Rezonansowe jądrowego rozpraszanie promieniowania synchrotronowego
czyli:
Druga młodość efektu Mössbauera

AGH
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K. Matlak
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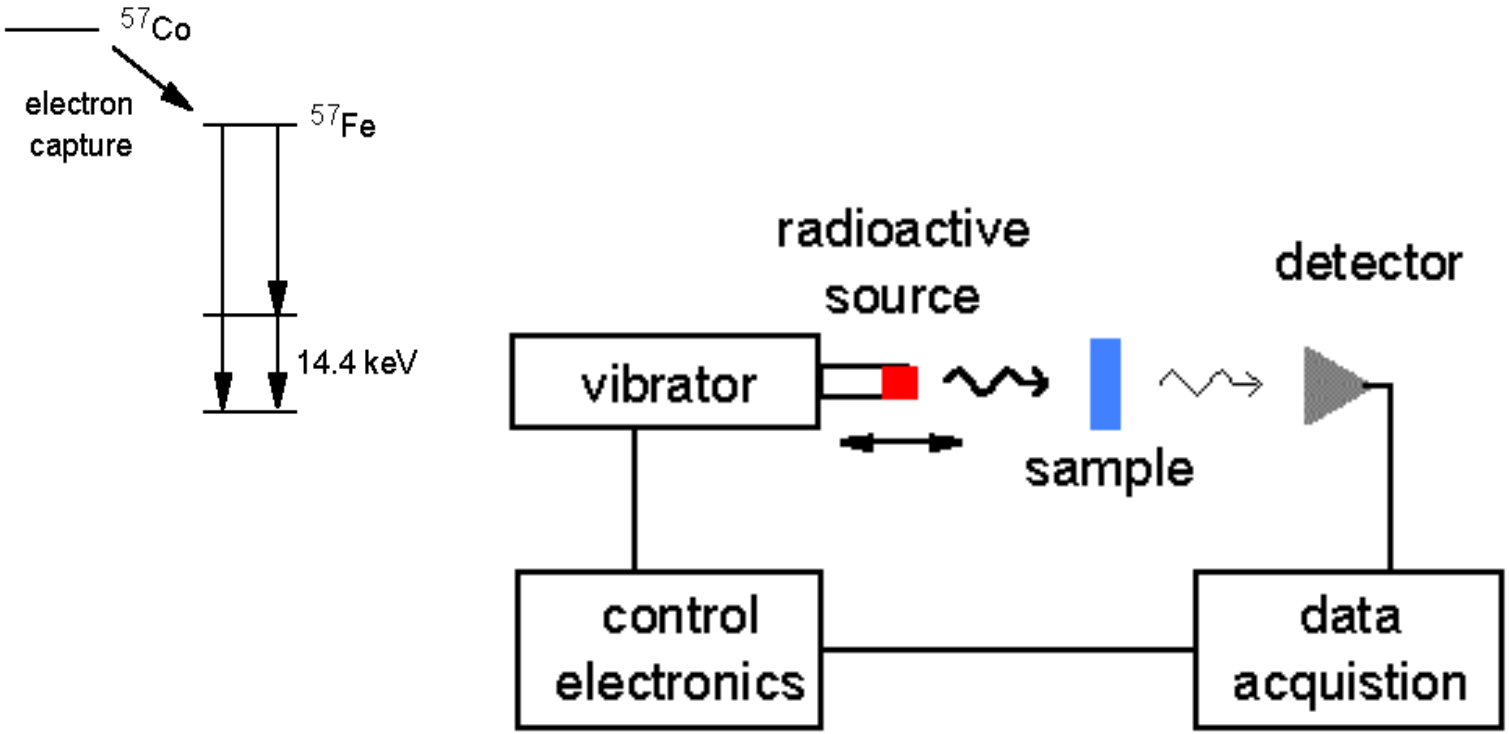
K. Parliński
J. Łażewski

- Efekt Mössbauera w synchrotronie
- Koherentne elastyczne rozpraszanie jądrowe:

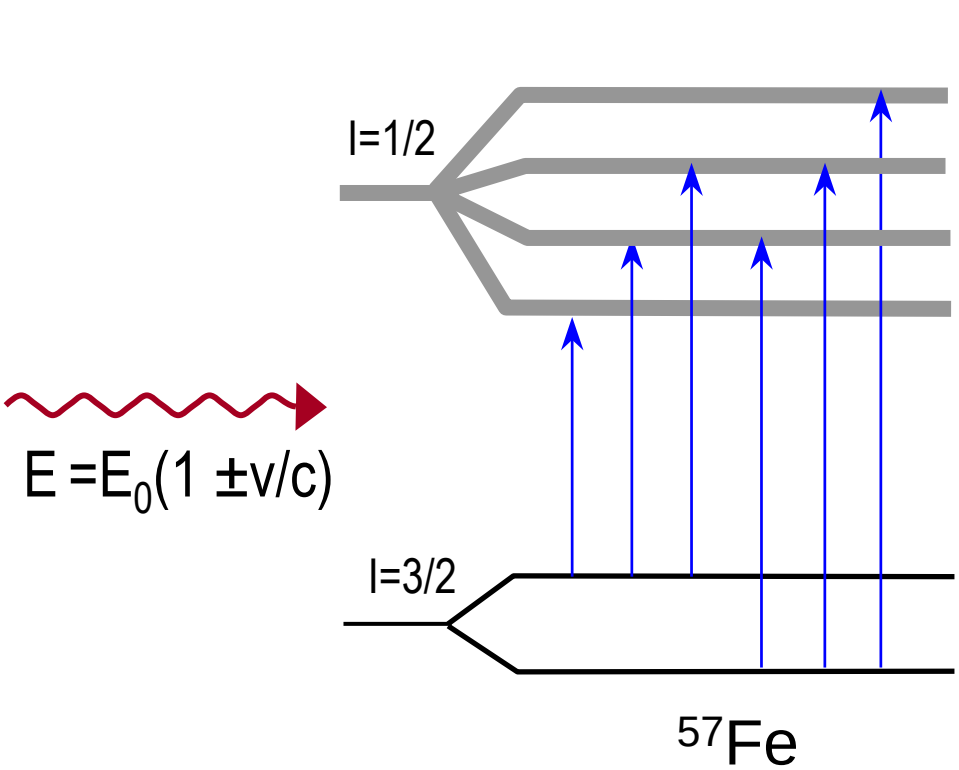
  20 lat później: Pola nadsubtelne na powierzchni Fe
- NIS – „Anty-Efekt Mössbauera"
- ..i jeszcze coś

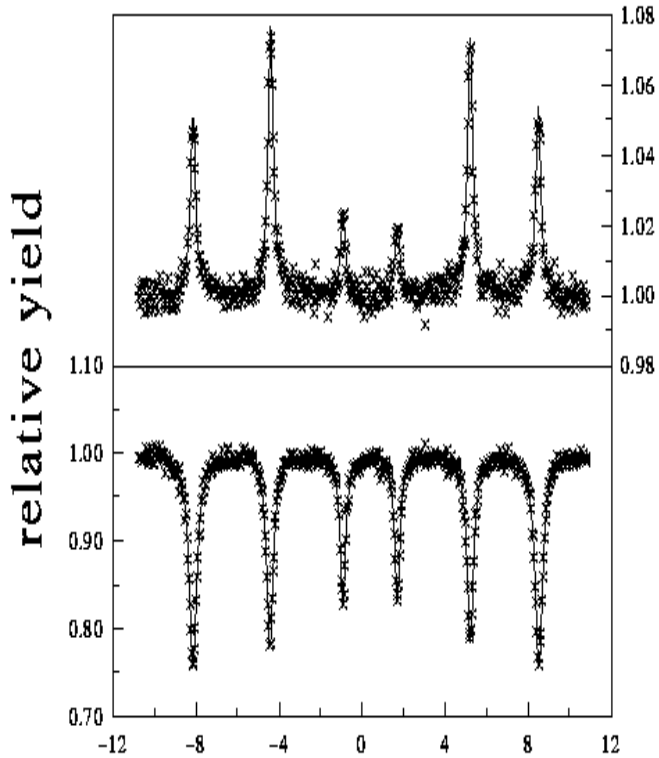


Mössbauer spectroscopy:
Recoilless, resonance adsorption of γ-radiation

structural, chemical and electronic information
on a local scale
(mainly ^{57}Fe)

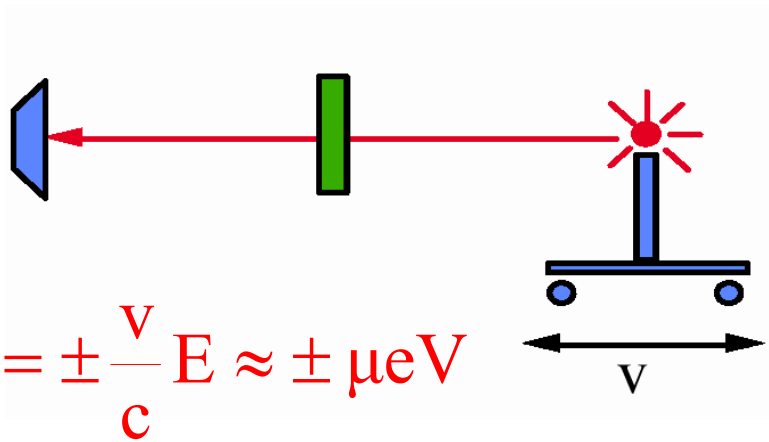
Conventional (energy-domain) MS

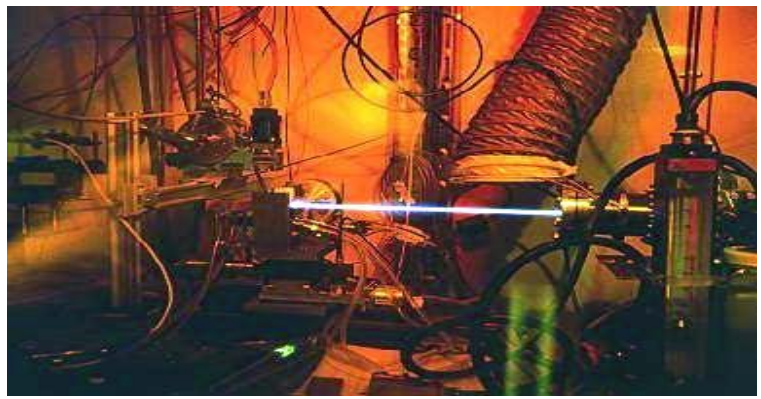




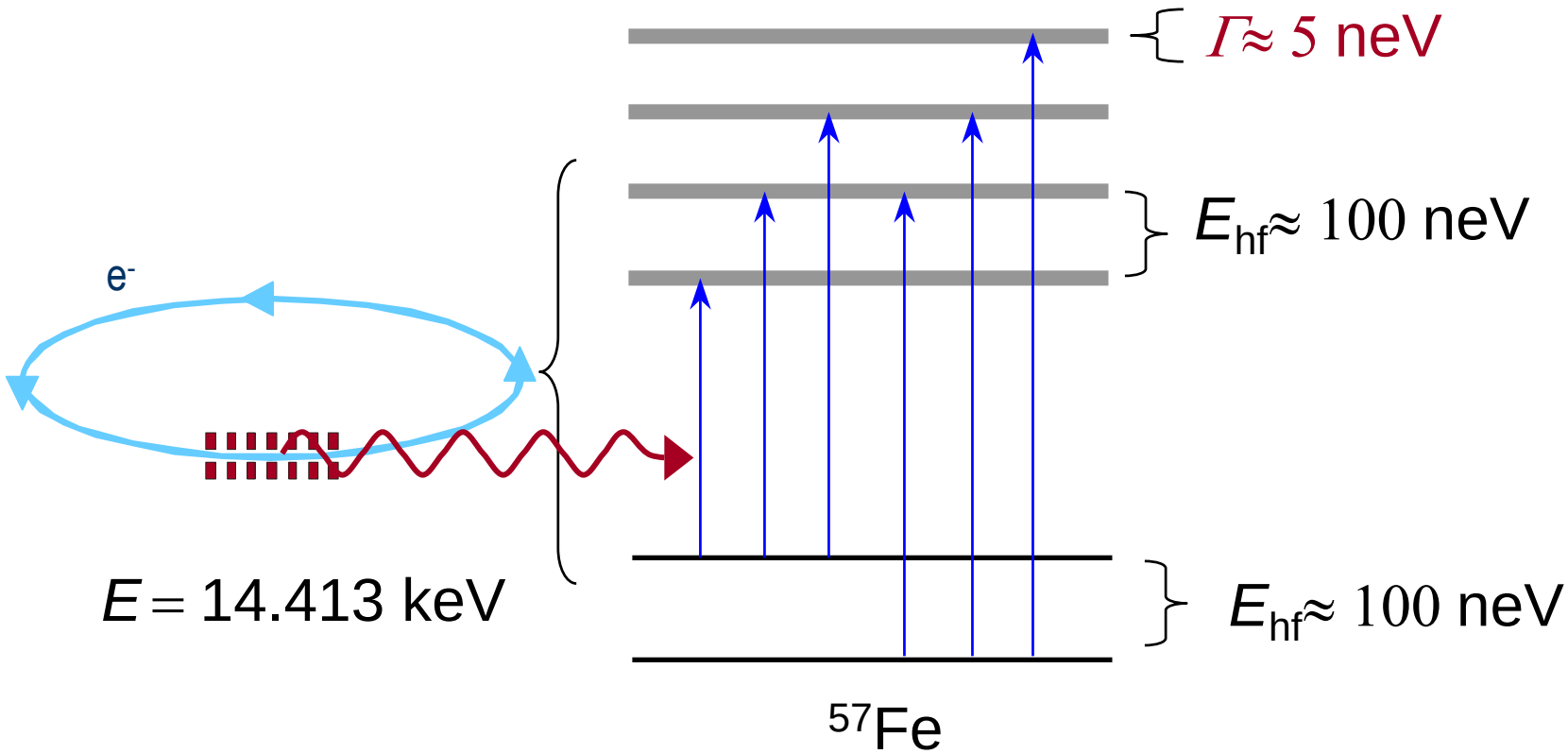
Only one transition is excited at the same time, therefore the resultant spectrum is the incoherent sum of the individual transitions (the intensities are added).

Tunable source of EM radiation in Mössbauer transition range





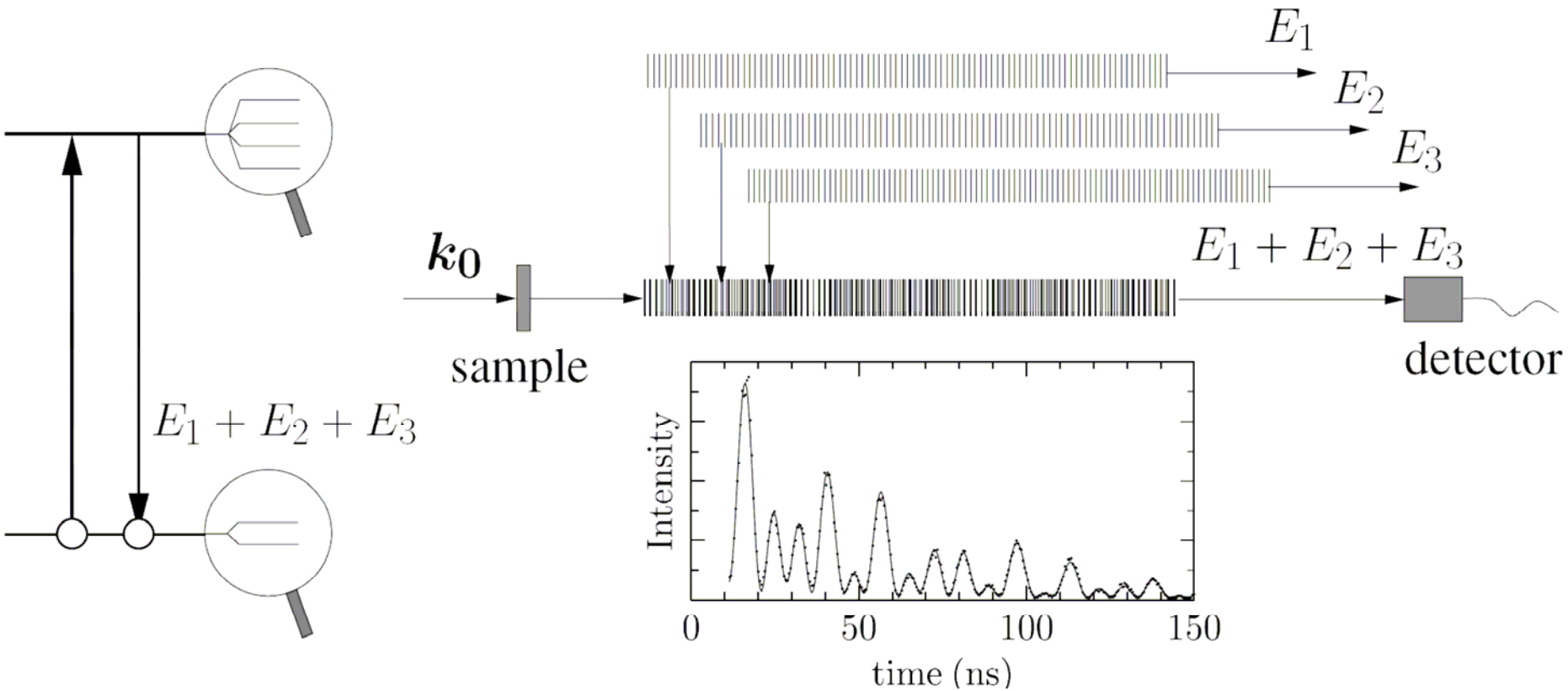
Hyperfine splitting of nuclear levels



is hf spectroscopy with SR possible?

hf spectroscopy in energy domain requires a tuneable source of X-rays with energy monochromatization ~5 neV (feasible is 0.5 meV)

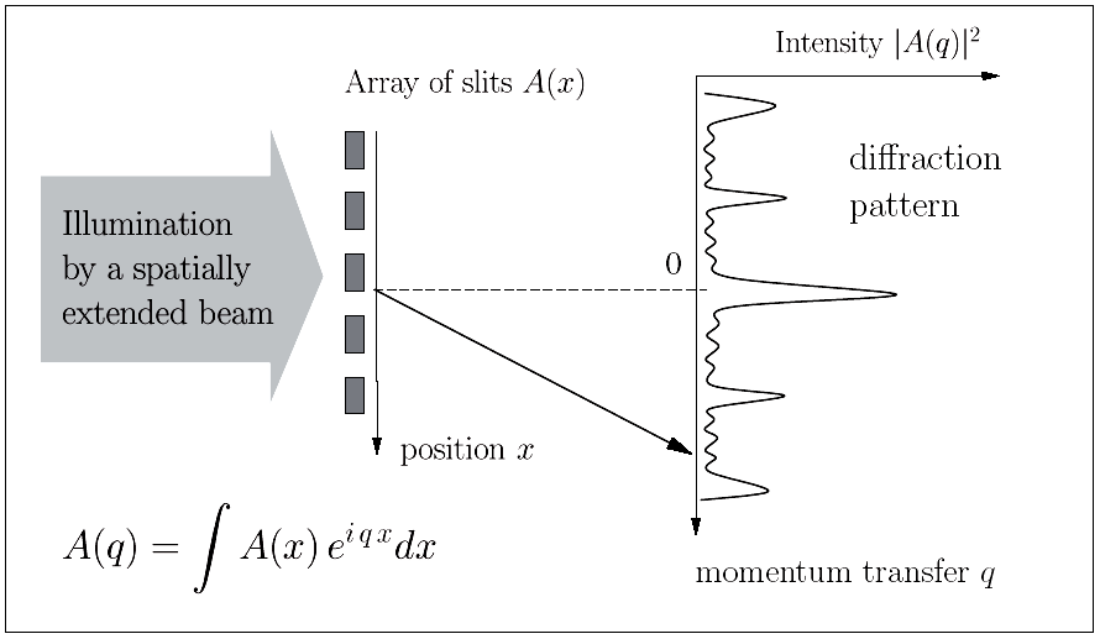
Hyperfine spectroscopy with SR? - YES
- however not in energy -
- but in time-domain -



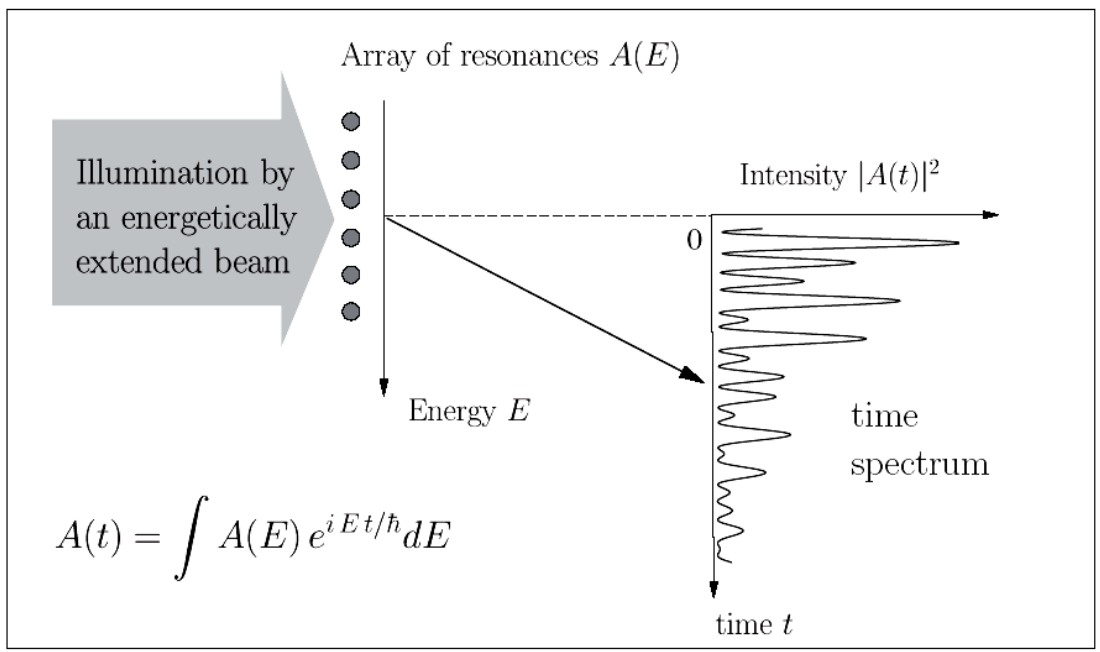
Nuclear Resonance Scattering of SR - NRS

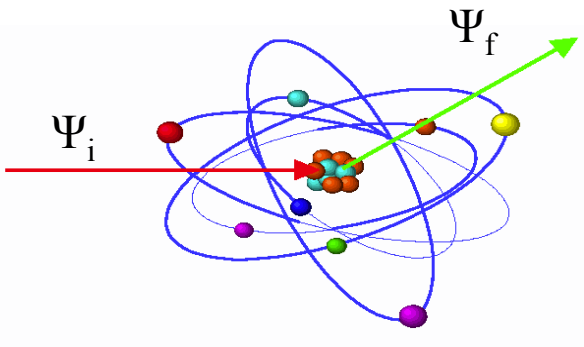
Reproduced from:
R. Röhlsberger, Nuclear Condensed Matter Physics with Synchrotron Radiation, Springer 2004

(a) Diffraction in position–momentum space



(b) Diffraction in energy–time space





$\Psi_i \rightarrow \Psi_f$

coherent
$\Psi_i = \Psi_f$

incoherent
$\Psi_i \neq \Psi_f$

elastic

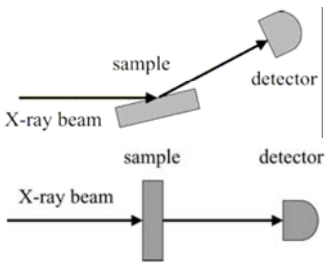
inelastic

elastic

inelastic

D-NRS

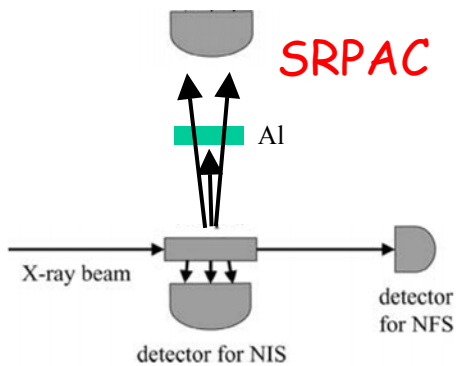
GI-NRS

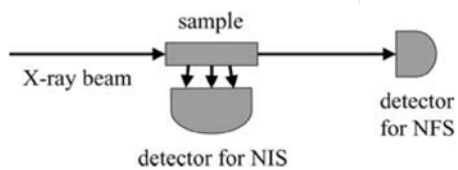


NFS

CEMS

SRPAC

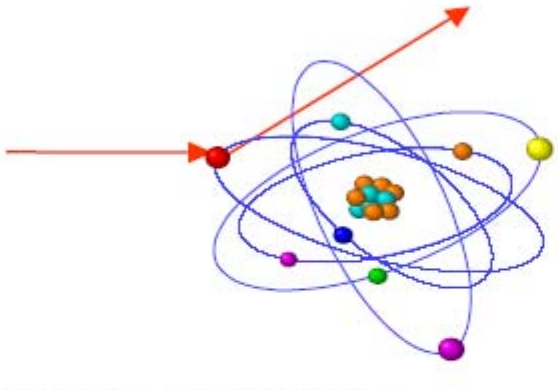




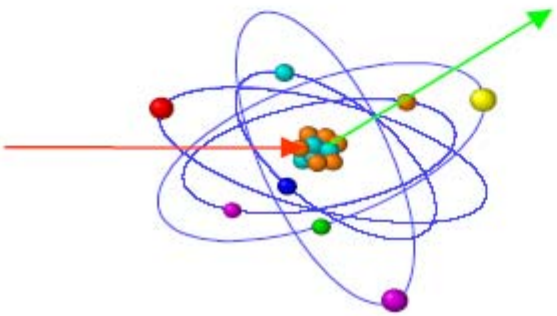
NIS

Methodology

SEPARATION OF ELECTRONIC AND NUCLEAR SCATTERING:

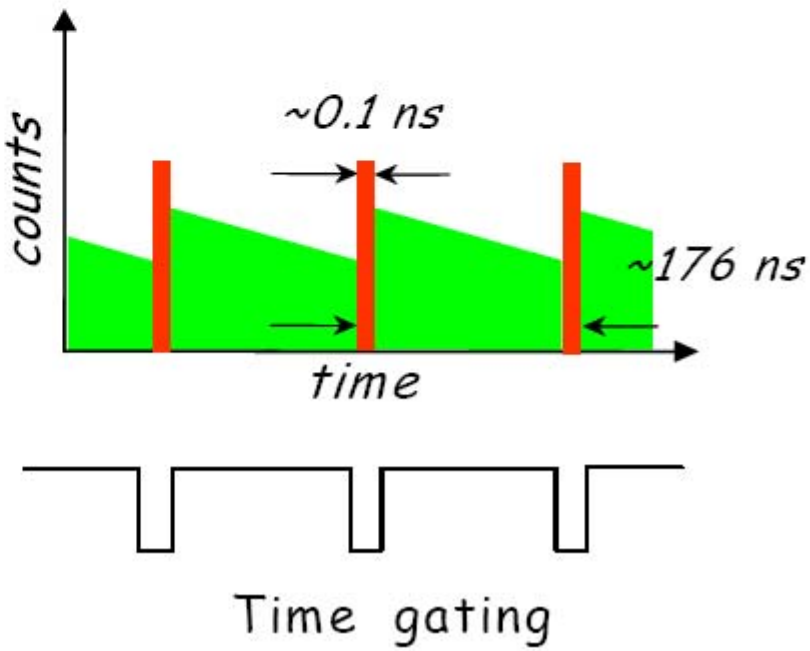


Prompt scattering: electronic



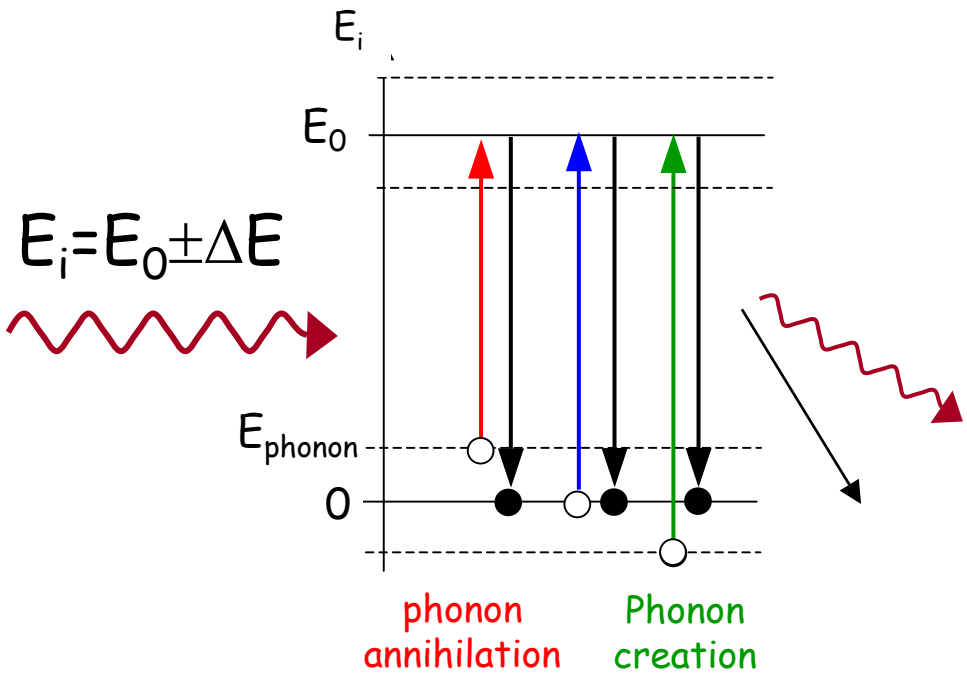
Delayed scattering: nuclear

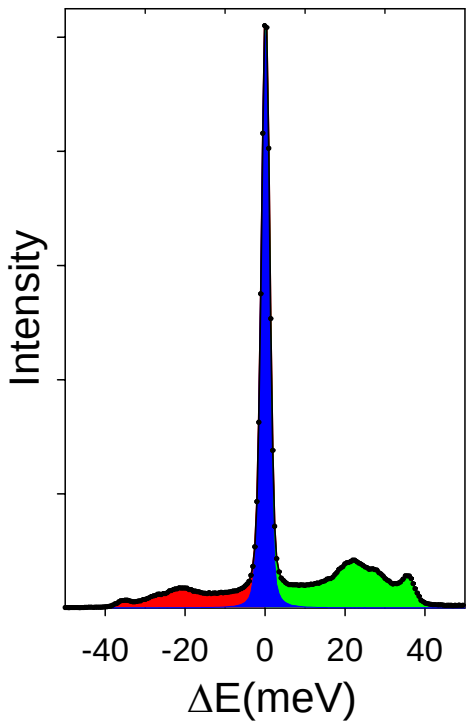
pulsed structure
of synchrotron radiation:

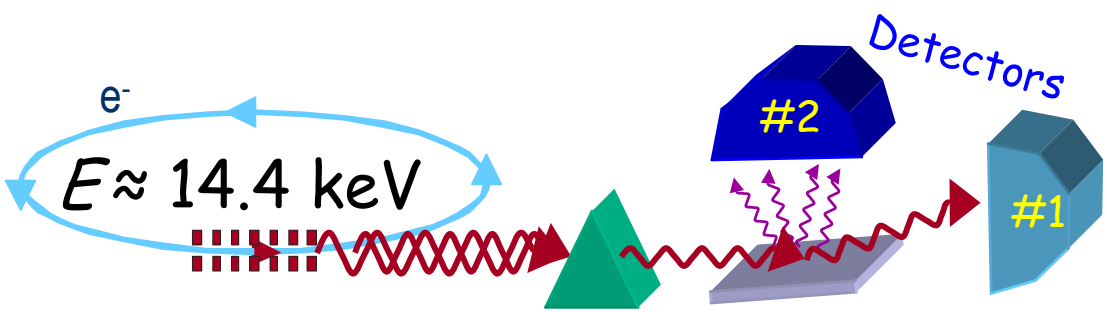


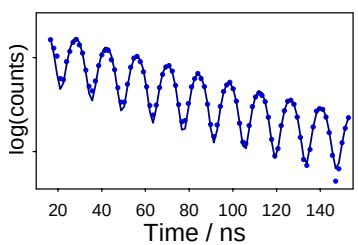
Nuclear Resonance Scattering of SR - NRS

Nuclear Inelastic Scattering of SR - NIS
(precisely – Inelastic Nuclear Resonant Adsorption)



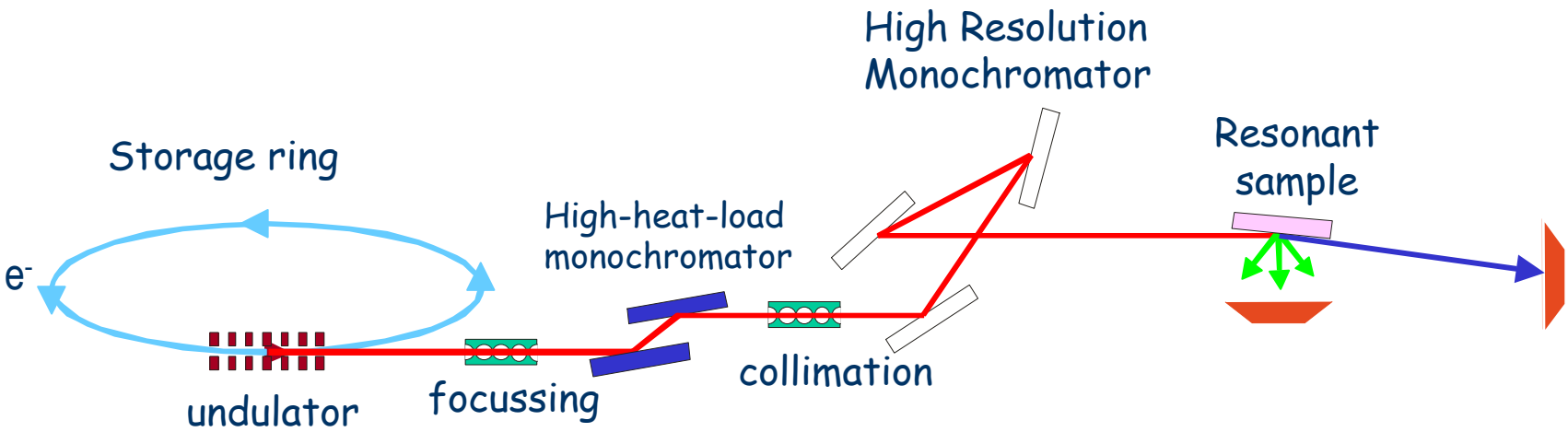




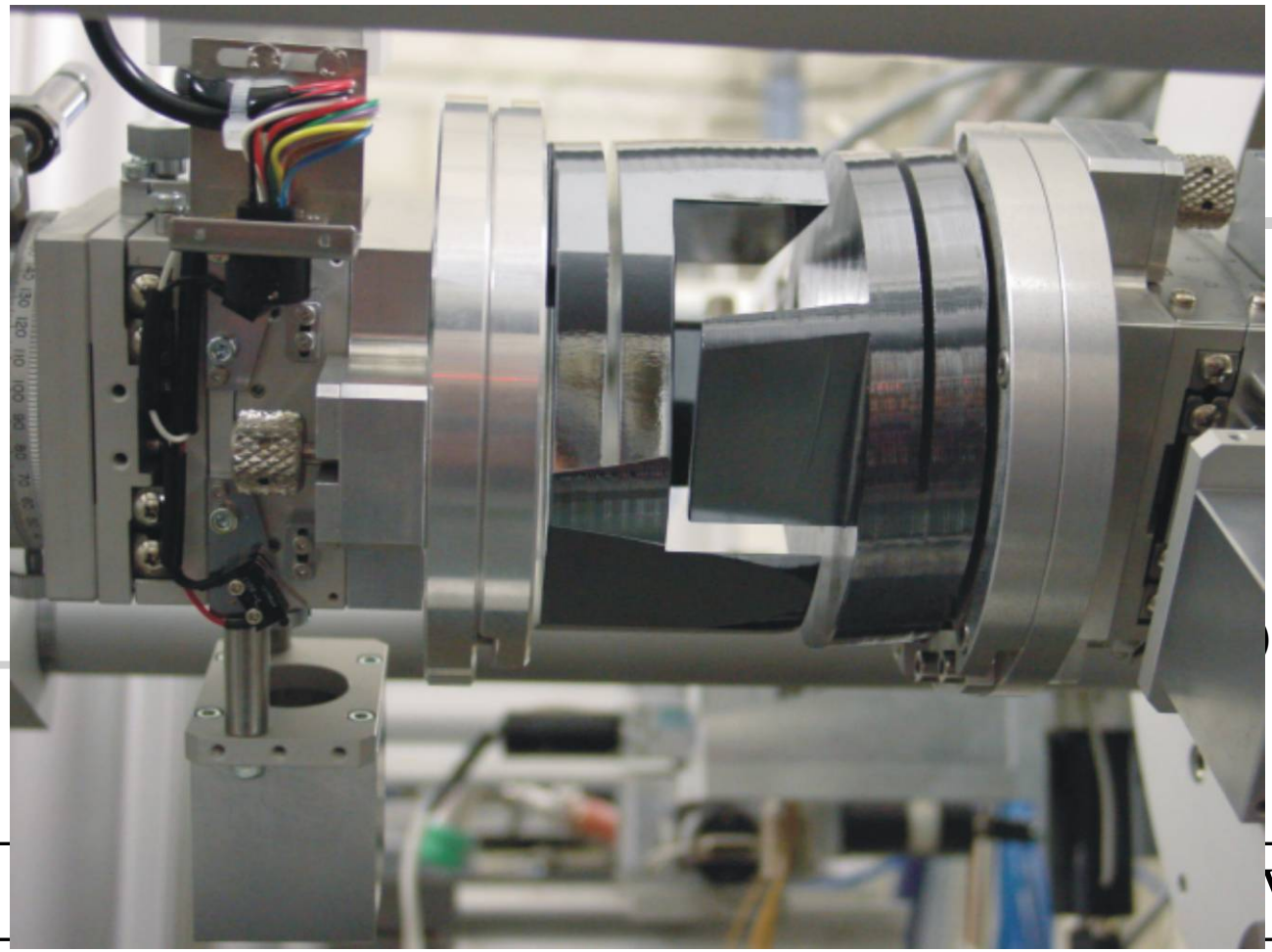


Instrumentation

ID 18, ESRF Grenoble



High-heat-load premonochromator and high-resolution nested monochromator



2)

ΔE:

V

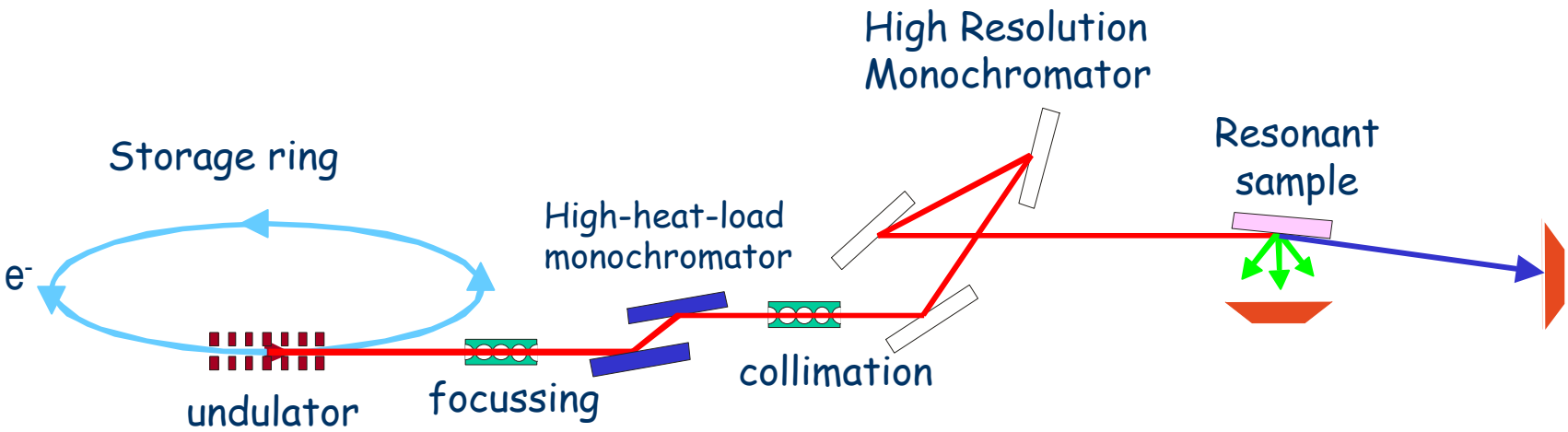
Mössbauer isotopes with used in synchrotron-based experiments

Isotope	E_γ (keV)	a (%)	Γ_0 (neV)	τ (ns)	σ_0 (10^{-22}m^2)	I_g	I_e	Multi polarity	μ_g (μ_N)	μ_e (μ_N)
^{181}Ta	6.23	99.9	0.067	9870	1.099	7/2	9/2	$E1$	2.360	5.220
^{169}Tm	8.41	100	114	5.8	0.242	1/2	3/2	$M1$	−0.232	0.520
^{83}Kr	9.40	12.0	3.3	212	1.226	9/2	7/2	$M1$	−0.967	−0.939
^{57}Fe	14.41	2.1	4.7	141	2.464	1/2	3/2	$M1$	0.090	−0.155
^{151}Eu	21.53	47.8	47.0	14.1	0.243	5/2	7/2	$M1$	3.464	2.590
^{149}Sm	22.49	13.8	64.1	10.3	0.120	7/2	5/2	$M1$	−0.665	−0.622
^{119}Sn	23.87	8.6	25.7	25.7	1.381	1/2	3/2	$M1$	−1.046	0.685
^{161}Dy	26.65	18.9	16.2	40.8	1.110	5/2	5/2	$E1$	−0.470	0.558

R. Röhlsberger et al. Phys. Rev. B **67**, 245412 (2003)

Instrumentation

ID 18, ESRF Grenoble



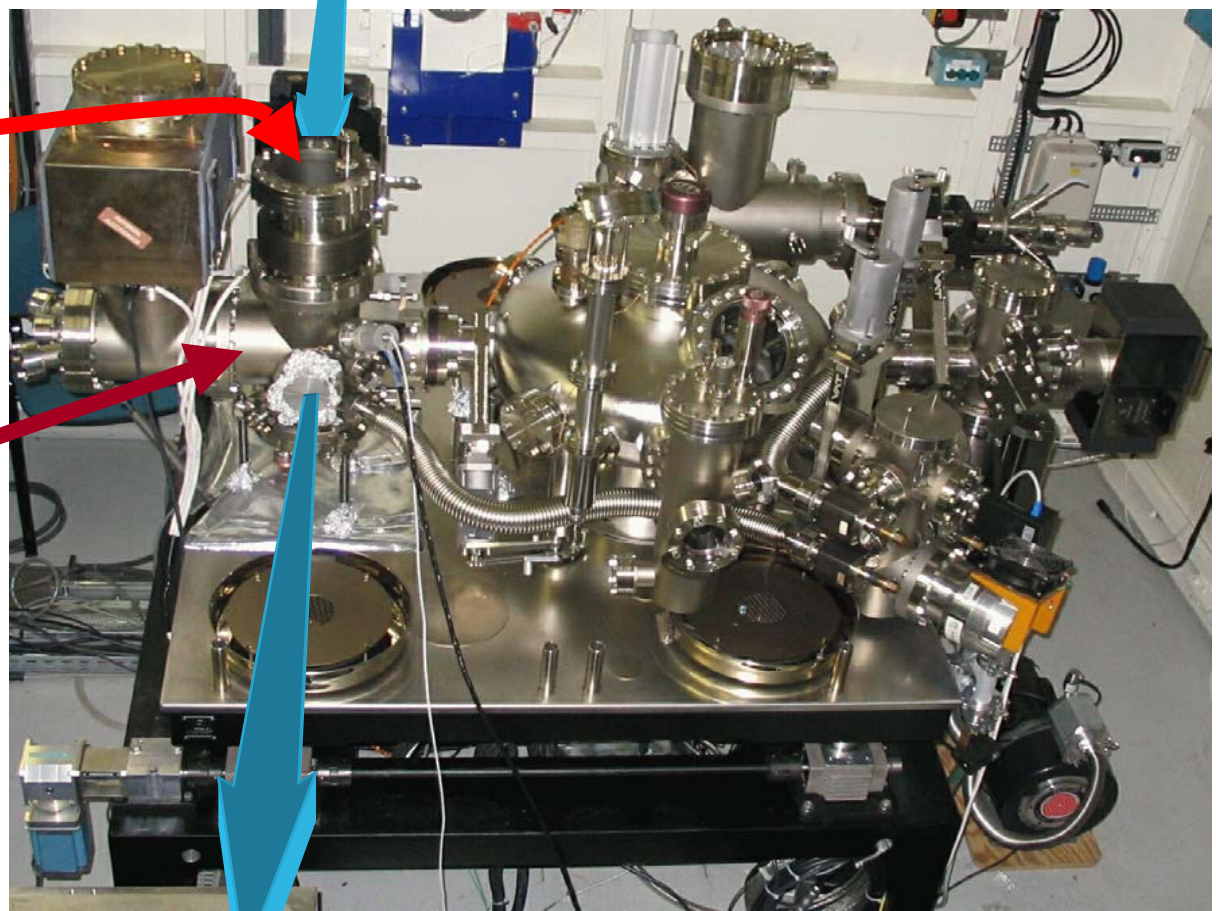
Instrumentation

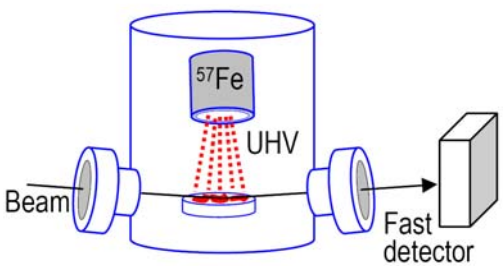
ID 18, ESRF Grenoble

SR-beam

Fast detector #2

NRS chamber on 2-circle goniometer



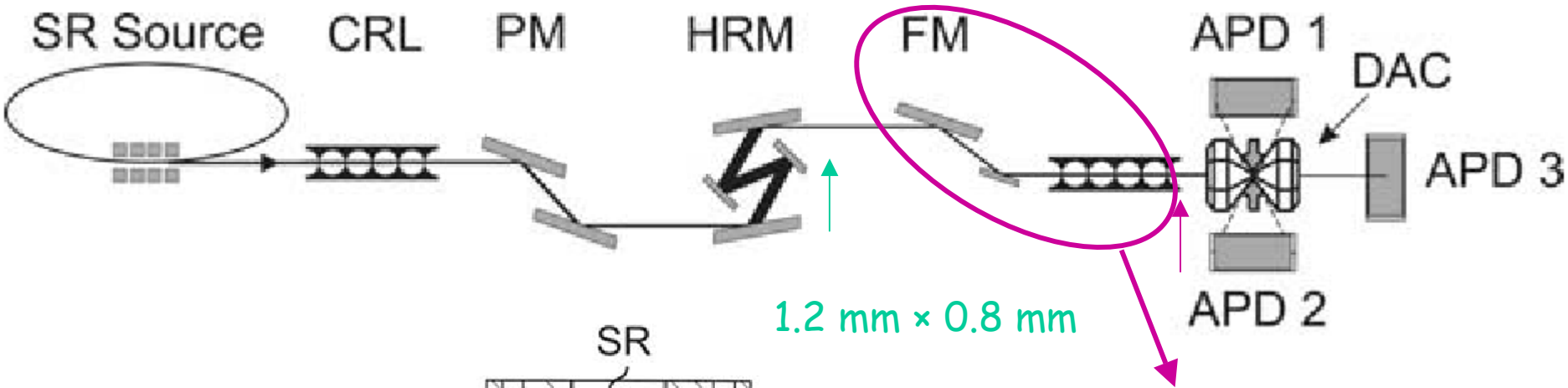


Fast detector #1

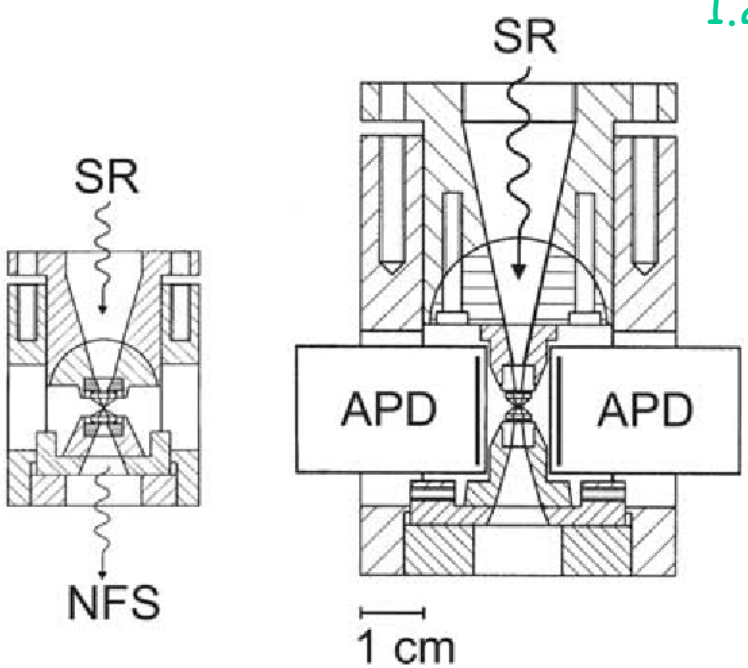
Density of Phonon States in Iron at High Pressure

R. Lübbers,[1] H. F. Grünsteudel,[2] A. I. Chumakov,[2] G. Wortmann[1]*

18 FEBRUARY 2000 VOL 287 SCIENCE



1.2 mm × 0.8 mm



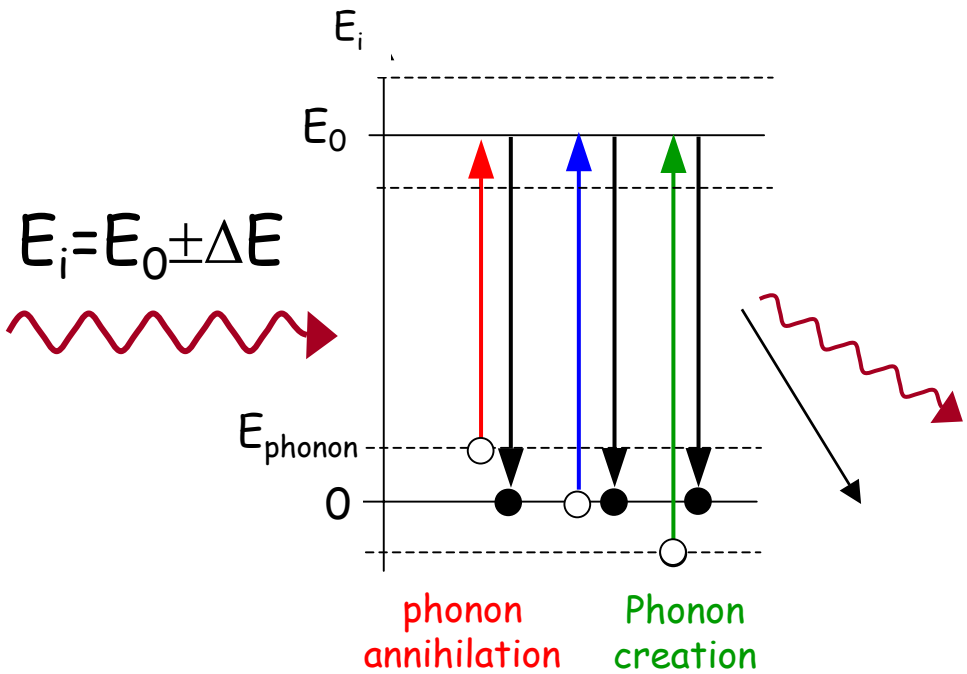
Dodatkowe ogniskowanie

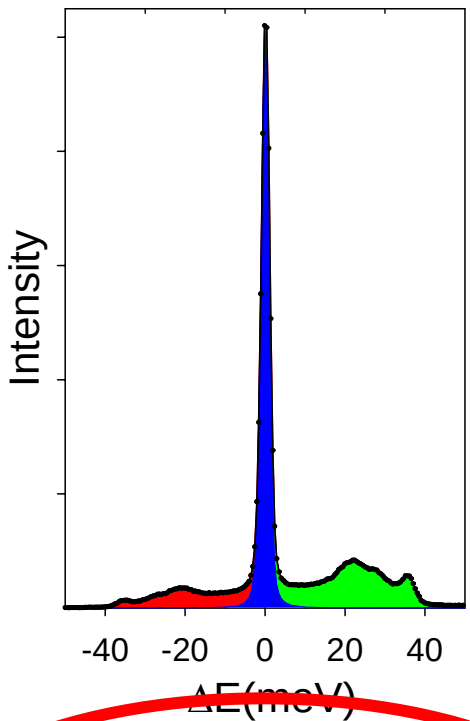
90 μm × 60 μm
3 ×10⁸ fotonów/s

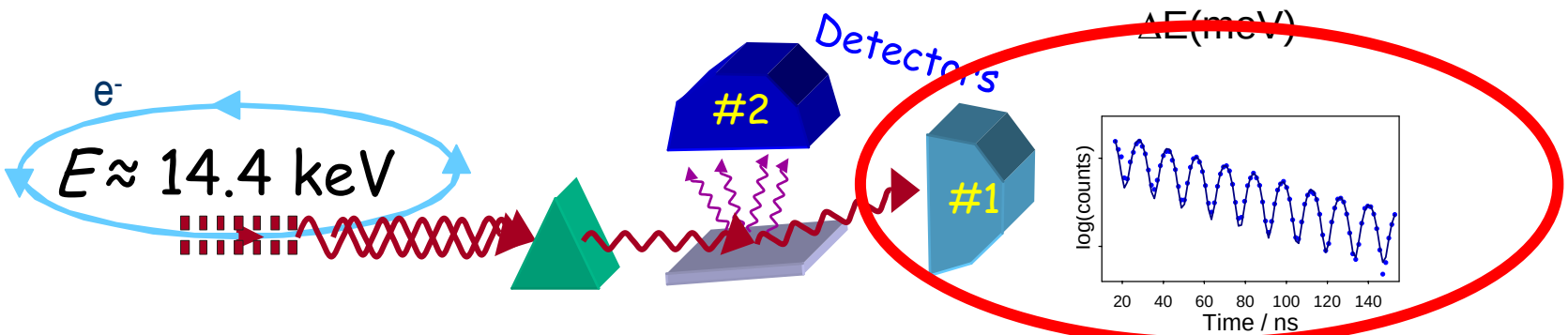
K-B multilayers
15 μm × 15 μm

Nuclear Resonance Scattering of SR - NRS

Nuclear Inelastic Scattering of SR - NIS
(precisely – Inelastic Nuclear Resonant Adsorption)



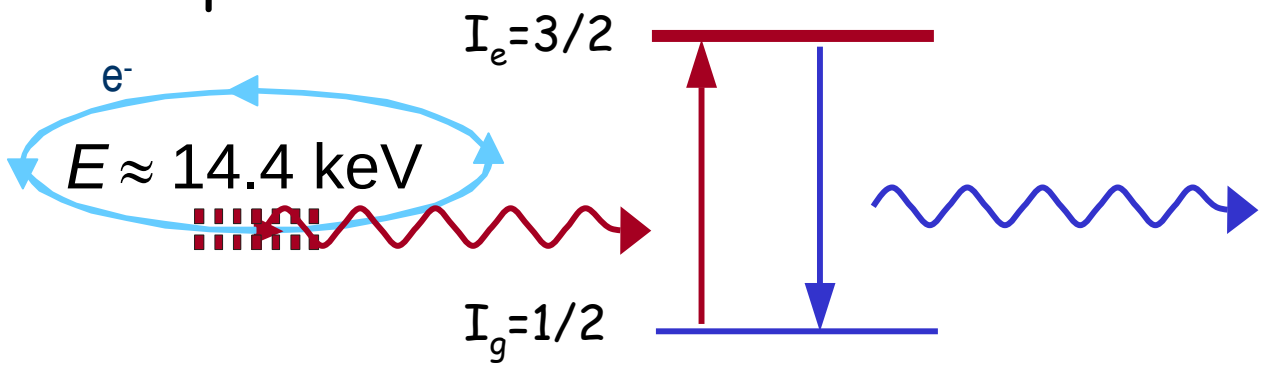


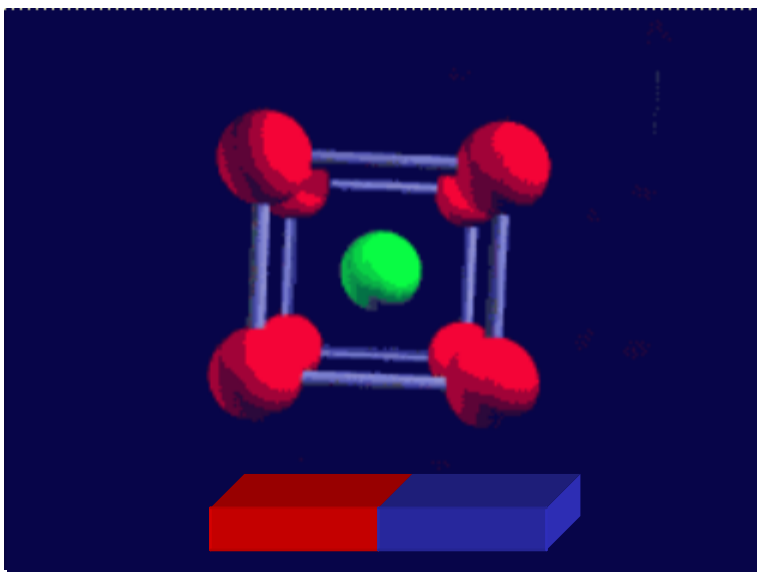


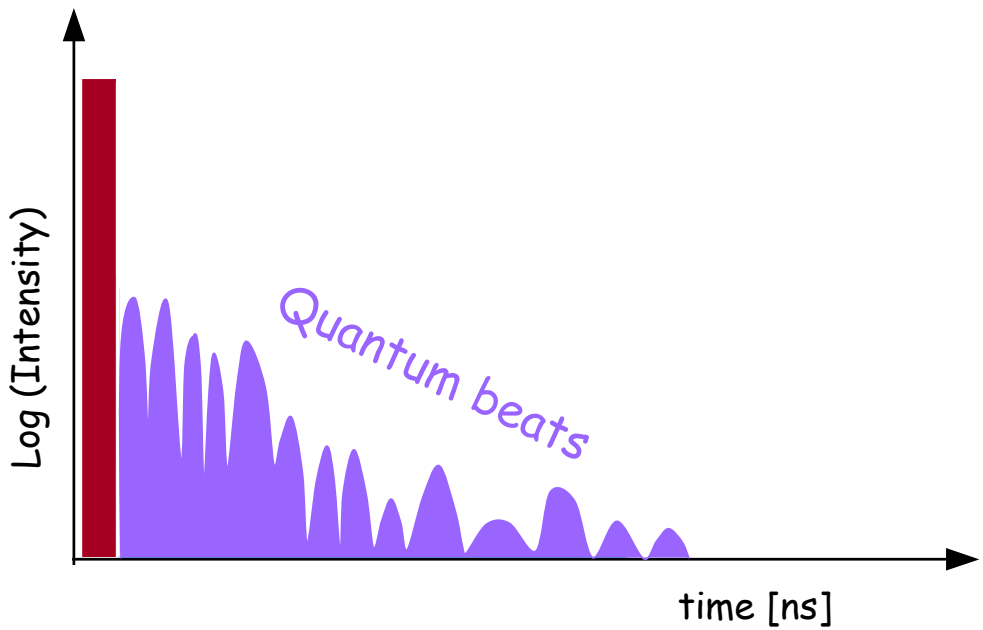
Nuclear Resonance Scattering of SR - NRS

^{57}Fe Mössbauer isotope

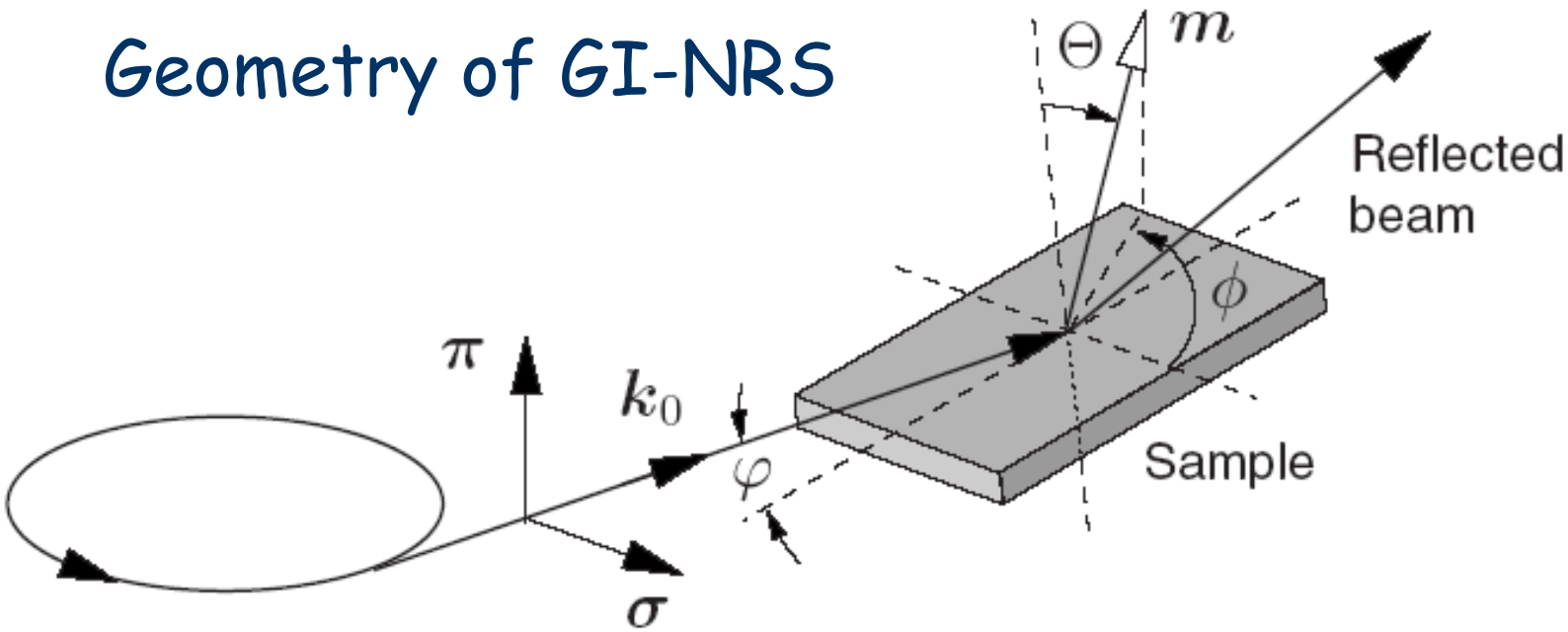
τ_0 = 141 ns

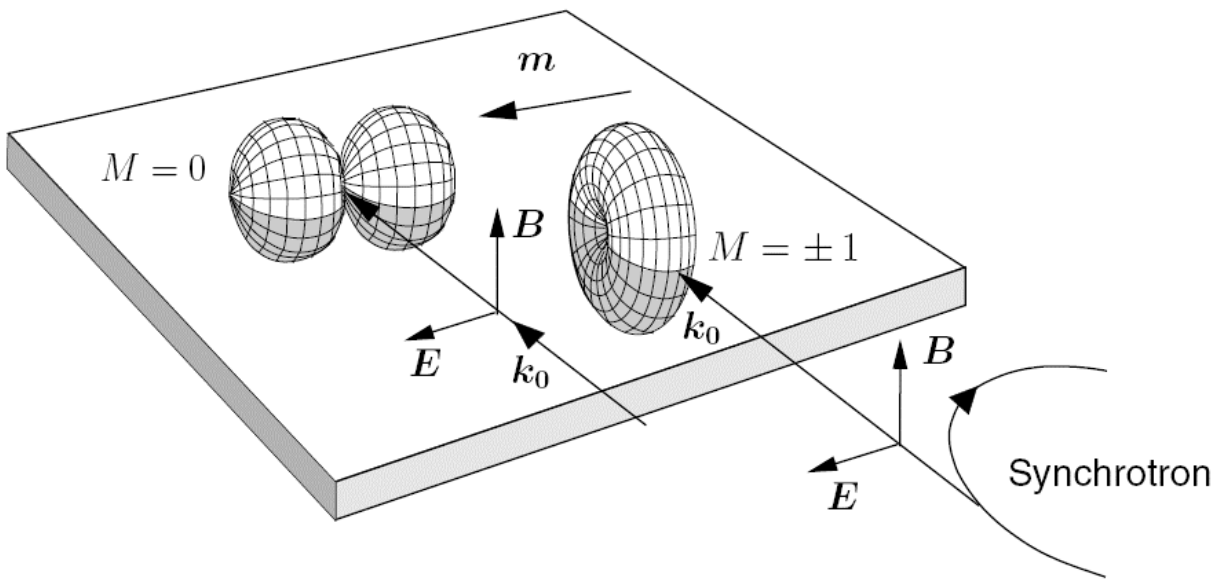




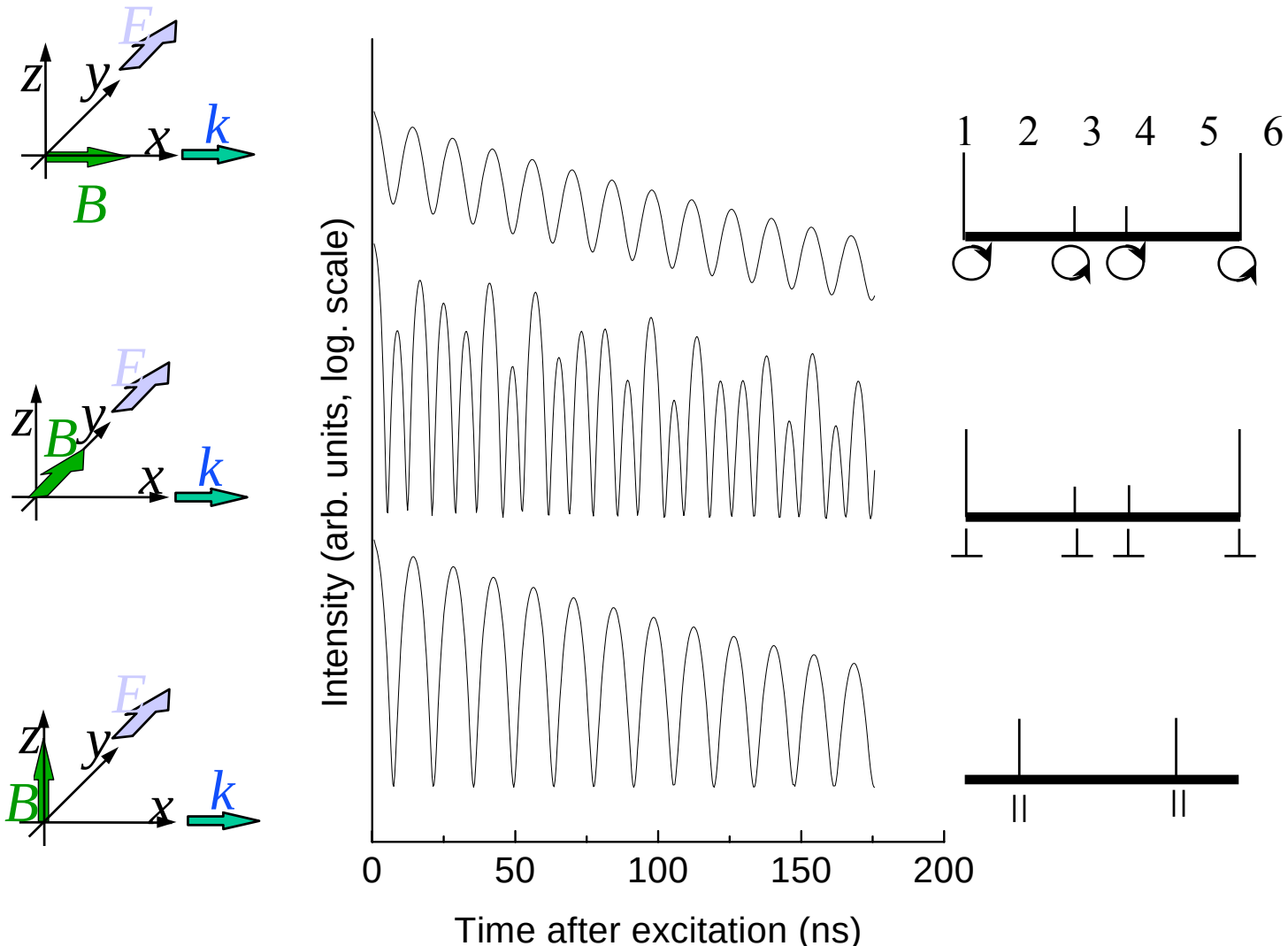


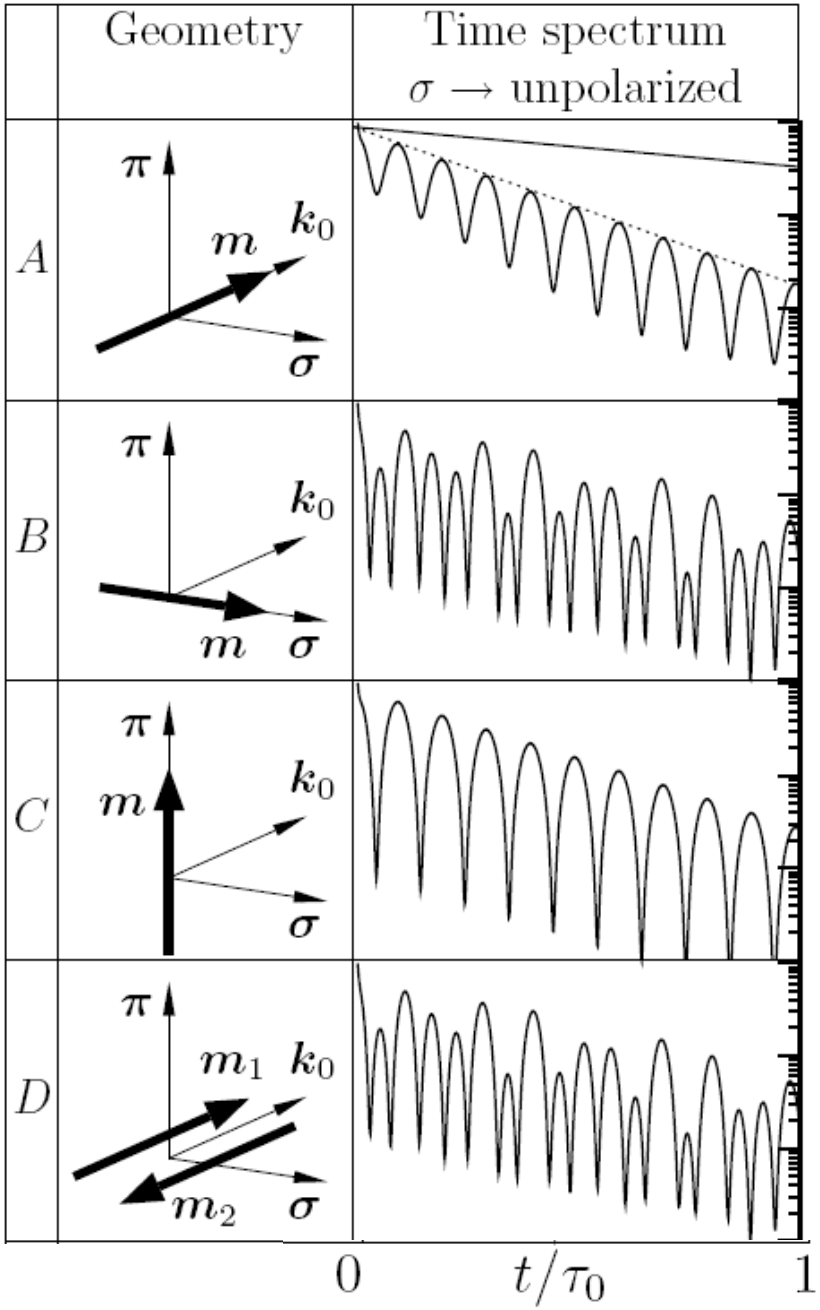
Geometry of GI-NRS

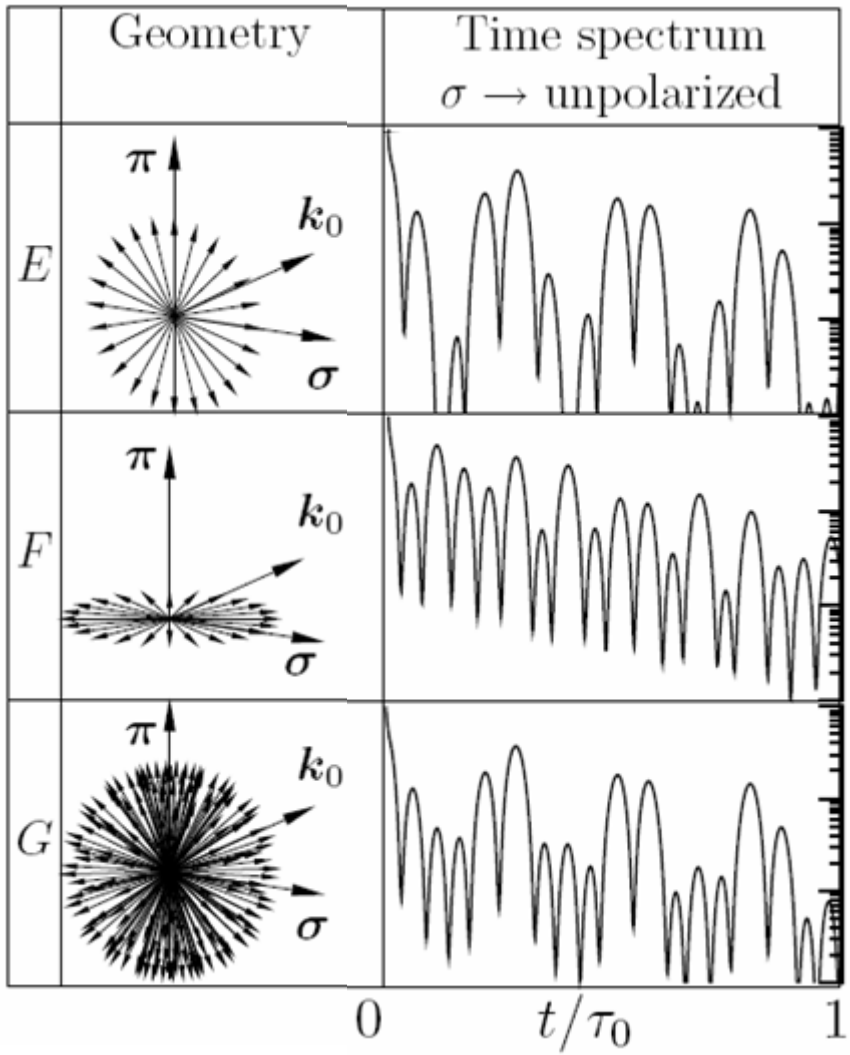




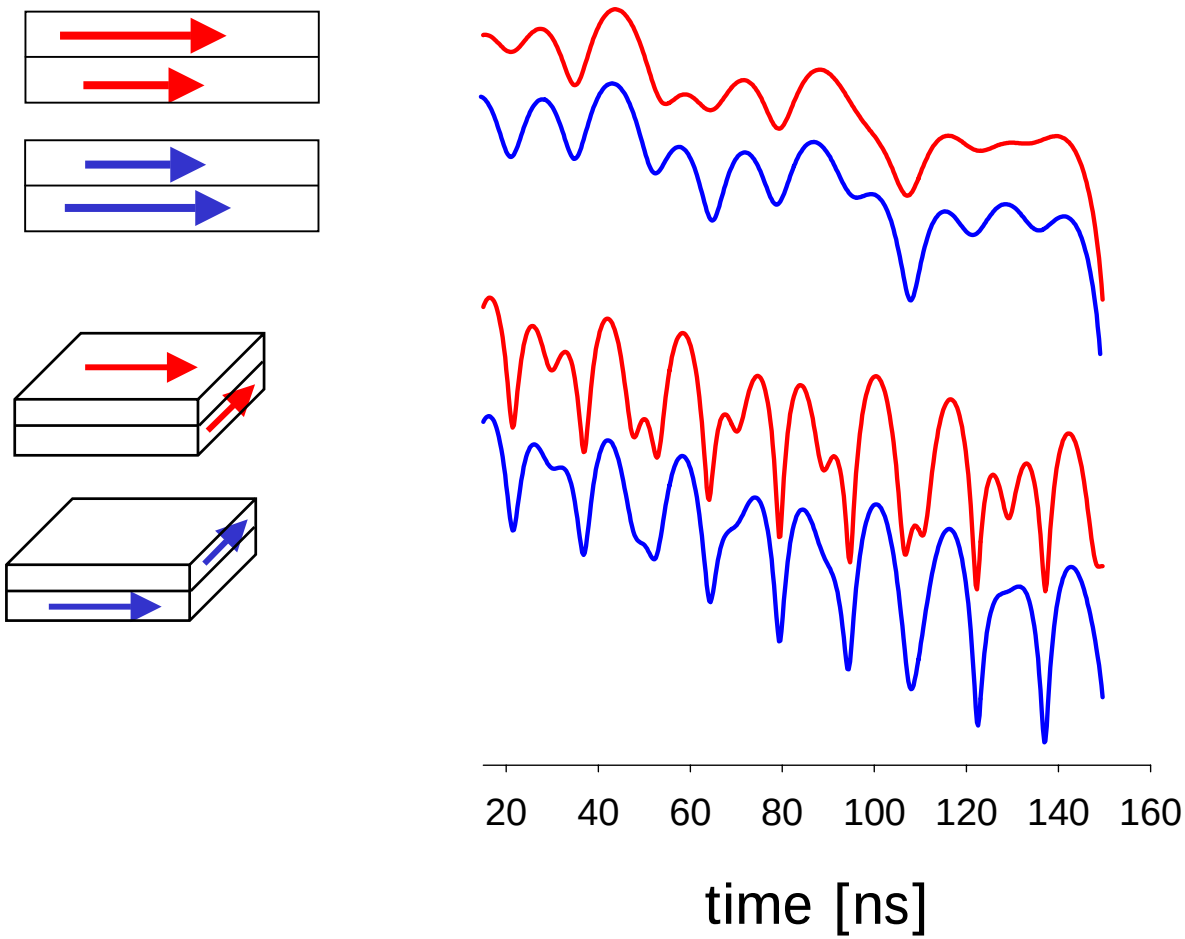
Orientation of the hyperfine field (the "Smirnov figures")

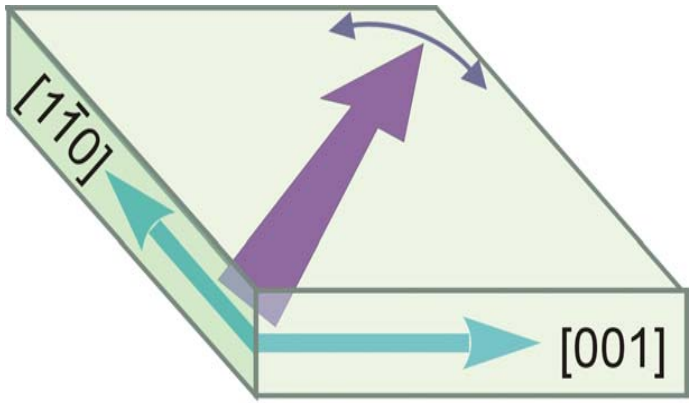


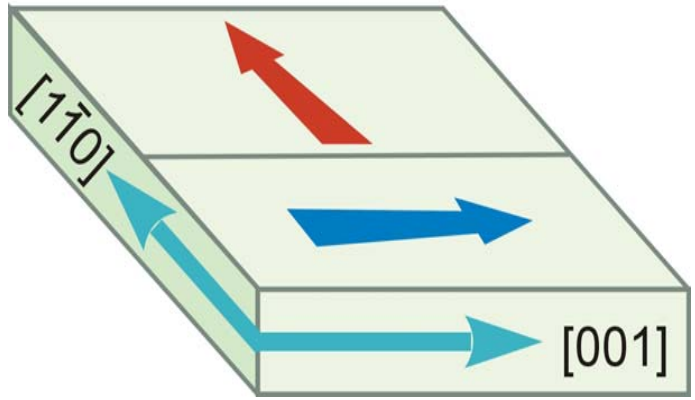

Geometry
Time spectrum
$\sigma \rightarrow$ unpolarized
A
B
C
D
π
k_0
m
m_1
m_2
σ
0
t/τ_0
1


Geometry
Time spectrum
$\sigma \rightarrow$ unpolarized
E
F
G
π
k_0
σ
0
t/τ_0
1

Depth selectivity




[1$\bar{1}$0]
[001]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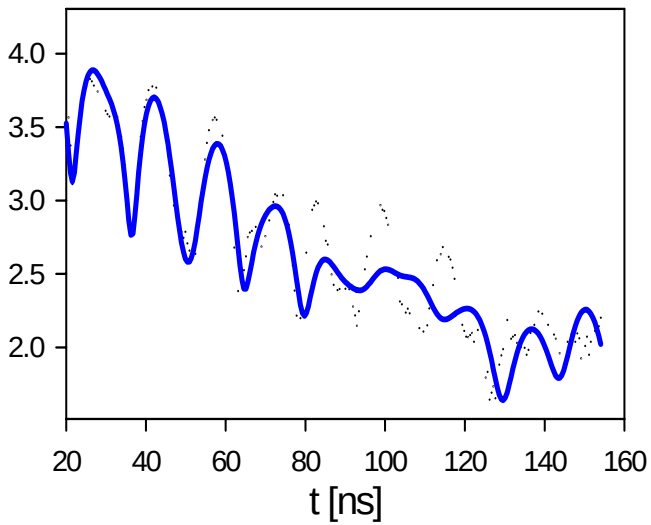
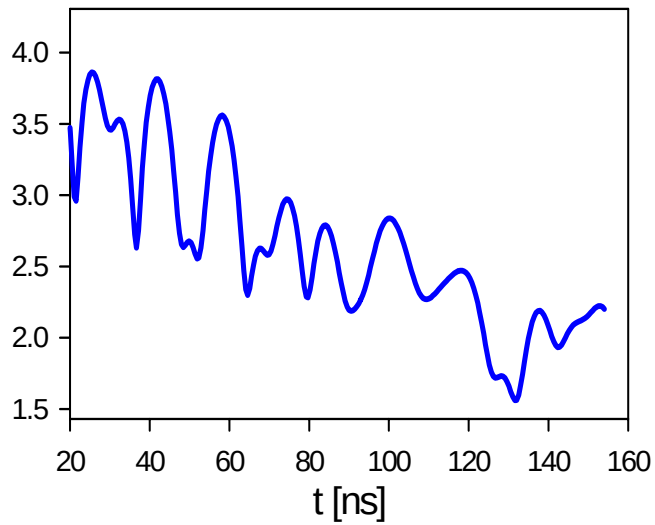
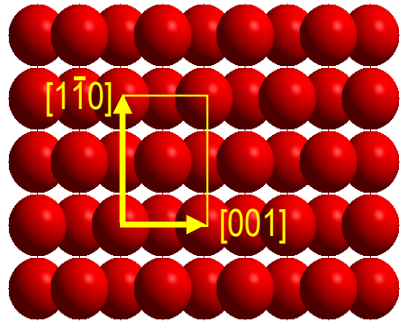
[001]

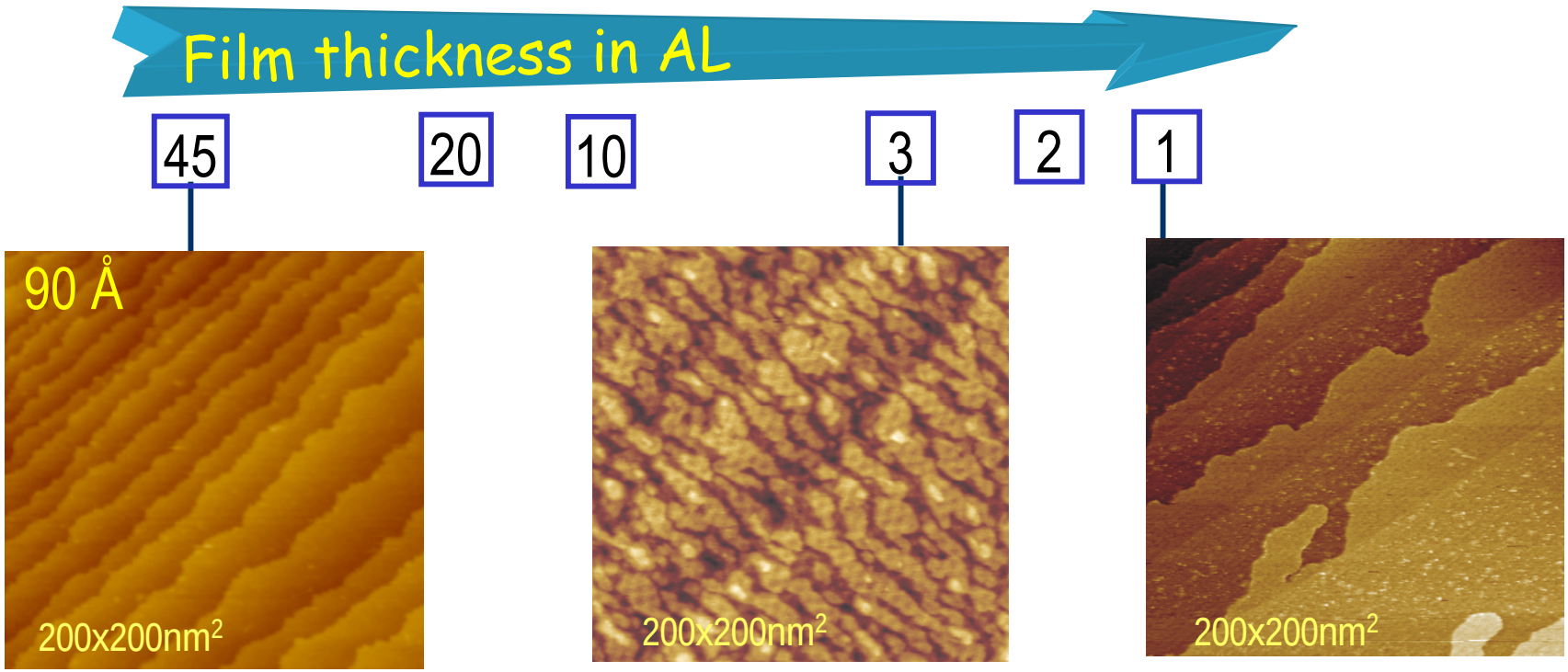

4.0
3.5
3.0
2.5
2.0
20
40
60
80
100
120
140
160
t [ns]


4.0
3.5
3.0
2.5
2.0
1.5
20
40
60
80
100
120
140
160
t [ns]

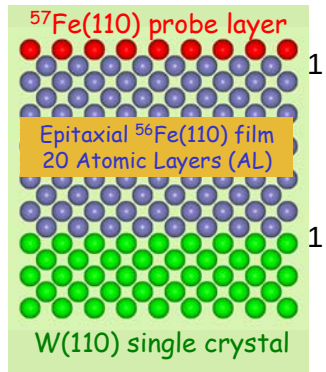
Model systemFe(110)/W(110)

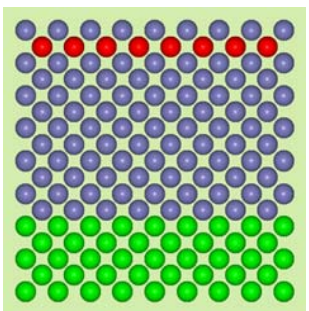


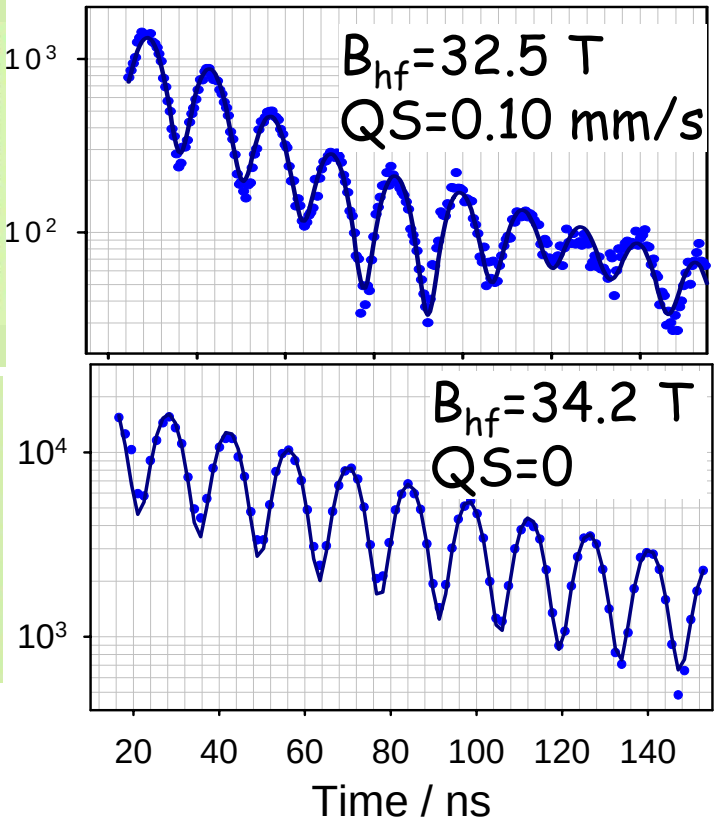
- Large lattice mismatch ~10% -layer-by-layer growth
- Pseudomorphic 1st (?) and 2nd (??) Fe atomic layer
- Complex strained Fe structure beyond 2nd AL
- Complex magnetic structure with several transitions

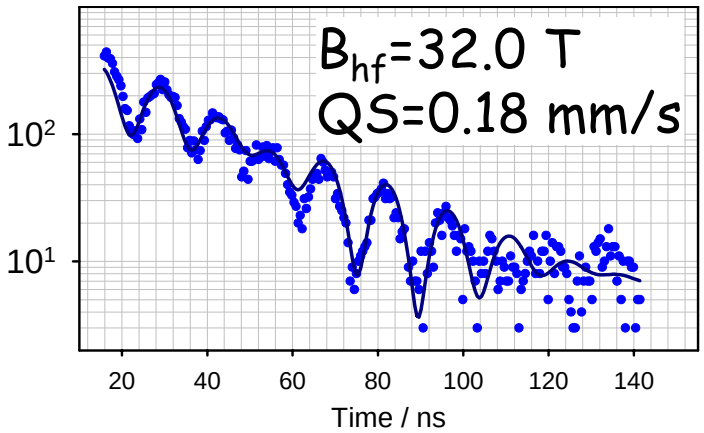


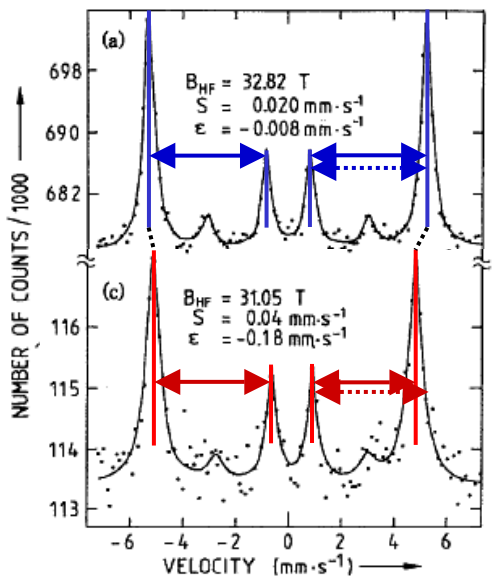
Surface magnetism





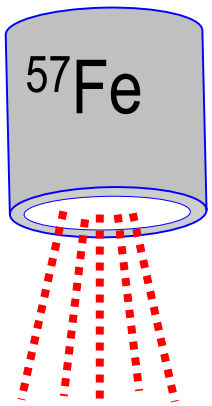




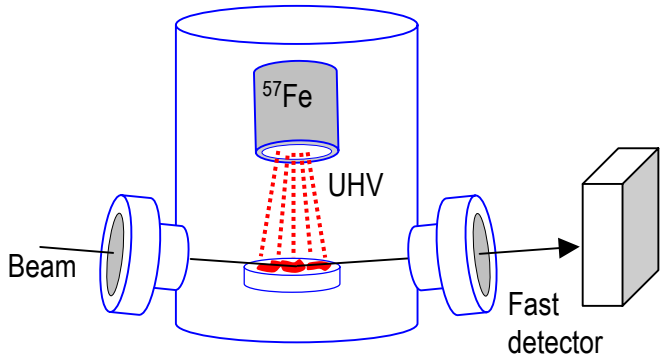


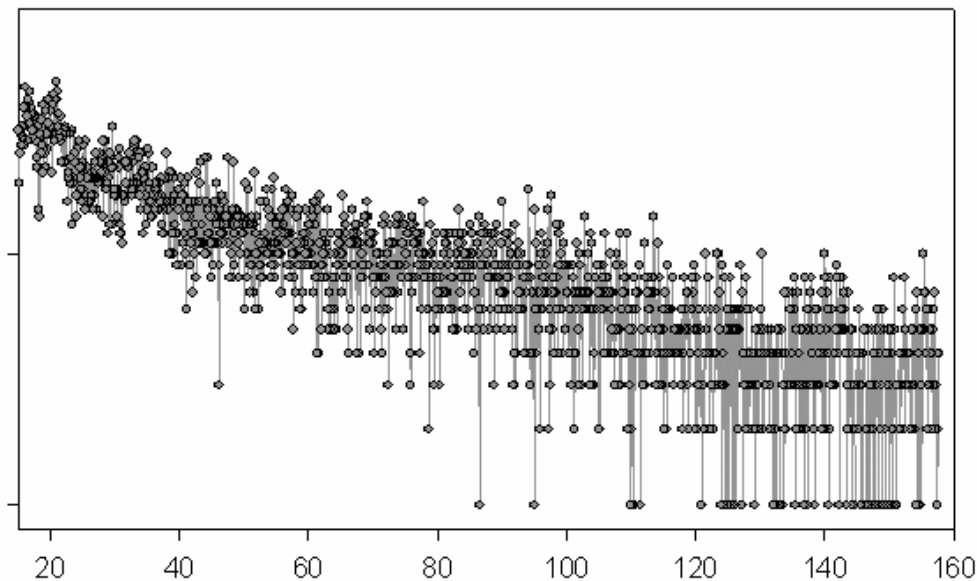
J.Korecki, U.Gradmann , Phys. Rev. Lett. 55(1985)2491.

NRS movie – growth of Fe on W(110)

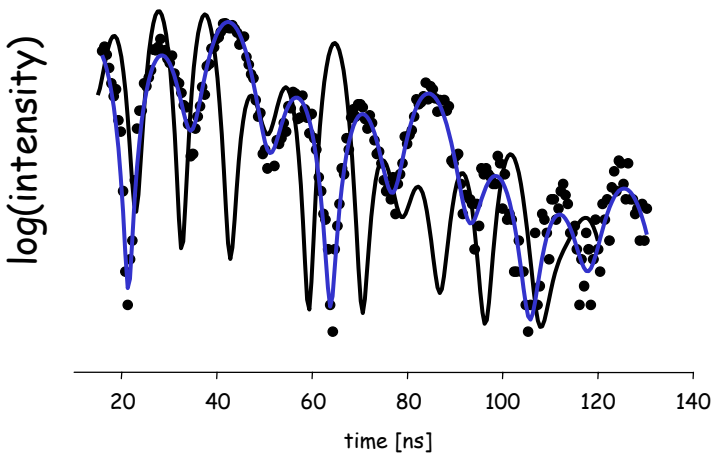


1- 28 ML

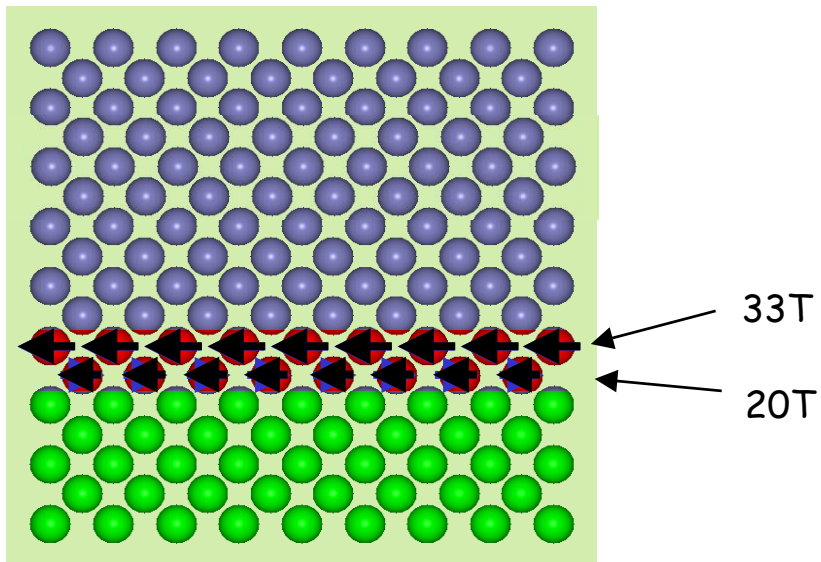




Fe/W(110) interface

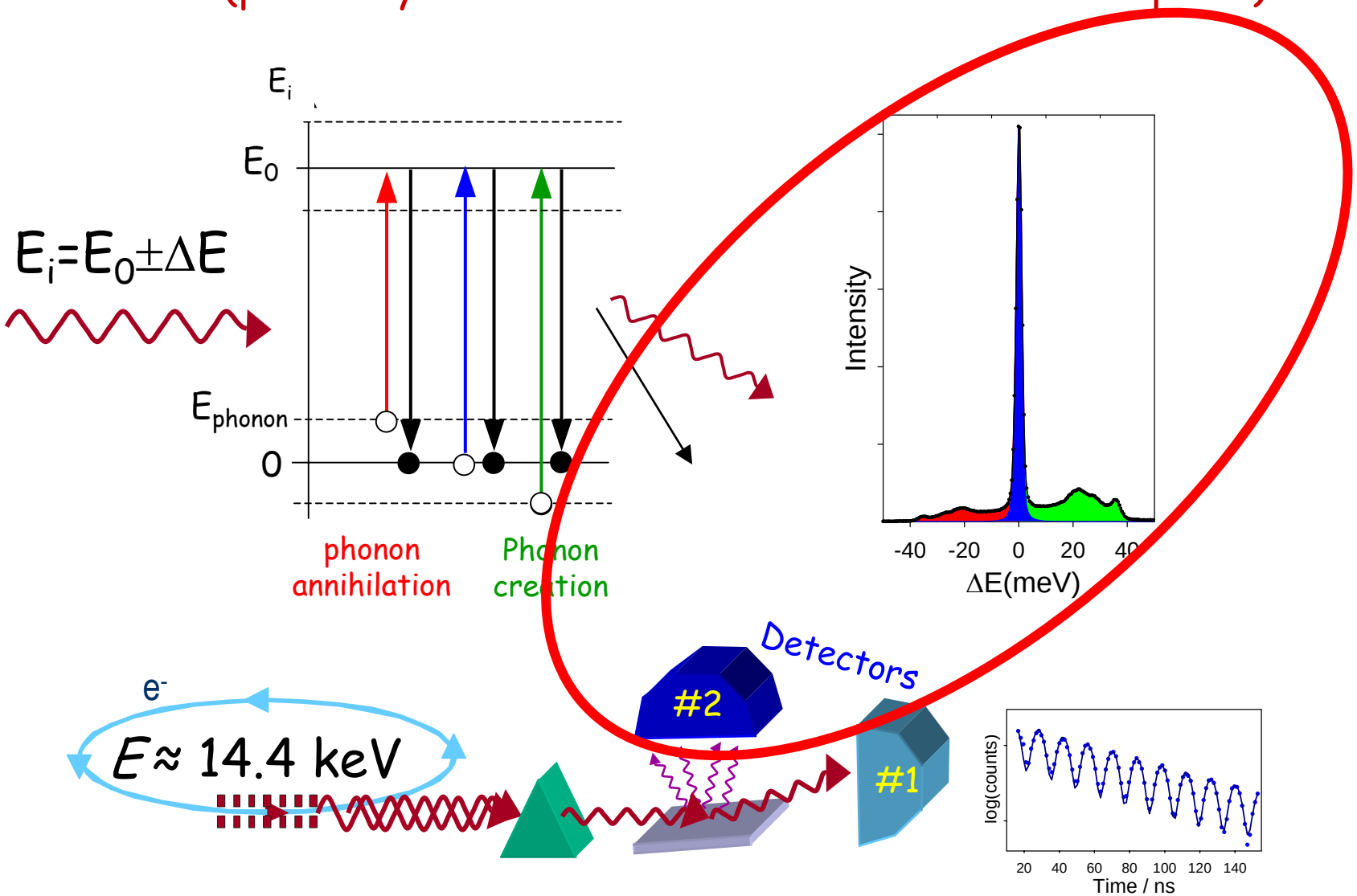


Sample:



AFM order at the Fe/W(110) interface

Nuclear Inelastic Scattering of SR - NIS
(precisely – Inelastic Nuclear Resonant Adsorption)

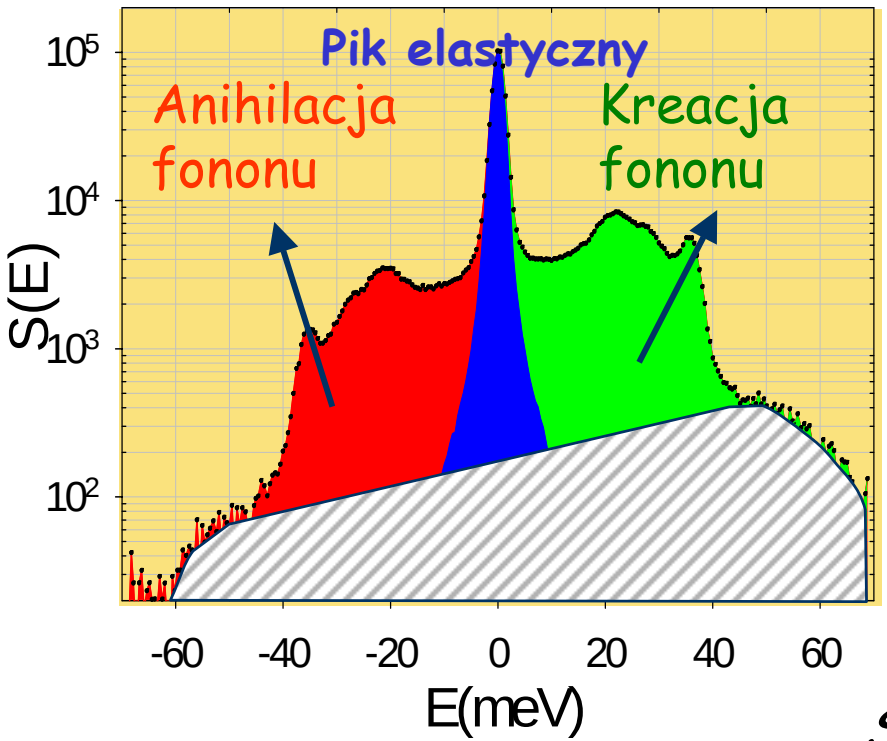


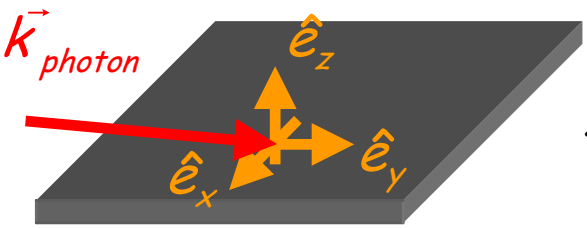
Analiza danych doświadczalnych

Cząstkowe DOS-y dla Fe g(E,s)

$$g(E,\hat{s}) = V_0 \sum_j \int \frac{d\vec{q}}{(2\pi)^3} \delta[E - \hbar\omega_j(\vec{q})] \left| \hat{s} \cdot \hat{e}_j(\vec{q}) \right|^2$$

Widmo NIS





$$\hat{s} = \frac{\vec{k}_{photon}}{k_{photon}}$$

Geometria poślizgu

$$\hat{s} \cdot \hat{e}_z \approx 0$$

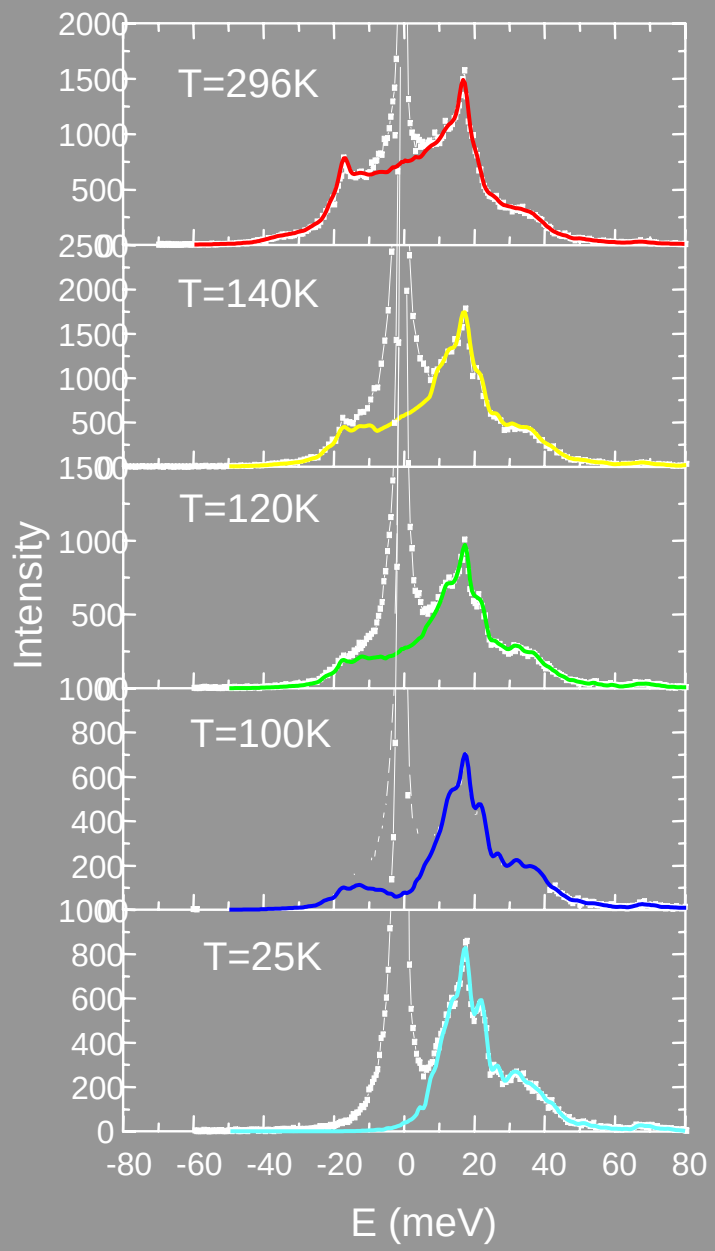
Metoda nieczuła na wibracje normalne

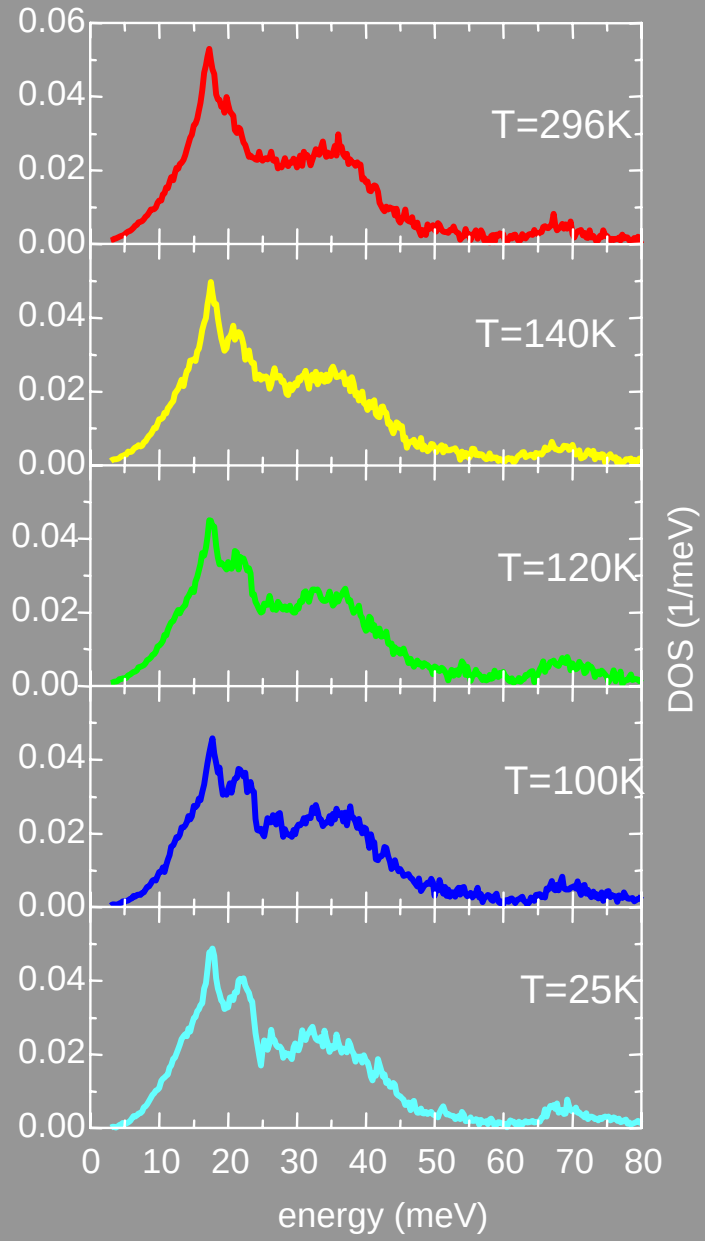
$$S(E) = f_{LM} \left(\delta(E) + S_1(E) + \sum_{n=2}^{\infty} S_n(E) \right)$$

Fononowe DOS-y g(E) „bezparametrowo"

$$S_1(E) = \frac{E_R \cdot g(|E|)}{E \cdot \left(1 - e^{-\beta E}\right)}$$

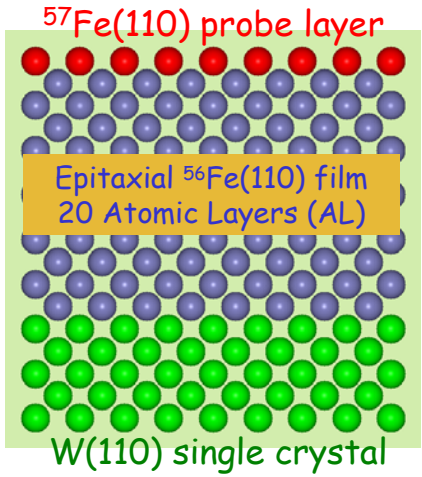
Od widm NIS do gęstości stanów - magnetyt

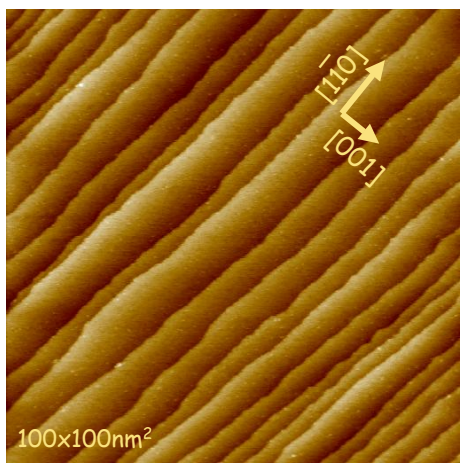


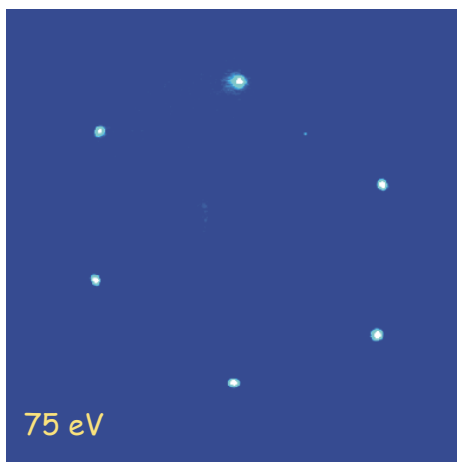


B. Handke et al. Phys. Rev. B 2005

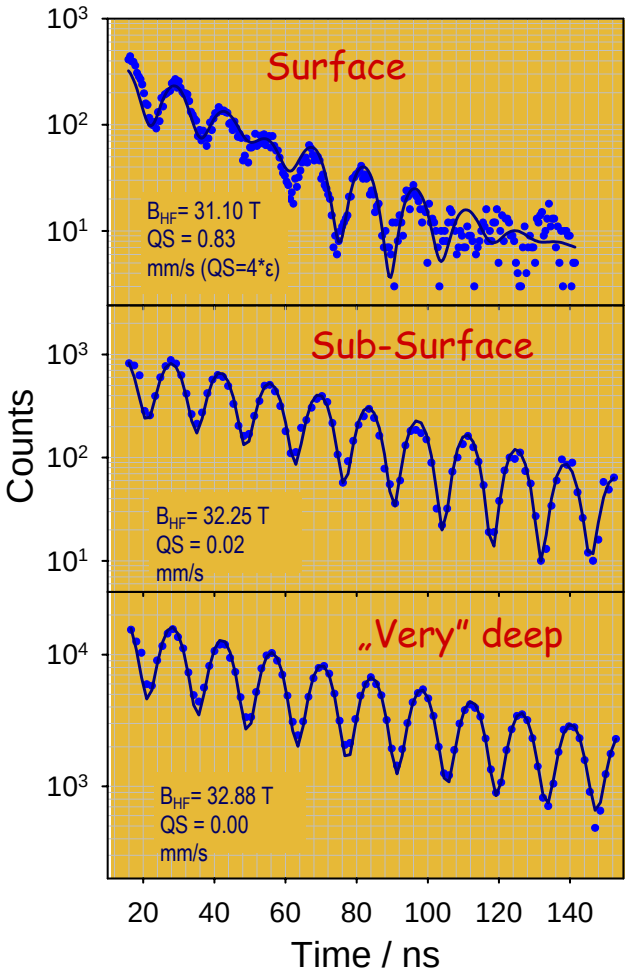
Monowarstwowa sonda ^{57}Fe w epitaksjalnej warstwie Fe(110) na W(110)





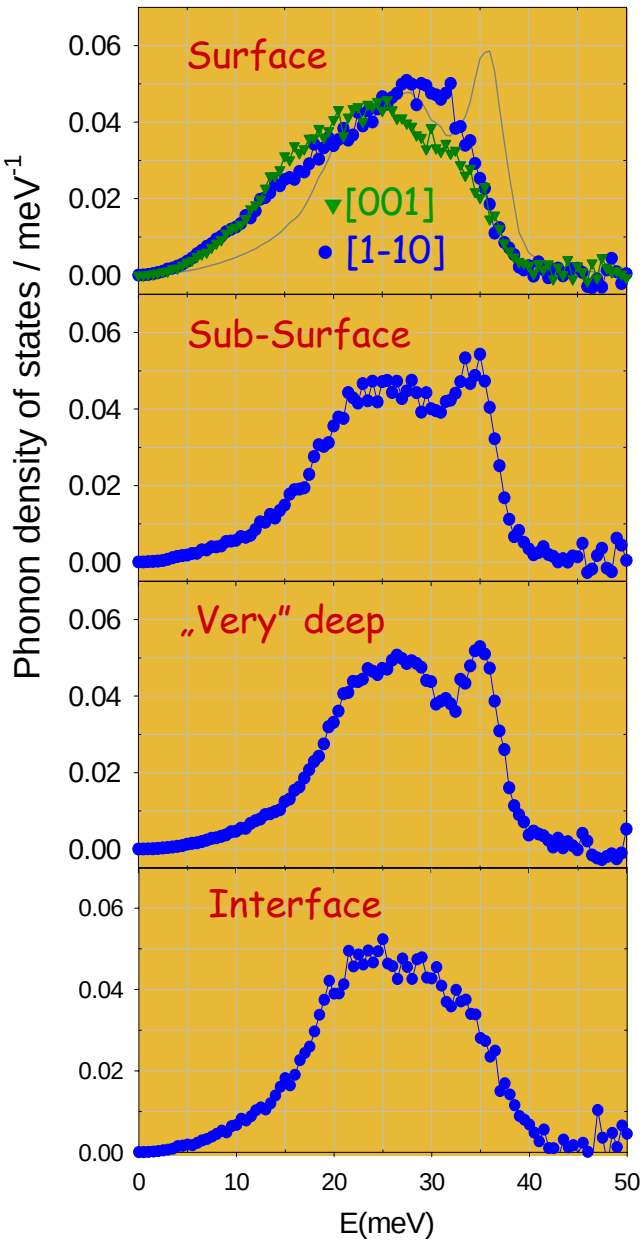


Widma czasowe



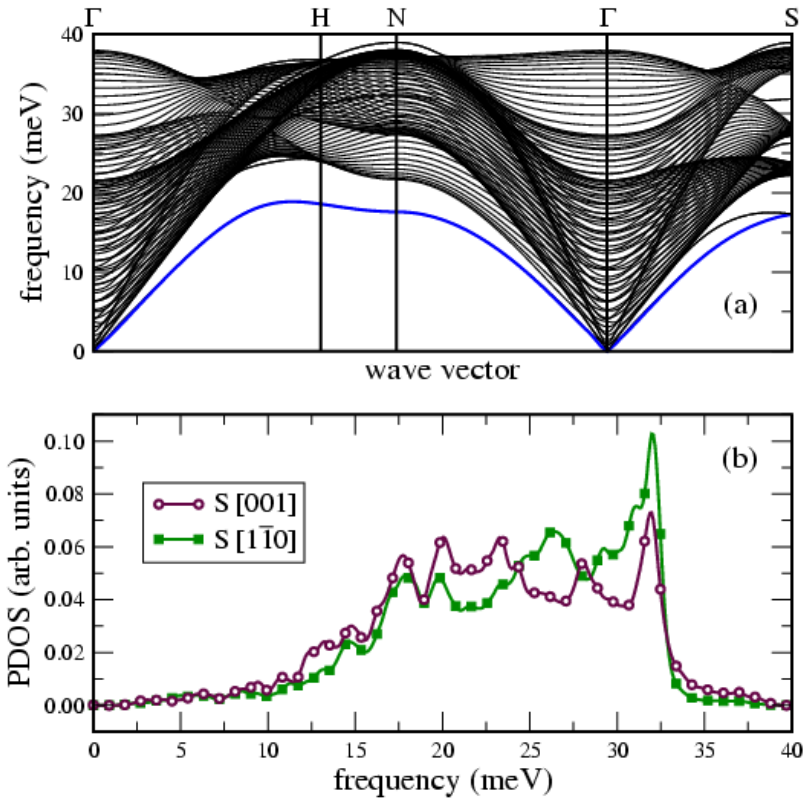
Fononowe DOS-y

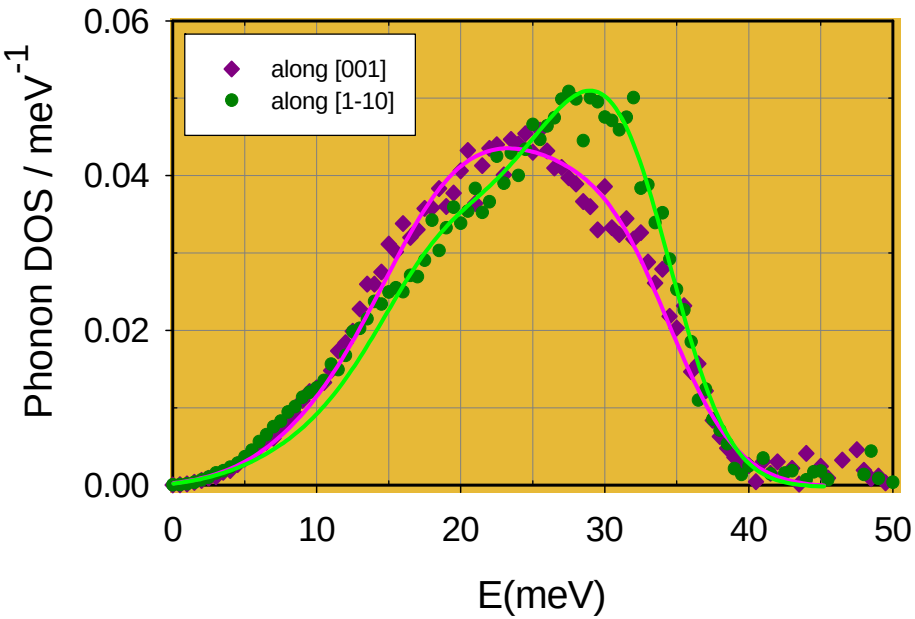
(cząstkowe: warstwowe i kierunkowe)



Dynasync, submitted

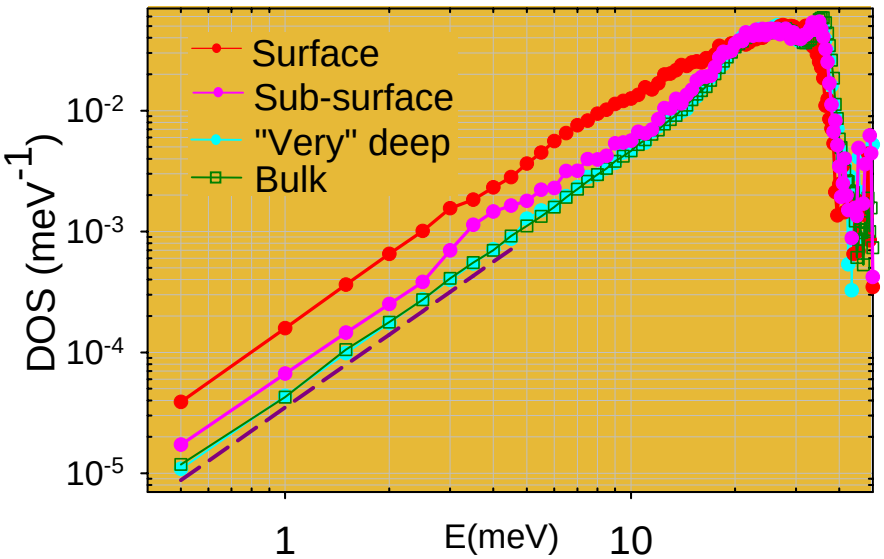
Modelowanie

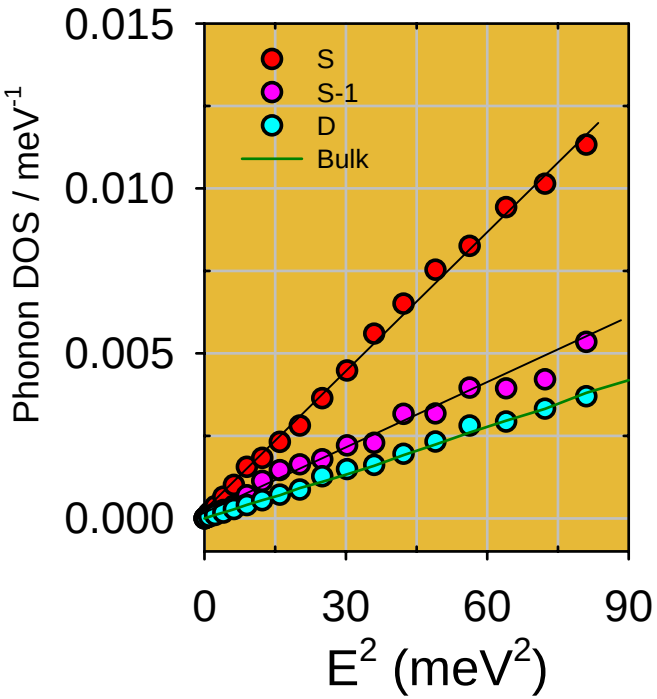




J. Łażewski, J. Korecki, K.Parliński, Phys. Rev. B, 2007

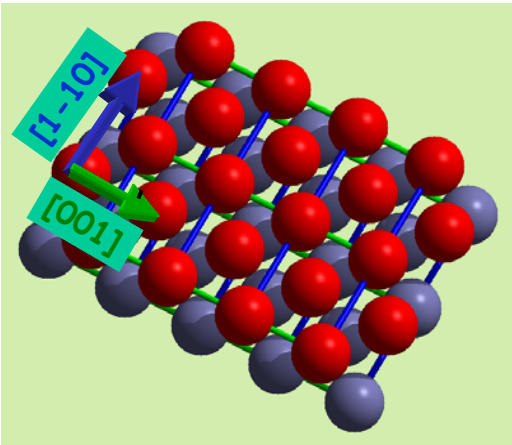
Czy przybliżenie Debye pracuje na powierzchni?





Dynasync, submitted

Właściwości termo-elastyczne



		S		S-1	D	Bulk
Kierunek wiązki X		[1-10]	[001]			
$\sqrt{\langle x^2 \rangle}$ [Å]	E	0.083	0.084	0.069	0.065	0.065
	T	0.077	0.082	0.066	0.064	0.064
$\langle\gamma\rangle$ [N/m]	E	138.1	128.7	160.8	166.2	172.2
	T	132.0	119.7	185.3	174.0	171.2
Entropia [k_B/atom]	E	3.50	3.61	3.20	3.13	3.09
	T	3.46	3.63	2.99	3.04	3.09

Stała siłowa

$$\gamma(\vec{s}) = \langle \omega^2 \rangle M = \frac{M}{\hbar^2} \int g(E,\vec{s}) E^2 dE$$

$$\left\langle \Delta x^2 \right\rangle = -\frac{\ln(f_{LM})}{k^2}$$

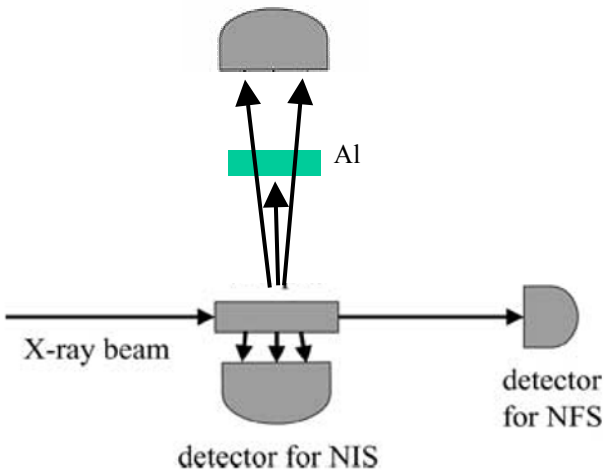
Wnioski:

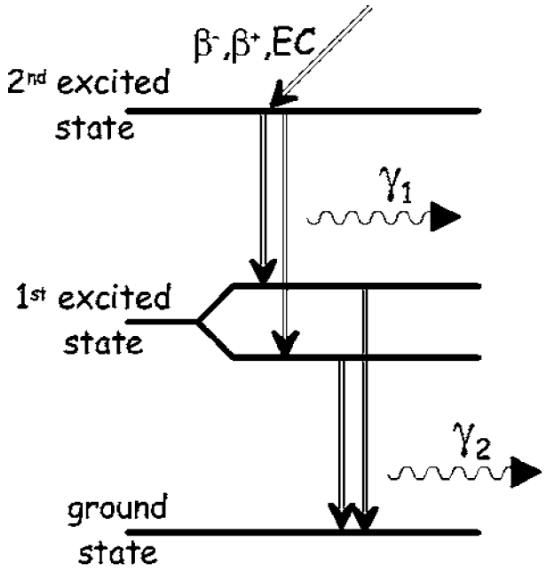
- brak widocznego tłumienia fononów
- powierzchnia jest harmoniczna.
- powierzchniowe drgania normalne są miękkie

Dynasync, submitted

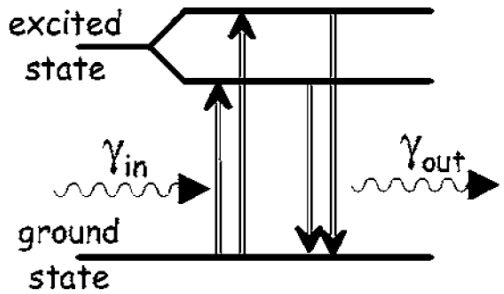
Synchrotronowe zaburzone korelacje kątowe

SRPAC detector

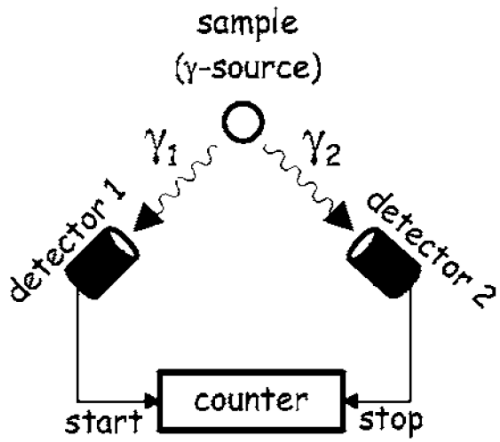


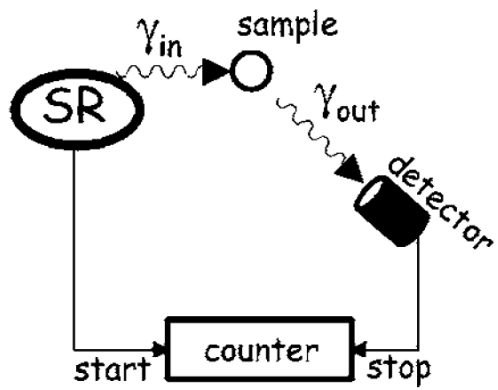


TDPAC



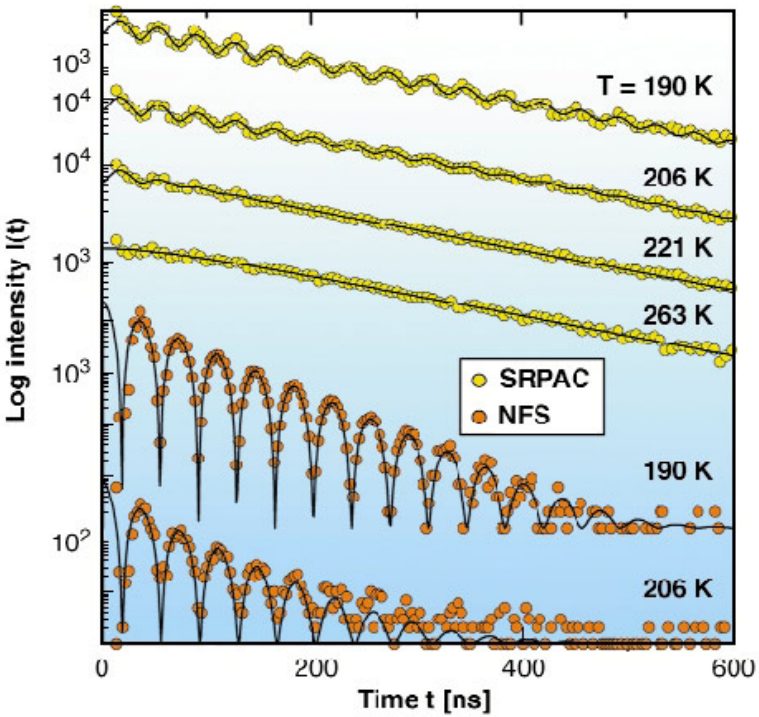
SRPAC





SRPAC – dynamika w fazie ciekłej ($f_{LM} \rightarrow 0$)

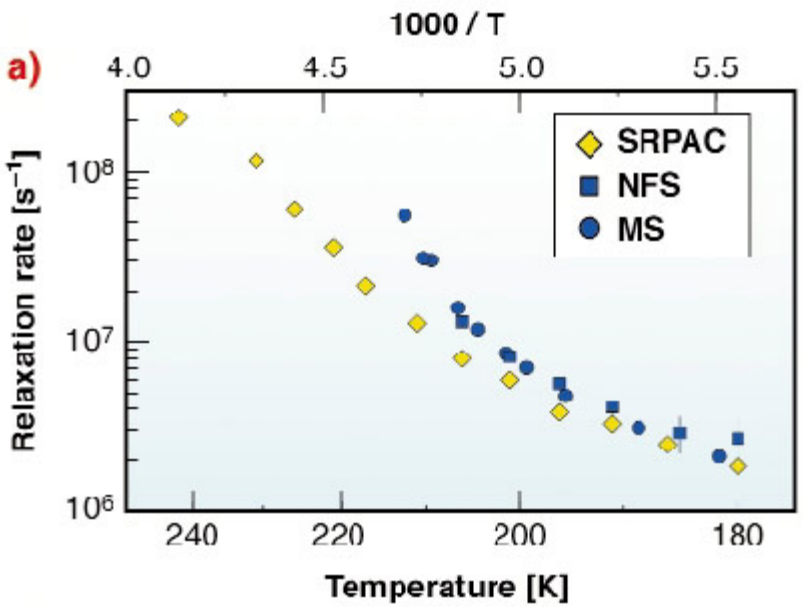
Organic glass (DBP) (Tg = 178 K)
doped with 5% (mol) of ferrocene



Relaxation damps beats:

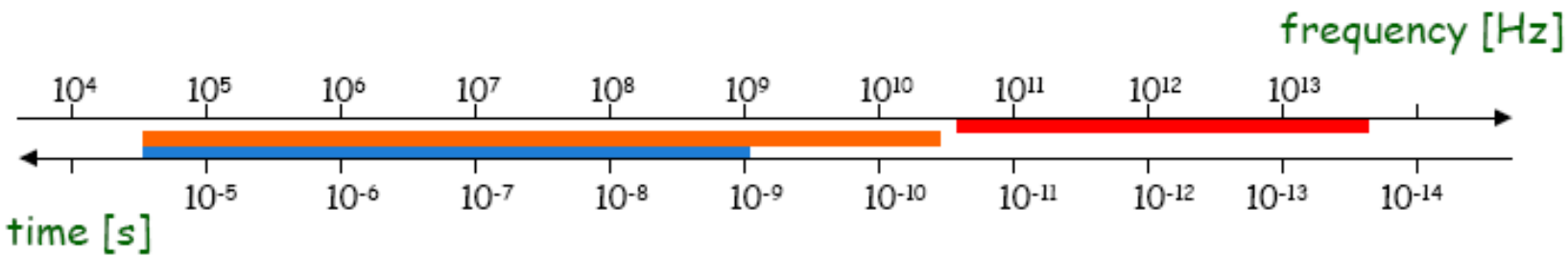
SRPAC – damping rate
~rotational dynamics

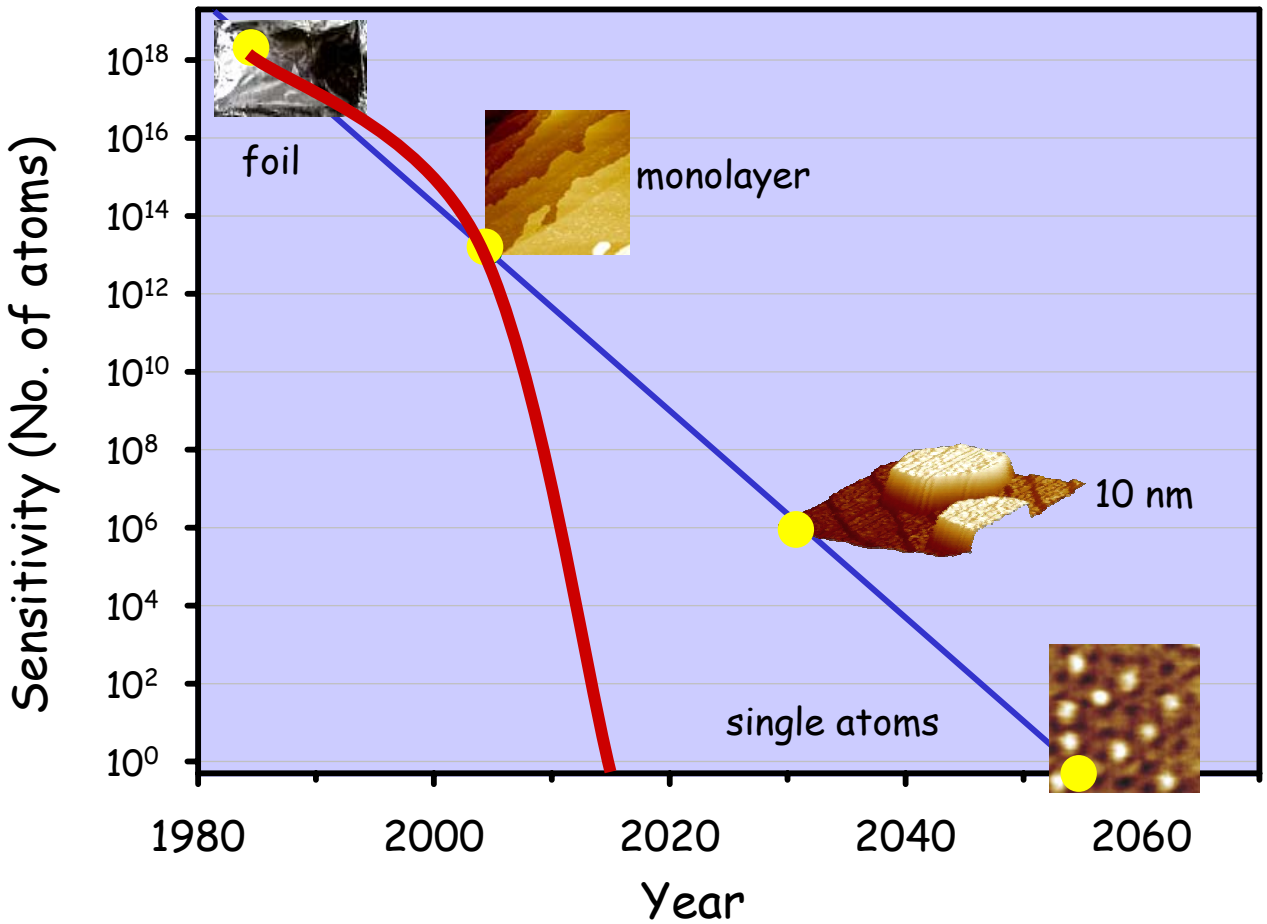
NIS –
damping rate ~
rotational + translational dynamics



Dynamics with nuclear resonant scattering of x rays:

- translational diffusion
- rotational diffusion
- atomic vibrations




Sensitivity (No. of atoms)
10^18
10^16
10^14
10^12
10^10
10^8
10^6
10^4
10^2
10^0
foil
monolayer
10 nm
single atoms
1980
2000
2020
2040
2060
Year