^{\uparrow\downarrow})/2$. It is common in the XMCD literature[1,7,15] to refer to the first integral in the numerator of eq 2 as "A", the second integral as "B", and the denominator as "$3C$". The necessary integrals are illustrated in Figure 1. One can thus re-express the sum rules in the following manner, in units of ℏ/atom:

$$\langle L_z \rangle = -n_{\mathrm{h}} \frac{2(A+B)}{3C} \qquad \langle S_z \rangle = -n_{\mathrm{h}} \frac{A-2B}{2C} \qquad (3)$$



XMCD Mn in Bi2Se3

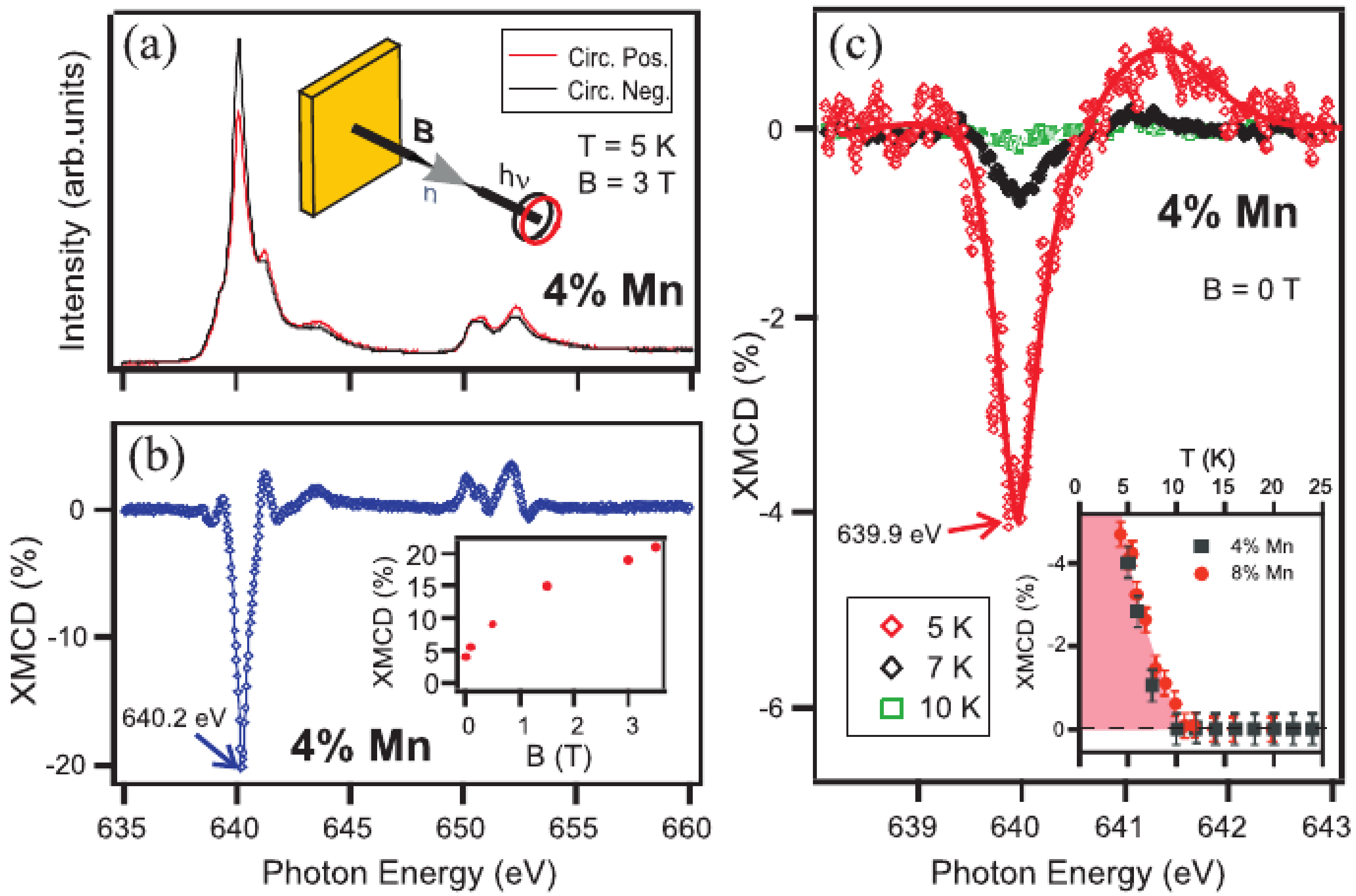


FIG. 4. (Color online) XMCD in total electron yield at the Mn $L_{2,3}$-edges. (a) X-ray aborption spectra measured for opposite helicities of the circularly polarized incident light at 5 K with a out-of-plane applied magnetic field of 3 T. A sketch of the experimental geometry is also shown. (b) Corresponding XMCD difference spectrum. The inset shows XMCD measurements for different applied magnetic fields. (c) Temperature dependence of the remanent XMCD for a Mn concentration of $x = 0.04$. Inset: Detailed temperature dependence for various Mn concentrations.

XMCD

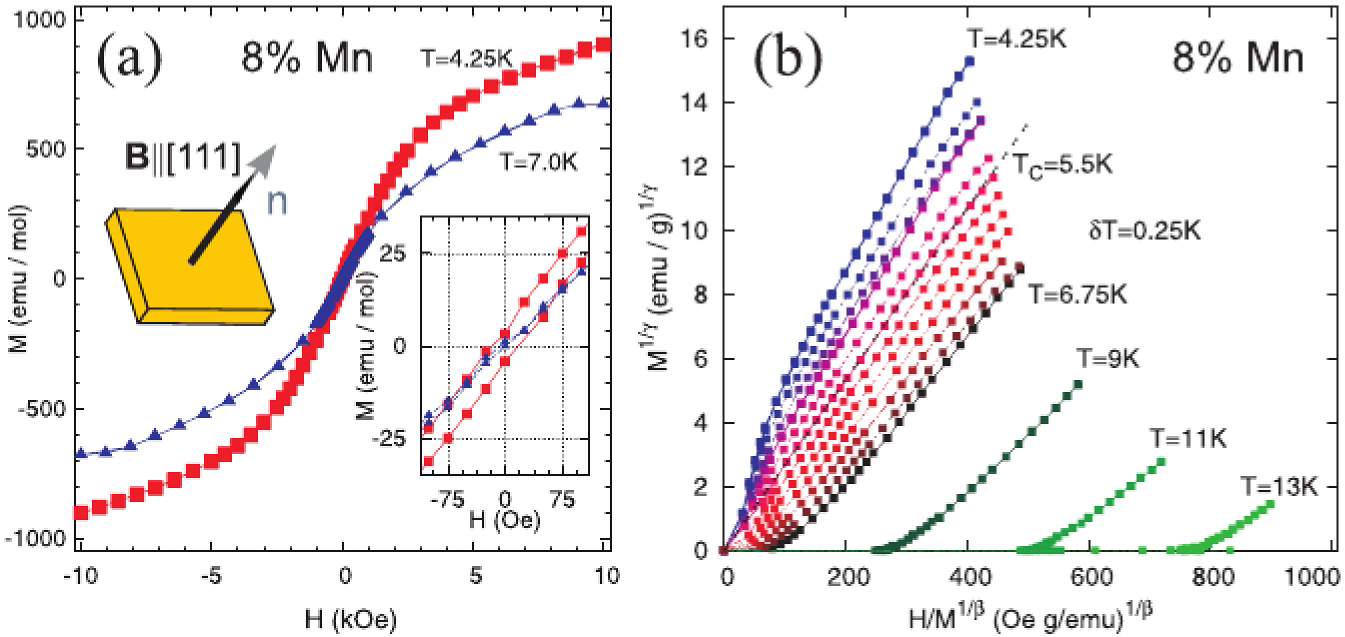
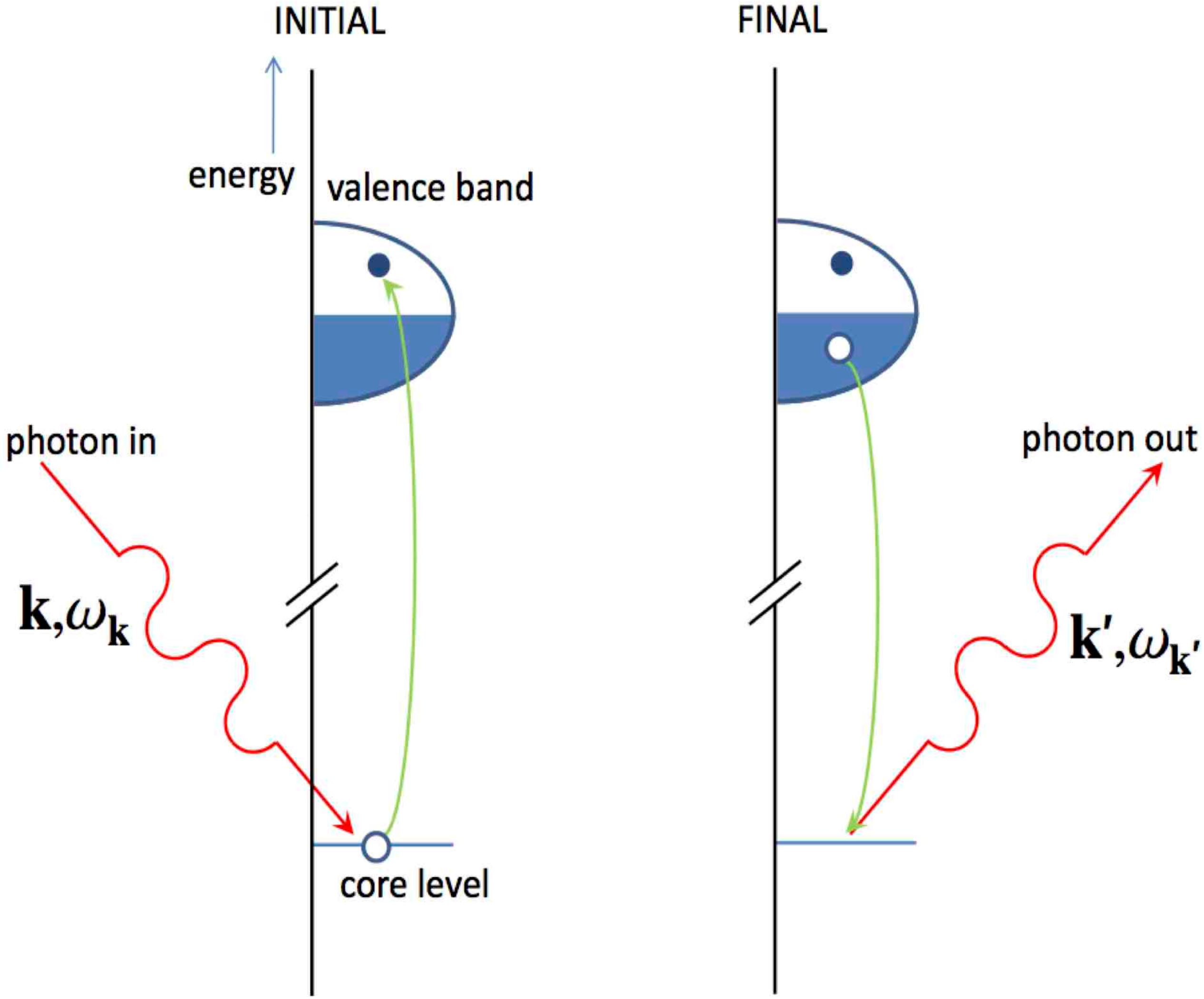


FIG. 3. (Color online) (a) Hysteresis loops measured at a temperature of 4.2 K (squares) and 7 K (triangles), respectively. The applied magnetic field is perpendicular to the (111) sample surface (see sketch). Inset: A zoom-in around zero magnetic field showing hysteresis at 4.2 K and a paramagnetic state at 7 K. (b) Modified normalized Arrott plots at various temperatures from which a Curie temperature of 5.5 K is deduced. Between 4.25 and 6.75 K, data are shown for increments of $\delta T = 0.25$ K.

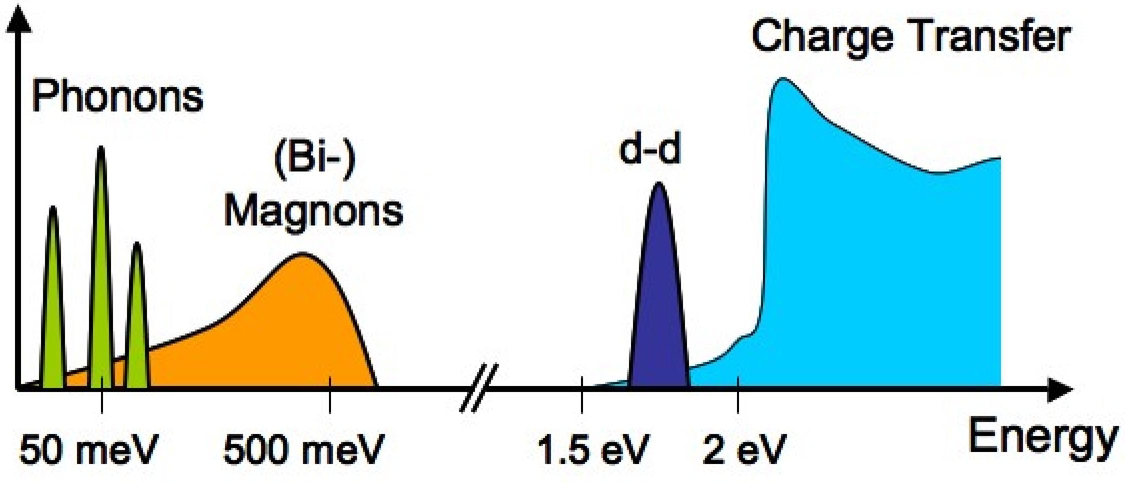
RIXS

Rezonanční neelastický rtg rozptyl – rezonanční “Ramanův” rozptyl
Výhoda Rtg proti VIS – směrové rozlišení, možnost pokrytí celé Brillouinovy zóny
Nevýhoda – slabší jevy, experimentální obtížnost energiového rozlišení

Rezonance –
Silné zesílení jevu

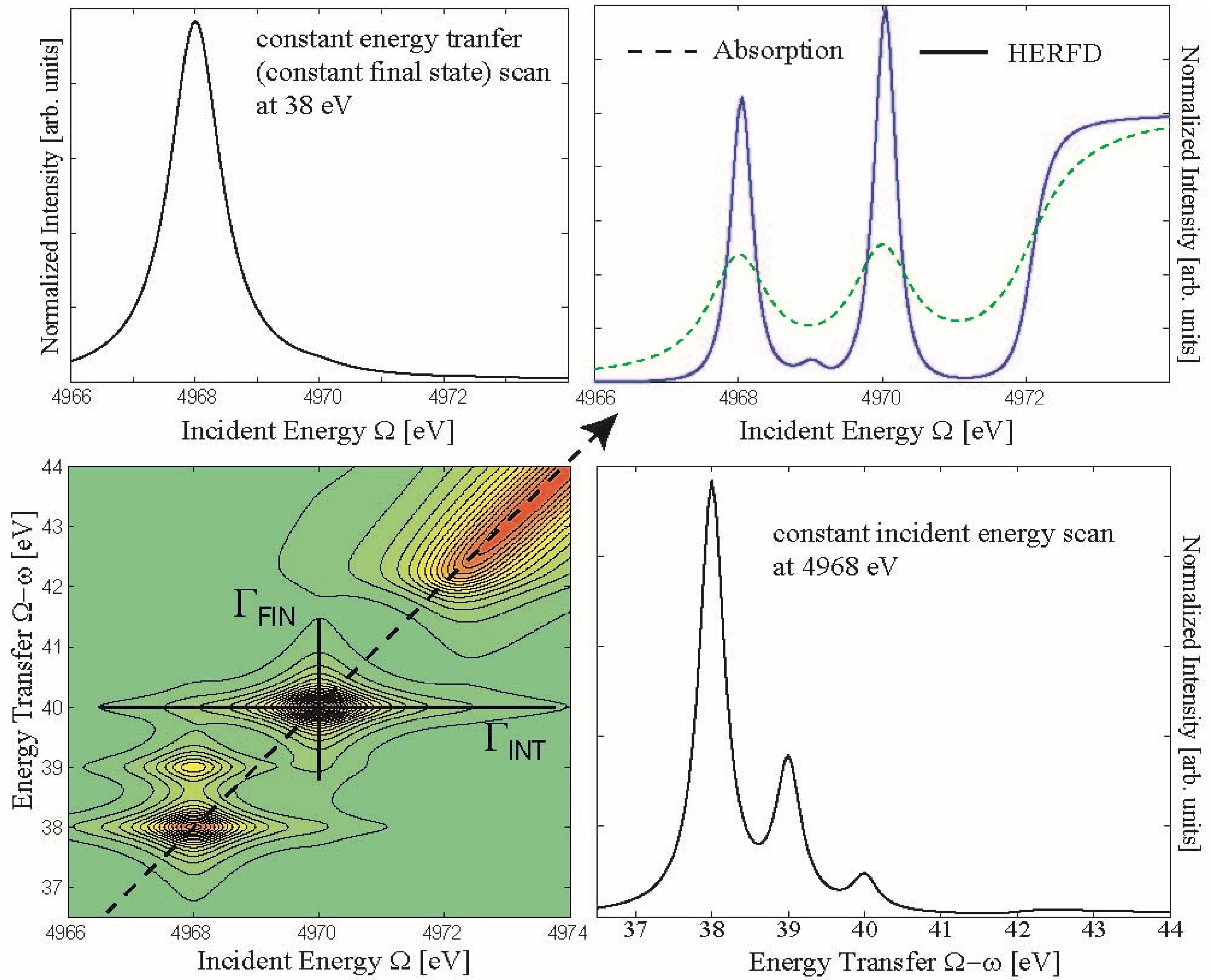


RIXS

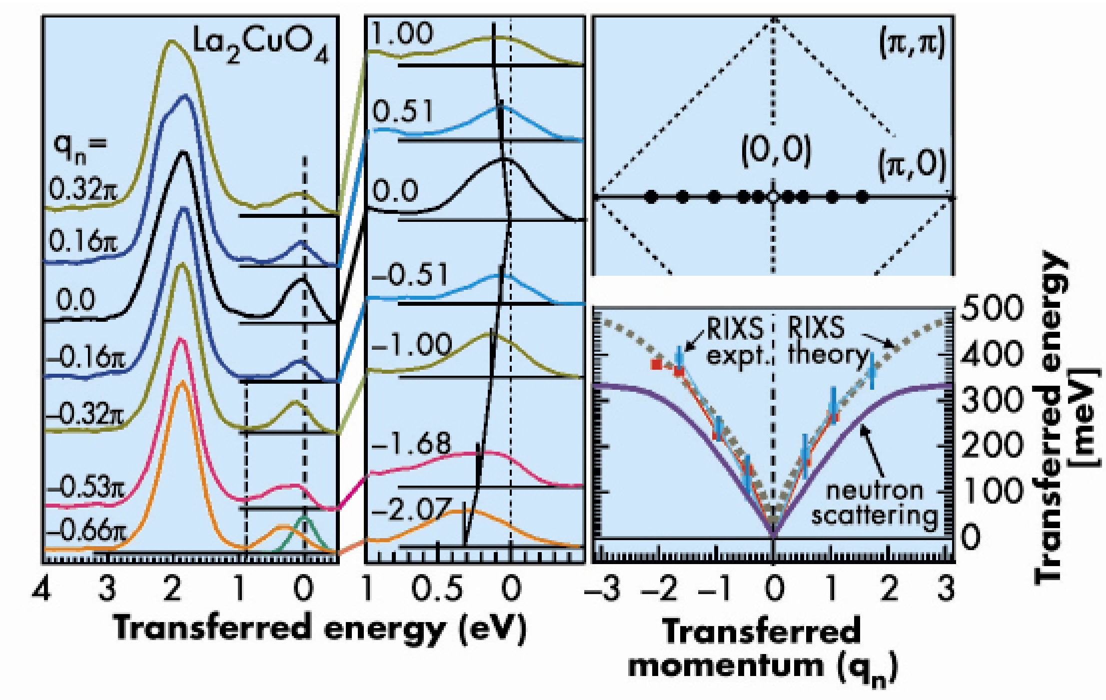


Elementary excitations in condensed matter systems that can be measured by RIXS. The indicated energy scales are the ones relevant for transition metal oxides.

RIXS


Normalized Intensity [arb. units]
constant energy tranfer (constant final state) scan at 38 eV
4966
4968
4970
4972
Incident Energy Ω [eV]
Absorption
HERFD
Normalized Intensity [arb. units]
4966
4968
4970
4972
Incident Energy Ω [eV]
Energy Transfer Ω−ω [eV]
44
43
42
41
40
39
38
37
Γ_FIN
Γ_INT
4966
4968
4970
4972
4974
Incident Energy Ω [eV]
constant incident energy scan at 4968 eV
Normalized Intensity [arb. units]
37
38
39
40
41
42
43
44
Energy Transfer Ω−ω [eV]

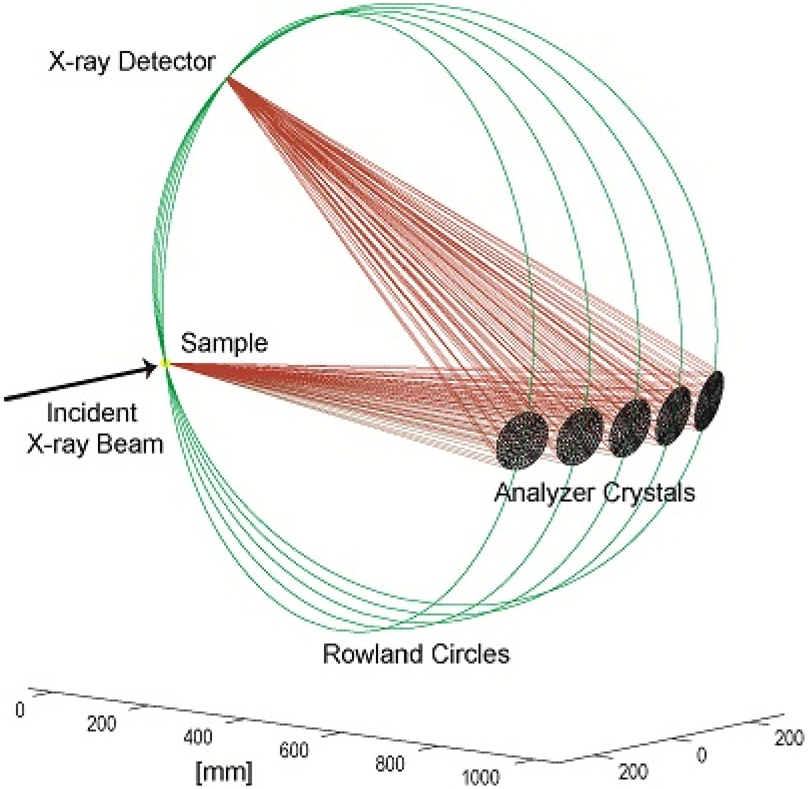
RIXS



Cu L3 RIXS results of La2CuO4. The peak dispersion curve was extracted from the raw data (left panel) corresponding to the given dots in the Brillouin zone.

L. Braicovich (a), L.J.P. Ament (b), V. Bisogni (c), F. Forte (b,d), C. Aruta (e), G. Balestrino (f), N.B. Brookes (c), G.M. De Luca (e), P.G. Medaglia (f), F. Miletto Granozio (e), M. Radovic (e), M. Salluzzo (e), J. van den Brink (b,g), and G. Ghiringhelli (a), arXiv:0807:1140v1, (2008).

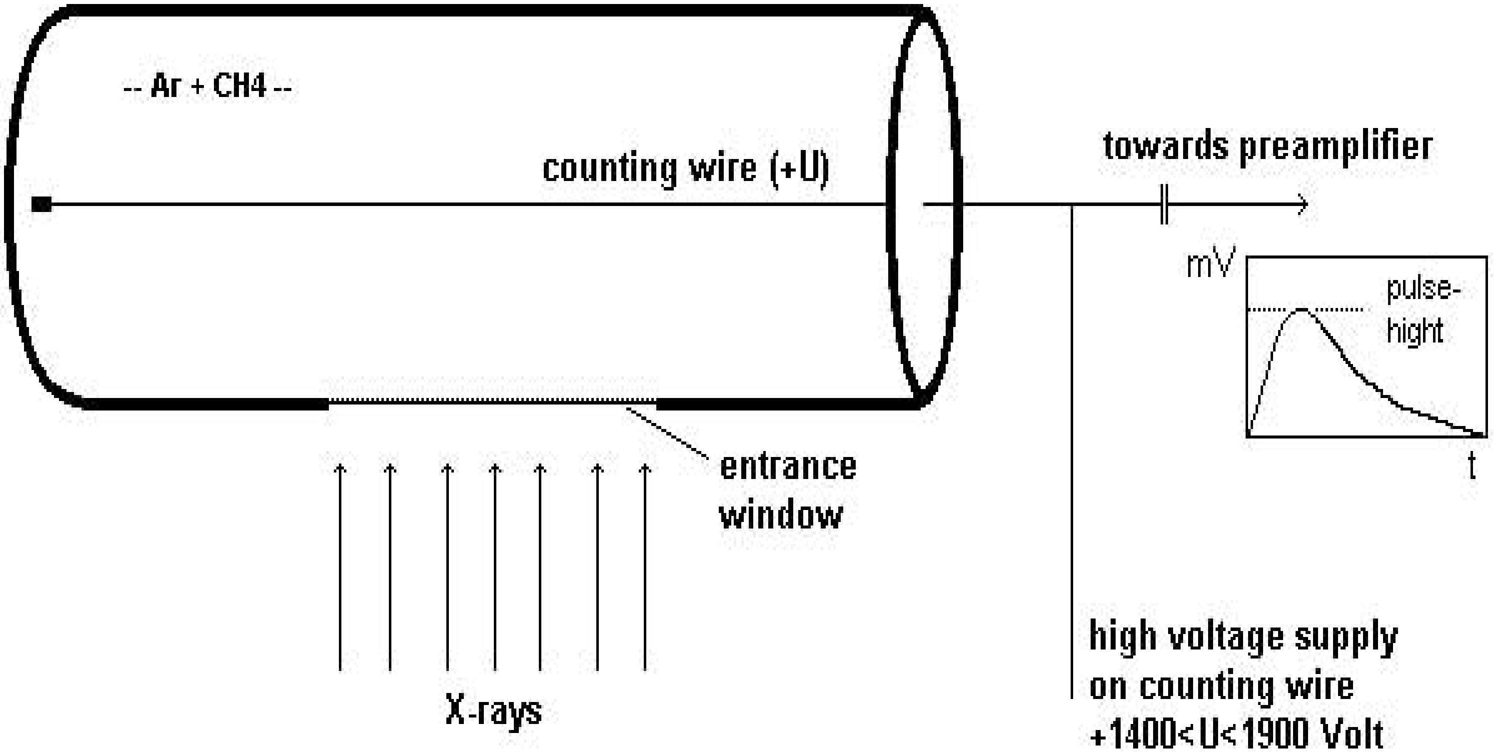
RIXS



$$F(\Omega,\omega)=\sum_f\left|\sum_n\frac{\langle f|T_2|n\rangle\langle n|T_1|g\rangle}{E_g-E_n+\Omega-i\frac{\Gamma_{INT}}{2}}\right|^2 * \frac{\frac{\Gamma_{FIN}}{2\pi}}{(E_g-E_f+\Omega-\omega)^2+\frac{\Gamma_{FIN}^2}{4}}$$

Bodové rtg detektory

- Ionizační
- Geiger-Müller – vysoké napětí, Townsendova lavina
- Proporcionální – nižší napětí, rozlišení > 20 % (> 10^3 eV)

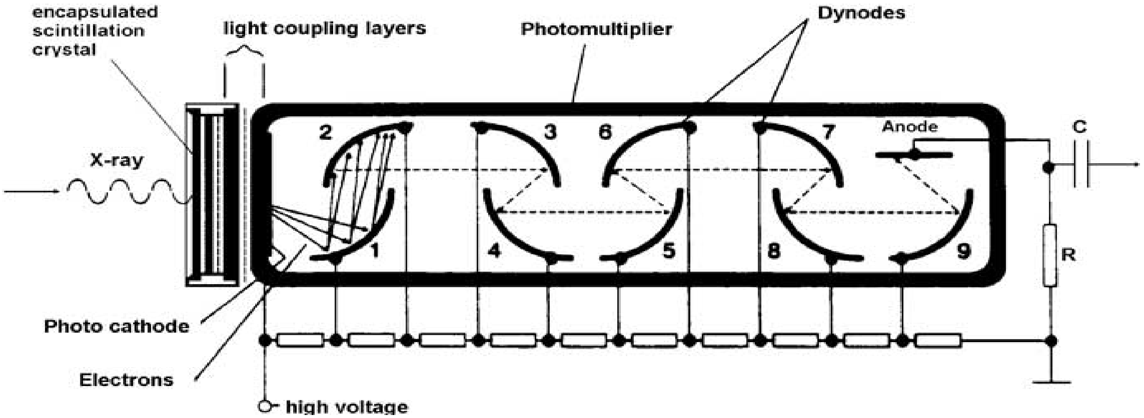


Bodové rtg detektory

- Scintilační – rozlišení 5 až 10 % (10^3 eV)

  NaI(Tl) – od 6keV účinnost téměř 100%

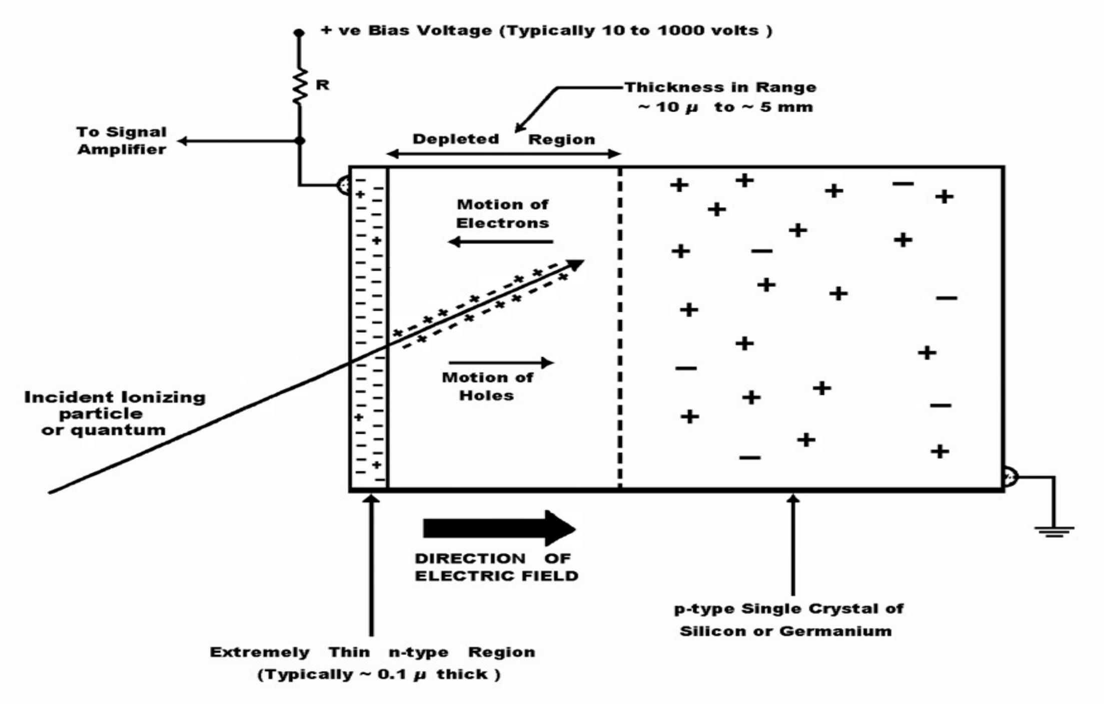
  Emise 410 nm – 3eV



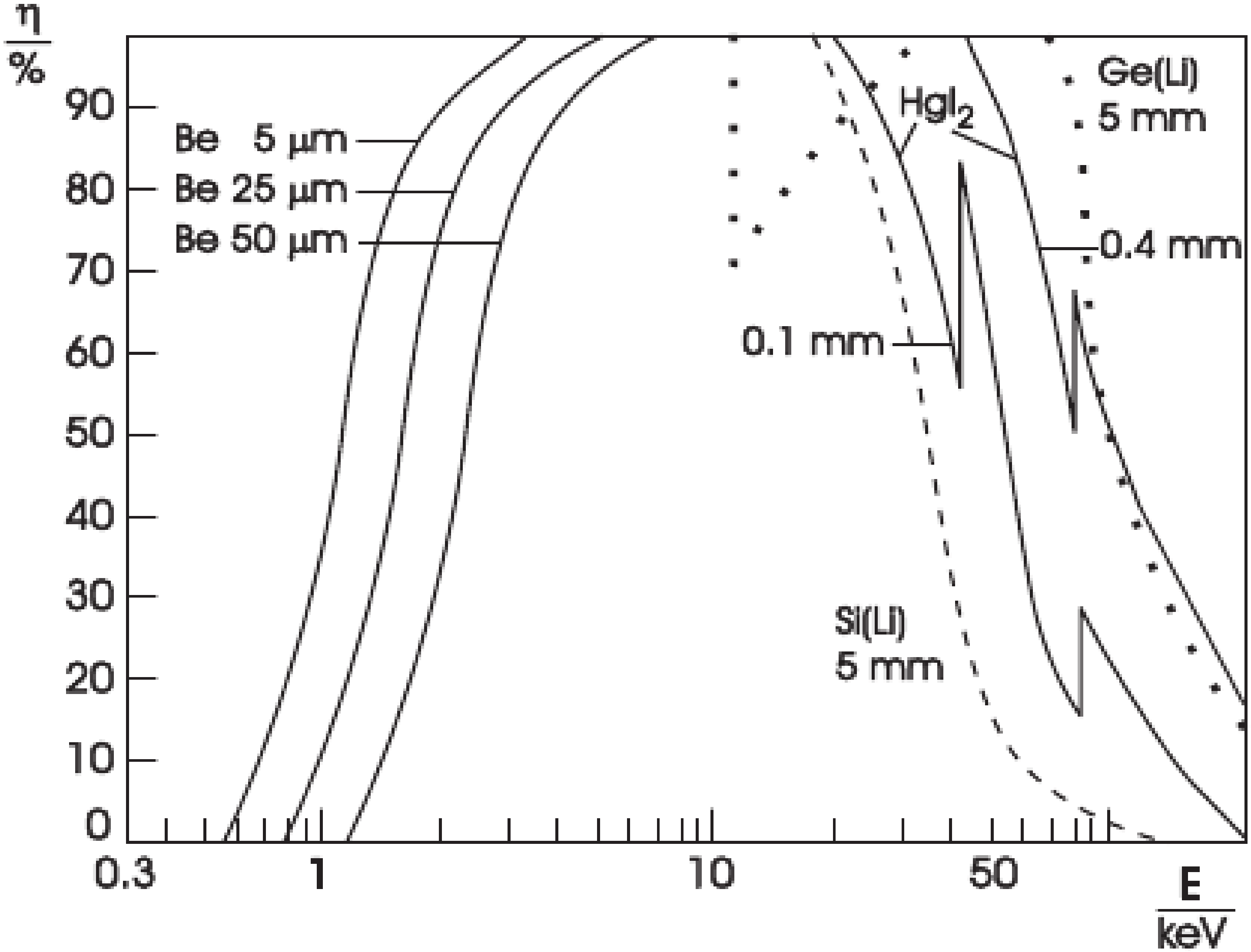
- Polovodičové

  – rozlišení až 2 % (10^1 - 10^2 eV)

Si, Ge



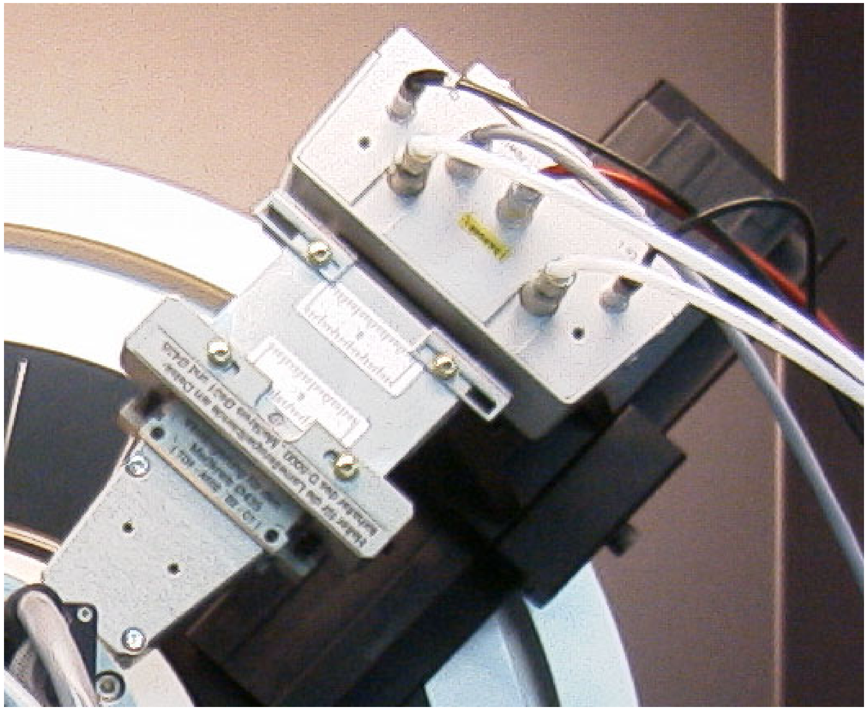
Polovodičové rtg detektory

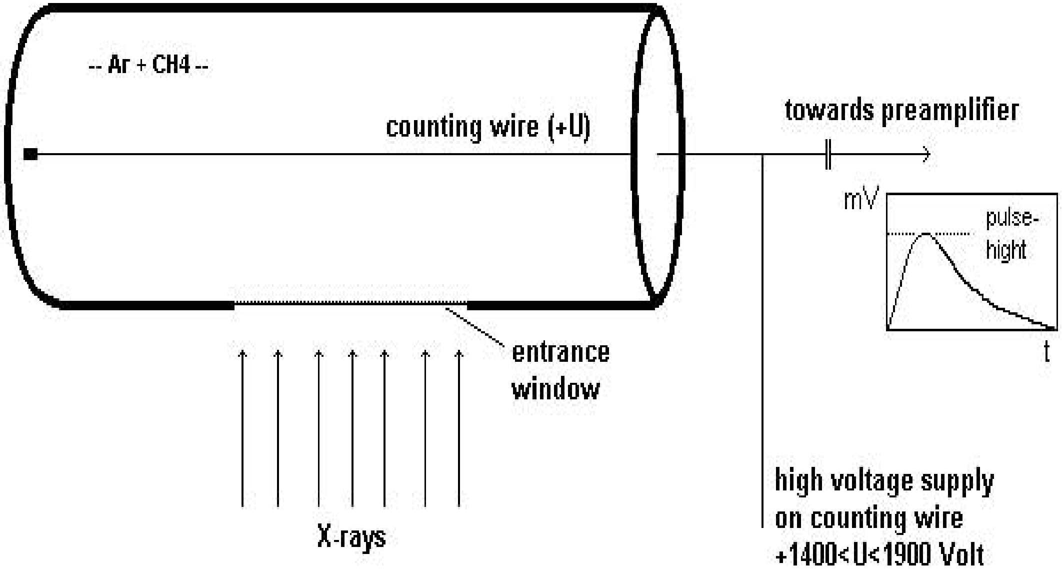


Lineární rtg detektory

- Plynové – ionizační, malý dynamický rozsah (50 kcps),

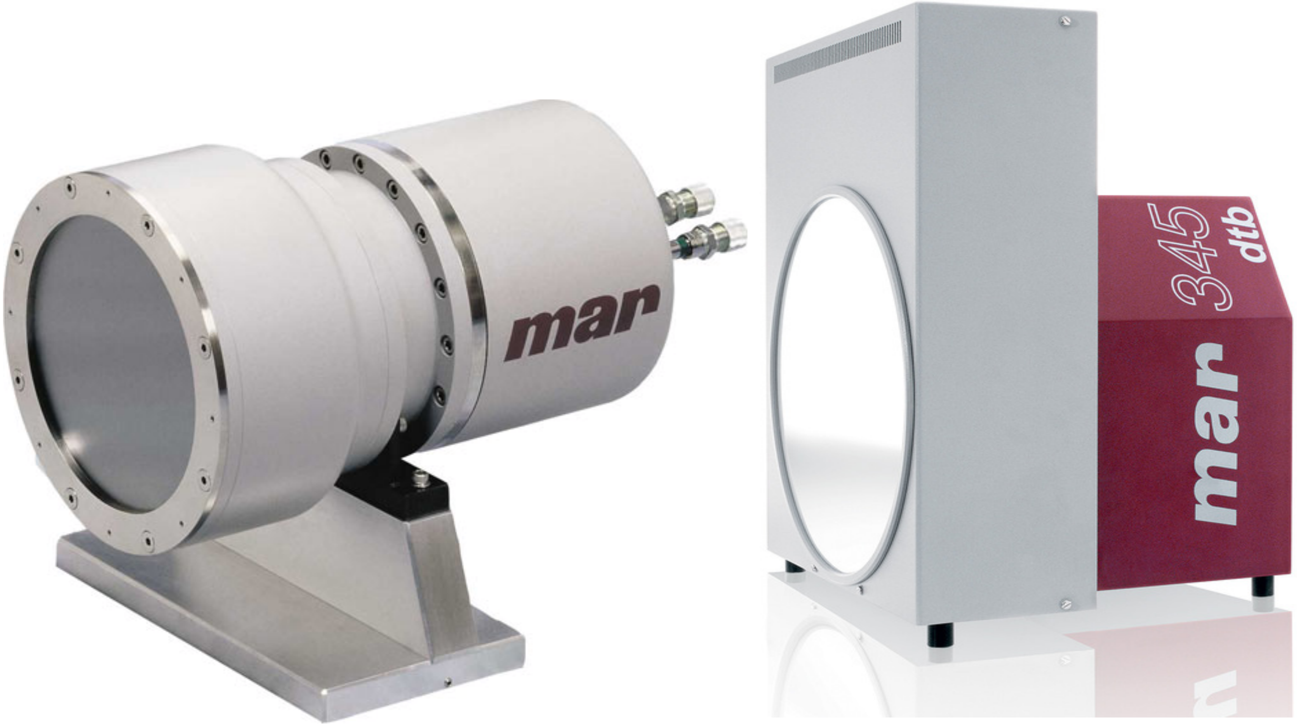
- Polovodičové – velký dynamický rozsah





Plošné rtg detektory

- Plynové - ionizační
- CCD - rozlišení cca (50μm)^2
- Film - rozlišení cca (1μm)^2, nelineární, velmi pomalé
- Luminiscenční („Image plate") - rozlišení cca (10μm)^2, velké plochy rychlost 1 snímek cca 3 až 10 minut.
- Scintilační - rozlišení až cca (3μm)^2, malá kvantová výtěžnost (tenký scintilátor)
- Polovodičové



Rtg detektory

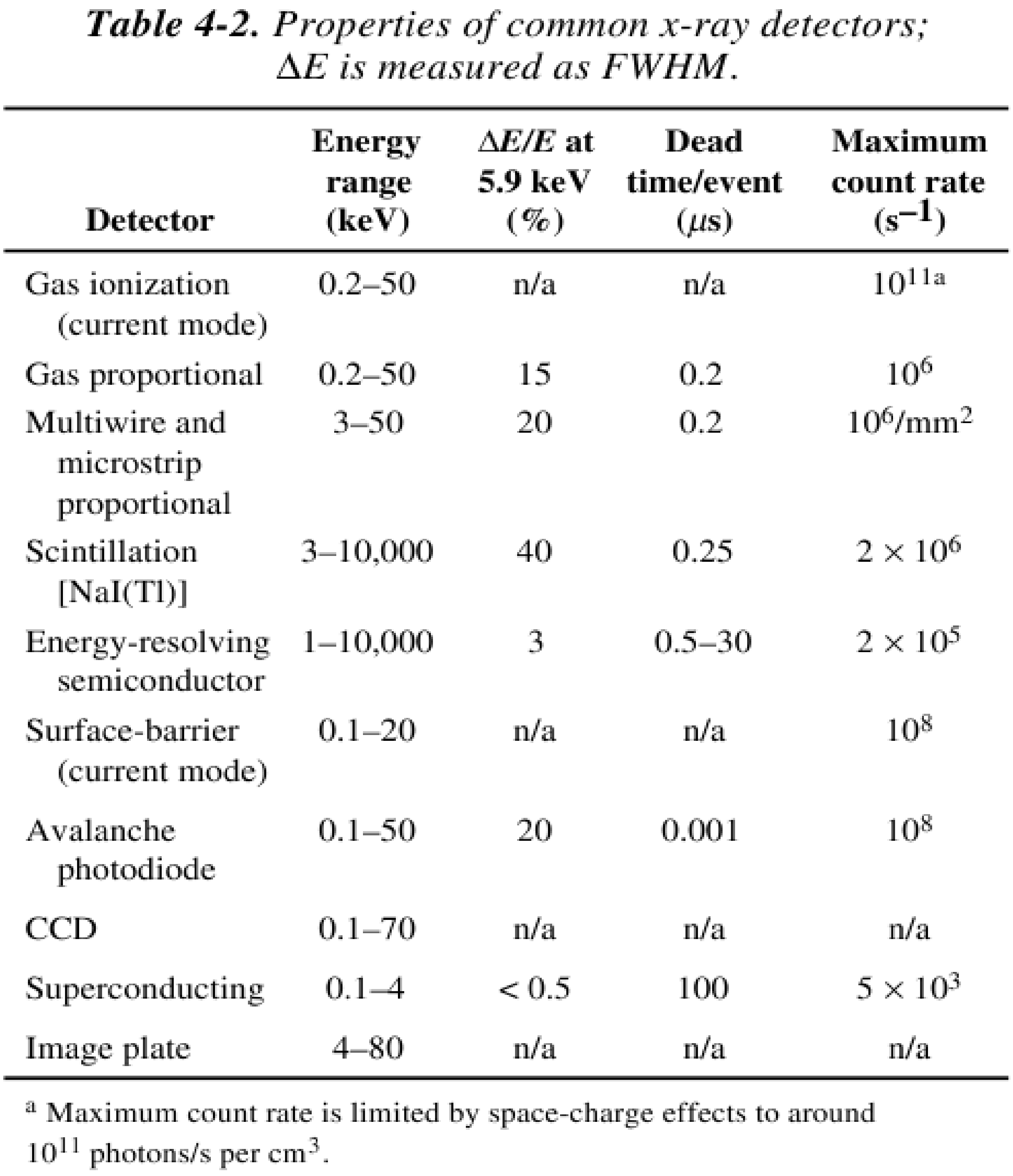


Table 4-2. *Properties of common x-ray detectors; ΔE is measured as FWHM.*

Detector	**Energy range (keV)**	**$\Delta E/E$ at 5.9 keV (%)**	**Dead time/event (μs)**	**Maximum count rate (s^{-1})**
Gas ionization (current mode)	0.2–50	n/a	n/a	10^{11}[a]
Gas proportional	0.2–50	15	0.2	10^6
Multiwire and microstrip proportional	3–50	20	0.2	$10^6/mm^2$
Scintillation [NaI(Tl)]	3–10,000	40	0.25	2×10^6
Energy-resolving semiconductor	1–10,000	3	0.5–30	2×10^5
Surface-barrier (current mode)	0.1–20	n/a	n/a	10^8
Avalanche photodiode	0.1–50	20	0.001	10^8
CCD	0.1–70	n/a	n/a	n/a
Superconducting	0.1–4	< 0.5	100	5×10^3
Image plate	4–80	n/a	n/a	n/a

[a] Maximum count rate is limited by space-charge effects to around 10^{11} photons/s per cm^3.