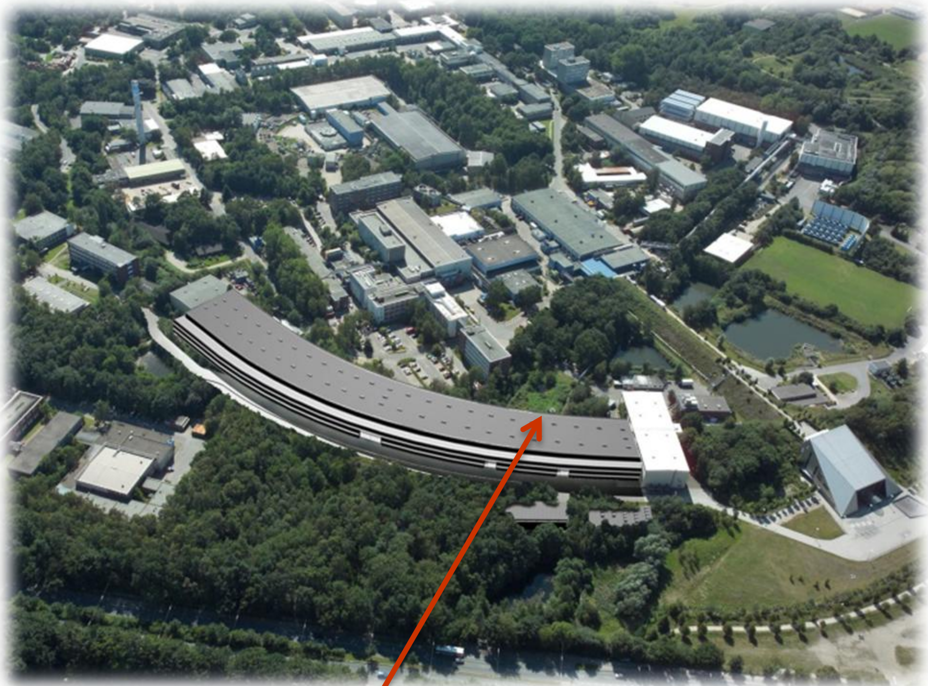
Ядерное резонансное рассеяние СИ при энергиях выше 30 кэВ. Развитие и применение метода.

Илья Сергеев, PETRAIII, Hamburg, Germany



Линии ядерного резонансного рассеяния:

P01 @ PETRA III

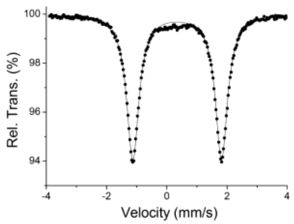
ID18 @ ESRF

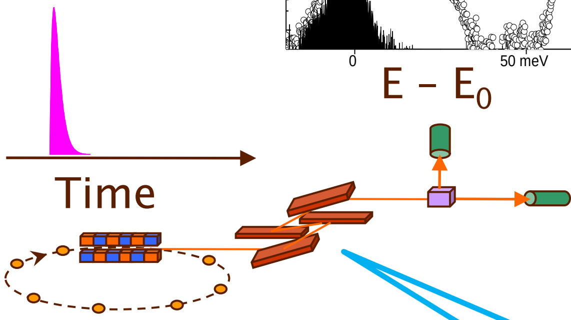
HELMHOLTZ GEMEINSCHAFT

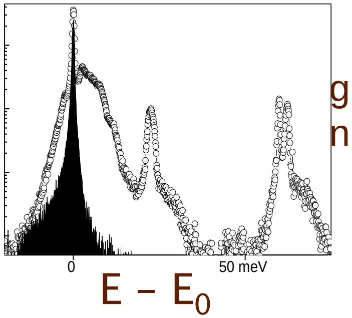
DESY

Nuclear Resonance Scattering

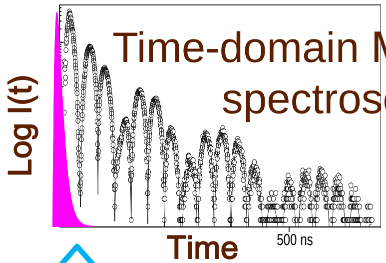
Mössbauer spectroscopy







Nuclear Inelastic Scattering
gives phonon density of states
nuclear resonance works as analyzer



Time-domain Mössbauer spectroscopy

Fourier transformation

Key optical element –
high resolution monochromator
$\Delta E \sim 1 - 5$ meV

Combines properties of

Mössbauer spectroscopy

- element (isotope) selectivity,
- sensitivity to electronic, magnetic and lattice properties

Synchrotron Radiation

- small beam size
- beam collimation

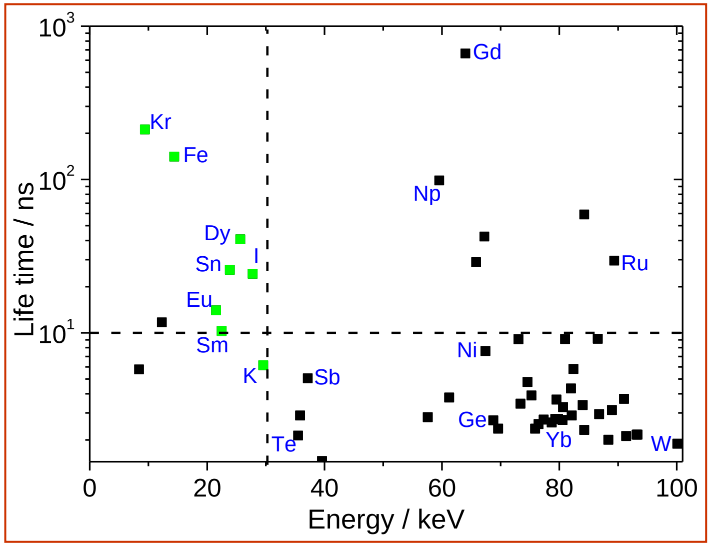
Mössbauer isotopes

W - Mössbauer isotopes

Fe - Nuclear Resonance Scattering

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac**															

Lanthanides*	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinides**	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



Available Mössbauer isotopes:

time MS:

^{57}Fe, ^{119}Sn, ^{151}Eu, ^{149}Sm, ^{161}Dy, ^{121}Sb, ^{125}Te, ^{61}Ni, ^{73}Ge

NIS:

^{57}Fe, ^{119}Sn, ^{151}Eu, ^{149}Sm, ^{161}Dy, ^{121}Sb, ^{125}Te

Aplications of time Mössbauer spectroscopy

Collimation of the beam

High brilliance of the source

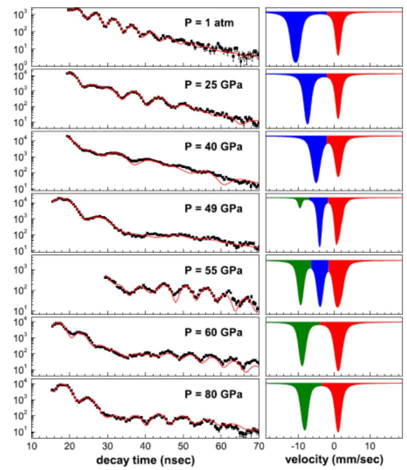
- measurements under
  extreme conditions
    high / low T
    high pressure
    magnetic field

- surfaces and nanoscale materials

PRL 109, 026403 (2012) PHYSICAL REVIEW LETTERS week ending 13 JULY 2012

Reentrant Valence Transition in EuO at High Pressures: Beyond the Bond-Valence Model

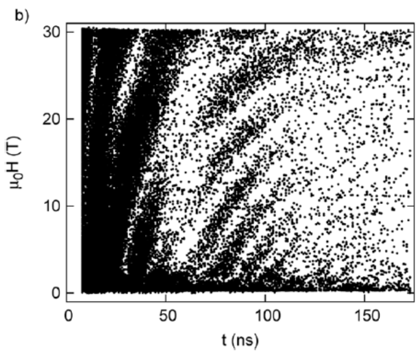
N. M. Souza-Neto,[1,2,*] J. Zhao,[1] E. E. Alp,[1] G. Shen,[3] S. V. Sinogeikin,[3] G. Lapertot,[4] and D. Haskel[1,†]



PRL 104, 087601 (2010) PHYSICAL REVIEW LETTERS week ending 26 FEBRUARY 2010

Nuclear Forward Scattering of Synchrotron Radiation in Pulsed High Magnetic Fields

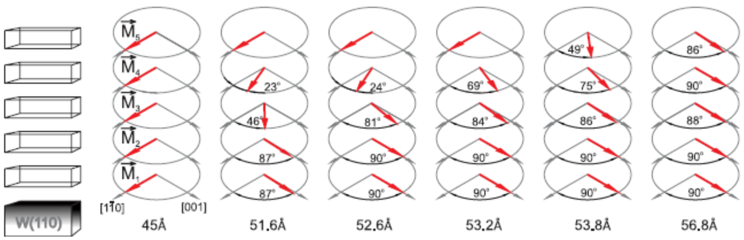
C. Strohm,* P. Van der Linden, and R. Rüffer



PRL 105, 027206 (2010) PHYSICAL REVIEW LETTERS week ending 9 JULY 2010

Noncollinear Magnetization Structure at the Thickness-Driven Spin-Reorientation Transition in Epitaxial Fe Films on W(110)

T. Ślęzak,[1] M. Ślęzak,[1] M. Zając,[1,2] K. Freindl,[1,3] A. Kozioł-Rachwał,[1] K. Matlak,[1] N. Spiridis,[3] D. Wilgocka-Ślęzak,[3] E. Partyka-Jankowska,[4] M. Rennhofer,[1,*] A. I. Chumakov,[2] S. Stankov,[2,†] R. Rüffer,[2] and J. Korecki[1,3]



Applications of NIS

- Geoscience
- glass physics
- nanoscale materials
- thermoelectrics

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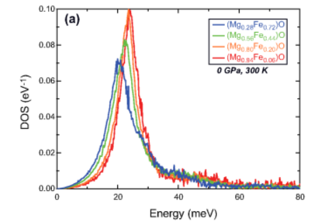
journal homepage: www.elsevier.com/locate/pepi

ELSEVIER

The influence of solid solution on elastic wave velocity determination in (Mg,Fe)O using nuclear inelastic scattering

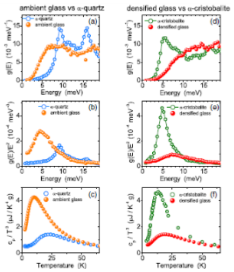
R. Sinmyo[a,*], K. Glazyrin[a], C. McCammon[a], I. Kupenko[a,b], A. Kantor[b], V. Potapkin[a,b,c], A.I. Chumakov[b,d], R. Rüffer[b], L. Dubrovinsky[a]



PRL 112, 025502 (2014) PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2014

Role of Disorder in the Thermodynamics and Atomic Dynamics of Glasses

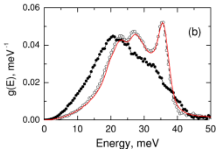
A. I. Chumakov,[1,*] G. Monaco,[2,1] A. Fontana,[2,3] A. Bosak,[1] R. P. Hermann,[4,5] D. Bessas,[4,5,†] B. Wehinger,[1] W. A. Crichton,[1,‡] M. Krisch,[1] R. Rüffer,[1] G. Baldi,[6] G. Carini Jr.,[7] G. Carini,[8] G. D'Angelo,[8] E. Gilioli,[6] G. Tripodo,[8] M. Zanatta,[9,3] B. Winkler,[10] V. Milman,[11] K. Refson,[12] M. T. Dove,[13] N. Dubrovinskaia,[14] L. Dubrovinsky,[15] R. Keding,[16] and Y. Z. Yue[17,§]



PRL 100, 235503 (2008) PHYSICAL REVIEW LETTERS week ending 13 JUNE 2008

Vibrational Properties of Nanograins and Interfaces in Nanocrystalline Materials

S. Stankov,[1] Y. Z. Yue,[2,3] M. Miglierini,[4] B. Sepiol,[5] I. Sergueev,[1] A. I. Chumakov,[1] L. Hu,[2,3] P. Svec,[6] and R. Rüffer[1]



Nanoscale RSCPublishing

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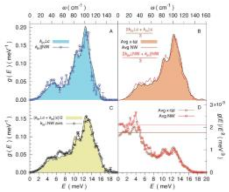
Phonon spectroscopy in a Bi_2Te_3 nanowire array

Cite this: *Nanoscale*, 2013, **5**, 10629

Dimitrios Bessas,[‡ab] William Töllner,[c] Zainul Aabdin,[d] Nicola Peranio,[d] Ilya Sergueev,[‡e] Hans-Christian Wille,[f] Oliver Eibl,[d] Kornelius Nielsch[c] and Raphaël P. Hermann[*ab]



DESY

Mössbauer Spectroscopy with ^{61}Ni and ^{73}Ge

^{61}Ni:

E = 67.4 keV

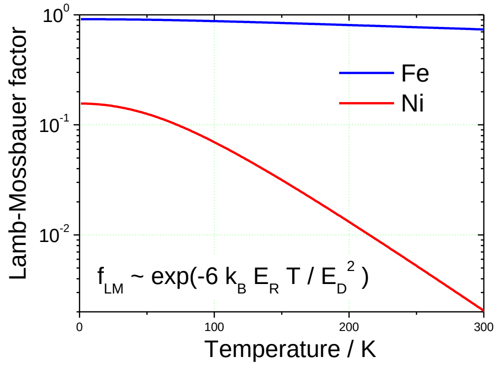
τ_0 = 7.60 ns

transition: $3/2^- \rightarrow 5/2^-$

Sources:

- ^{61}Co (β-, 99 min)
- ^{61}Cu (EC, 3.41 h)

High energy ⇒
small Lamb-Mössbauer factor



^{73}Ge:

E = 68.75 keV

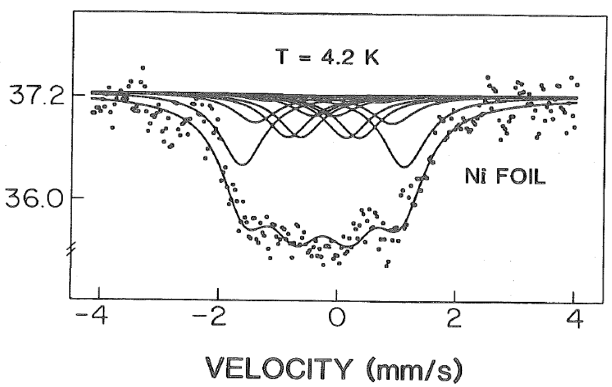
τ_0 = 2.51 ns

transition: $9/2^+ \rightarrow 7/2^+$

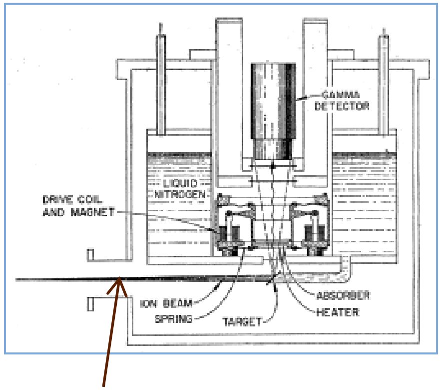
Source:

Coulomb excitation

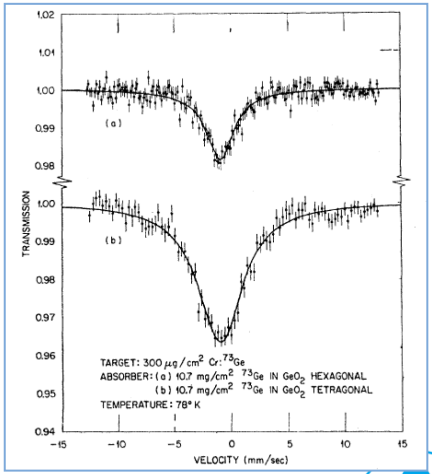
McCammon et al, Hyp. Int. ***28*** *(1986) 483*



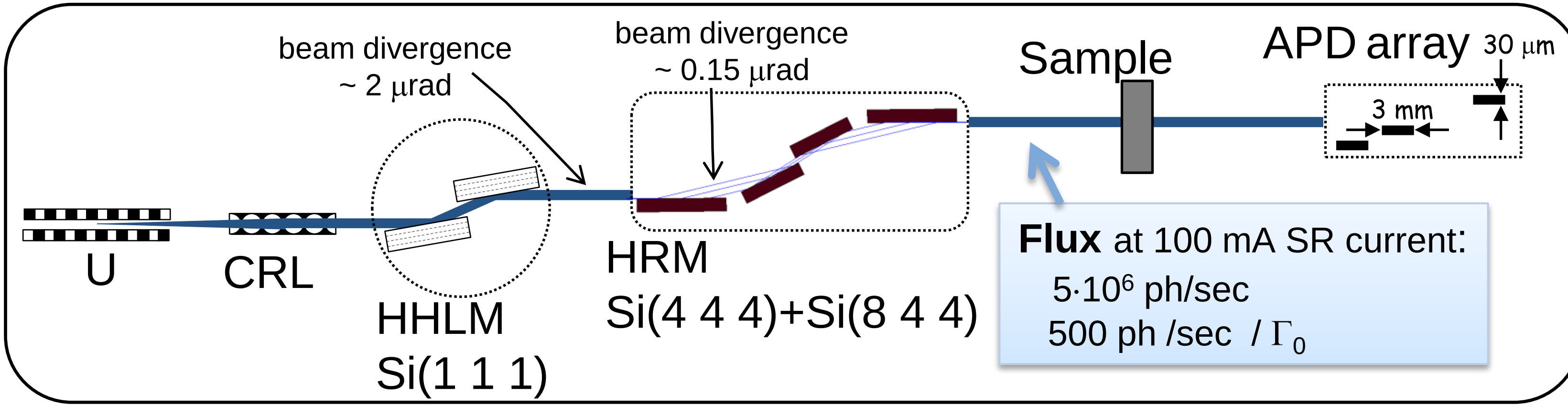
Czjzek et al, Physical Review ***174*** *(1968) 331*

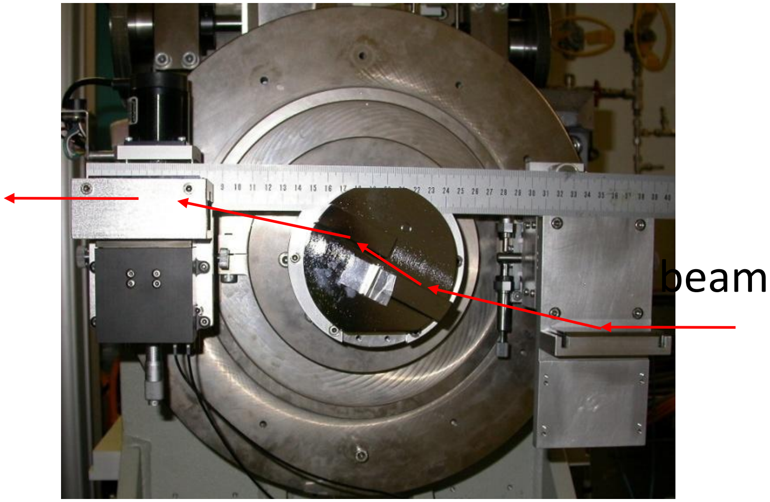


Ion beam



Experimental setup





Detector:

Array of 16 Si APDs

Efficiency

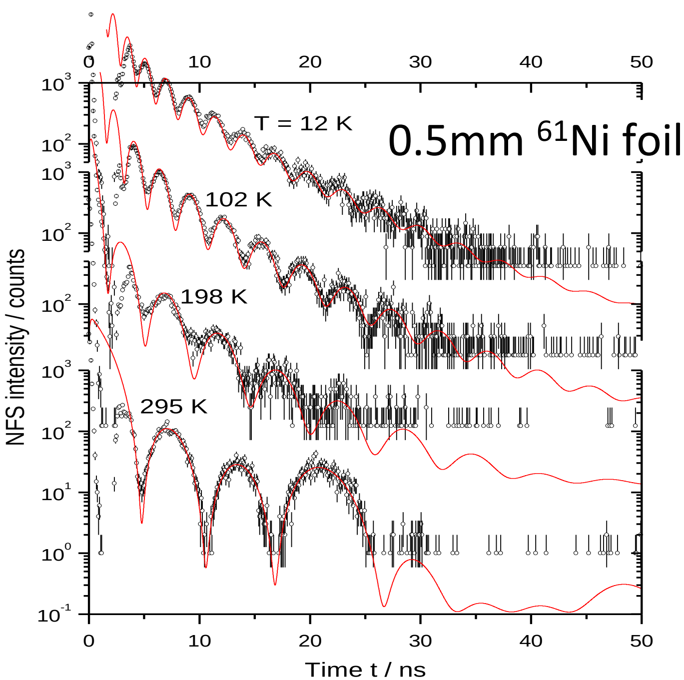
@ 67keV ~ 20%

Time MS with ^{61}Ni and ^{73}Ge

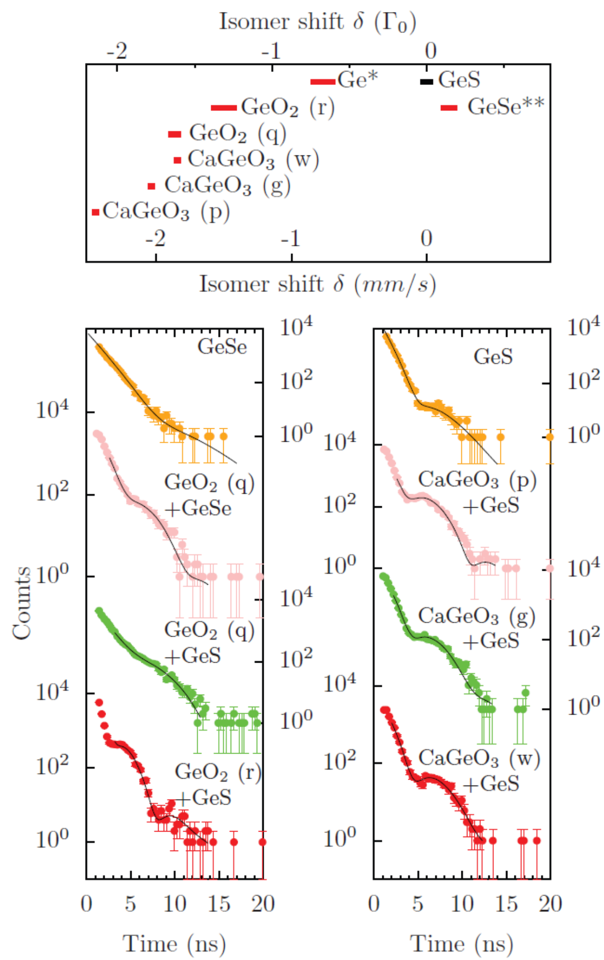
^{61}Ni, E = 67.413 keV → rotate x-tals by 0.1 – 0.3° → ^{73}Ge, E = 68.752 keV

Range: 64 keV < E < 77 keV

Magnetic and elastic properties of elemental nickel



I.Sergueev et al., PRL 99(2007)097601.



R. Simon et al., EPL 104(2013) 17006

Isomer shift (coordination number) of $CaGeO_3$:

wollastonite
garnet
perovskite

Highest pressure for magnetism

X-ray diffraction: fcc phase up to 150 / 200 GPa,

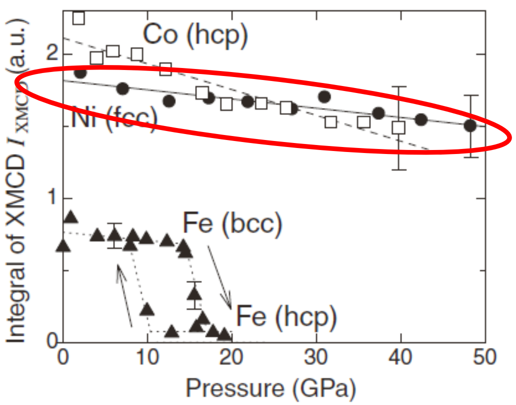
Theory: predicts continuous decrease of magnetic moment up to 300 – 34000 GPa

X-ray magnetic dichroism

Spring-8

Up to 50 GPa

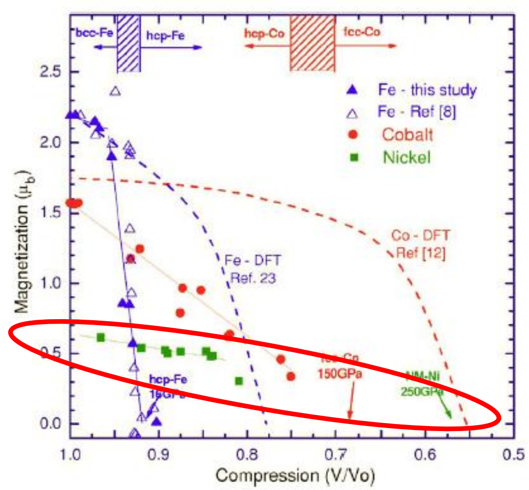
Ishimatsu et al., J. Phys.Soc.Jpn., 76(2007)064703



APS

Up to 70 GPa

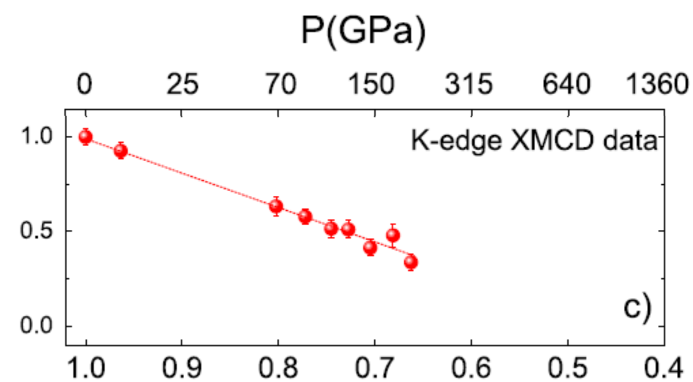
Iota et al., Appl. Phys. Lett. 90(2007)042505

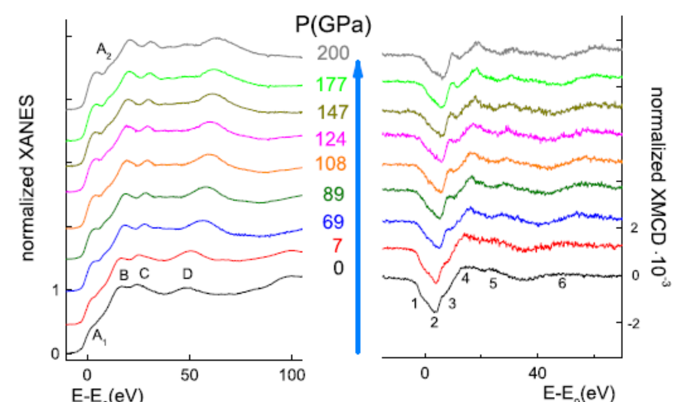


ESRF

Up to 200 GPa

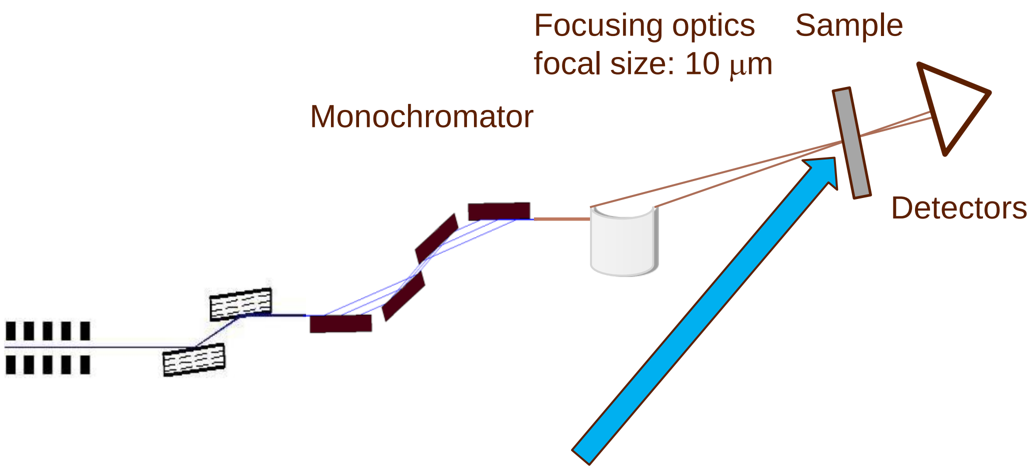
Torchio et al., PRL 107(2011)237202



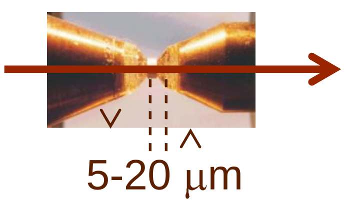


Highest pressure for magnetism

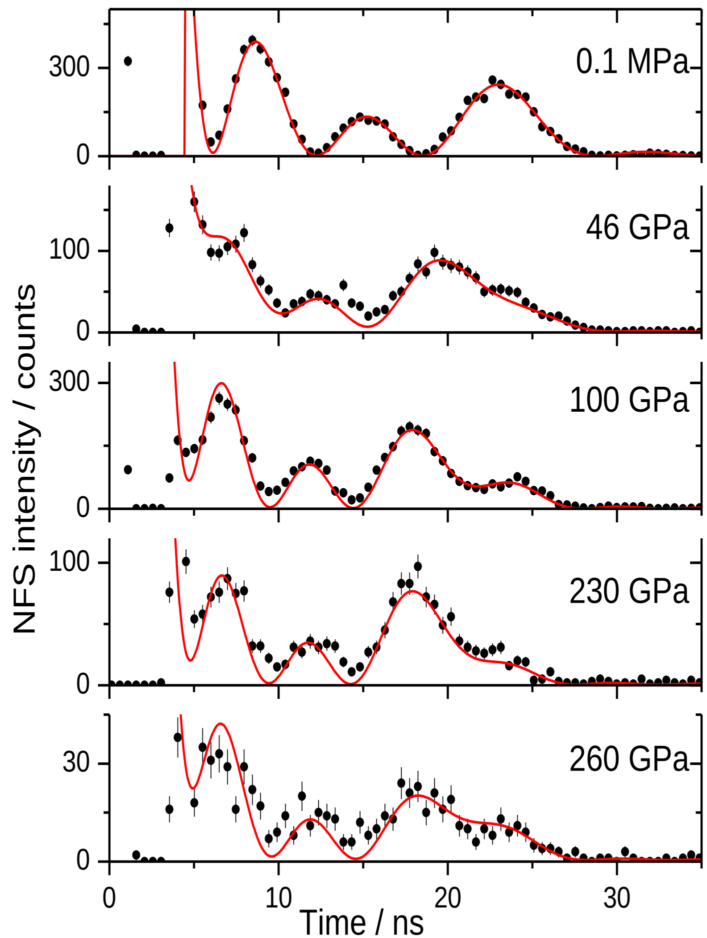
Experimental setup



^{61}Ni foil in diamond anvil cell



Measurements

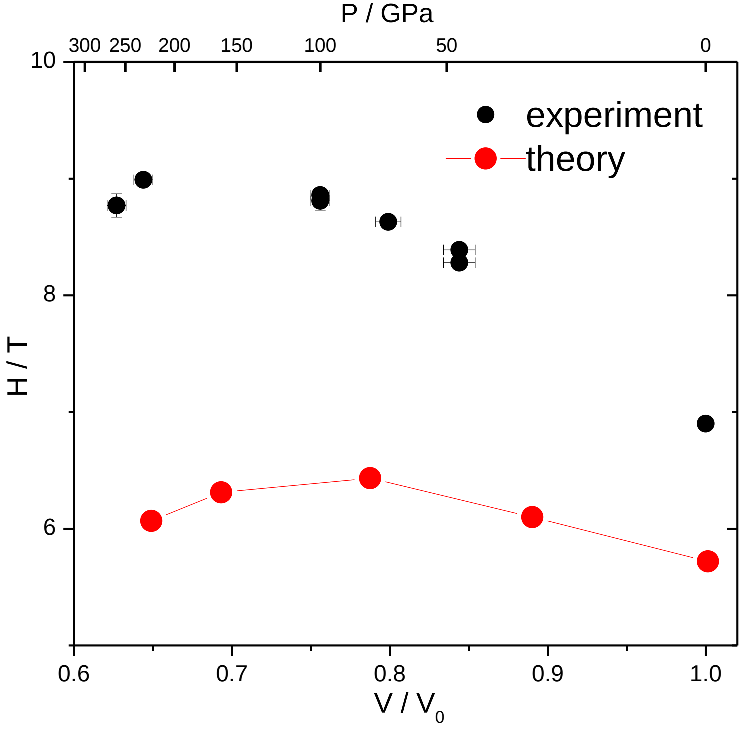


I.Sergueev et al., PRL 111(2013)157601.

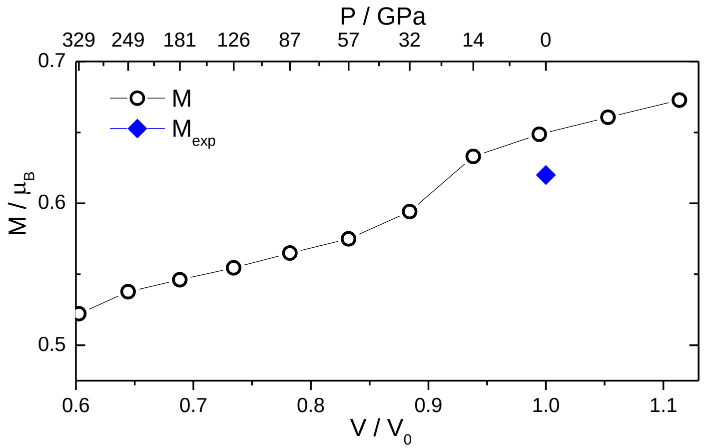
H – hyperfine magnetic field

Highest pressure for magnetism

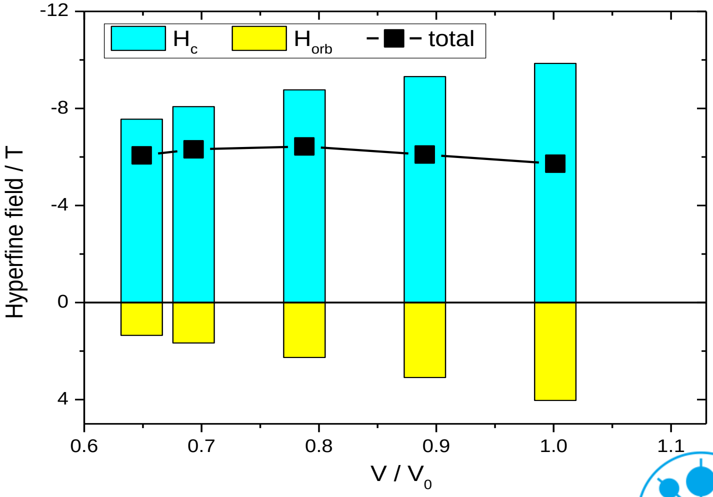
Experiment and theory



Magnetic moment vs volume (theory)

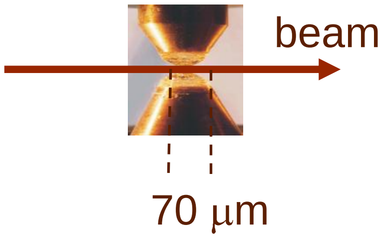


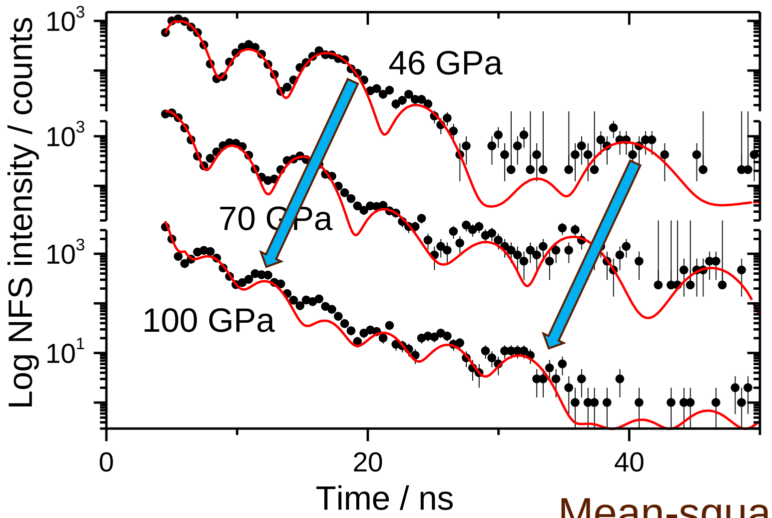
Hyp. magn. field vs volume (theory)



- Ni is ferromagnetic at room temperature up to 260 GPa.
- Measurements at higher pressure are required in order to find critical pressure.

Time MS of Ni at HP. Elastic properties

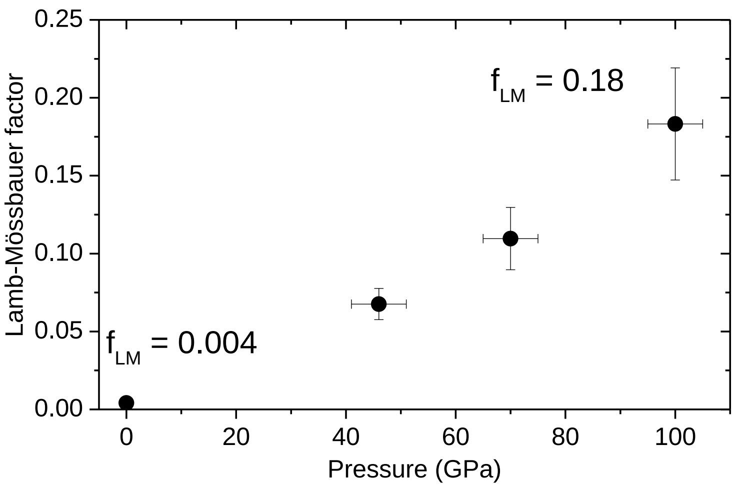


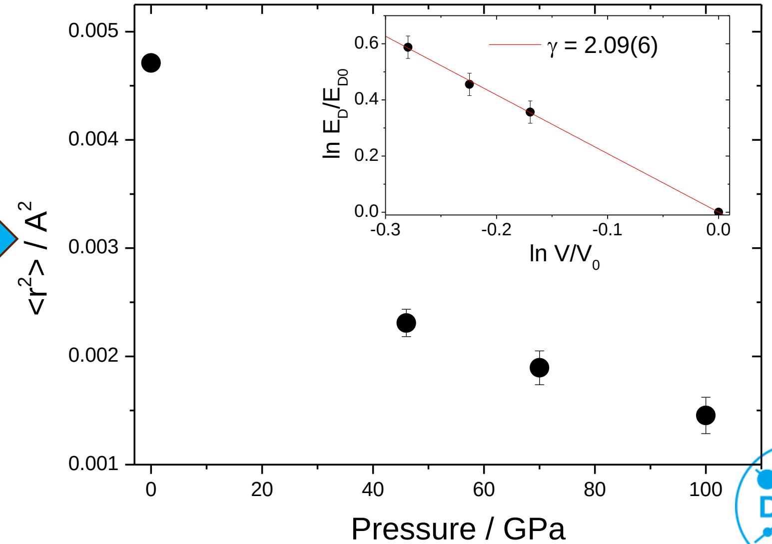


Changes of the spectra are due to increase of the Lamb-Mossbauer factor

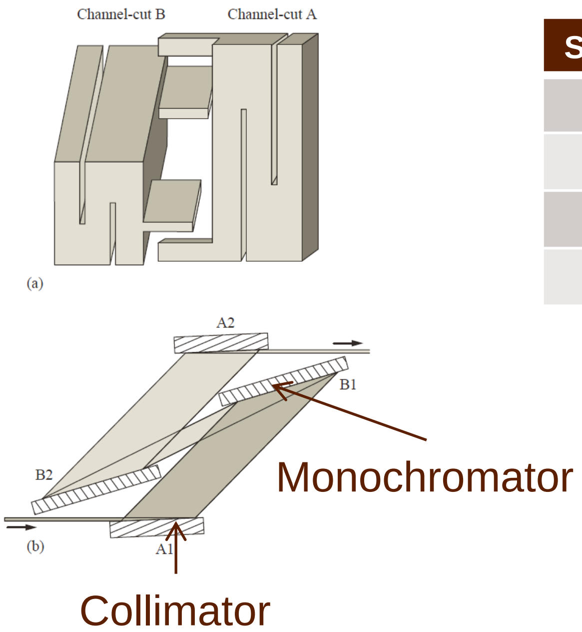
Mean-square vibrations, Debye energy, Grüneisen parameter

Lamb-Mossbauer factor at RT





High Resolution Monochromators. Multiple-crystal approach



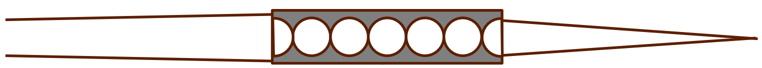
Si reflections with Bragg angle = 84º

Si reflection	7 7 7	12 12 12	17 17 17
E, keV	13.9	23.9	33.8
ΔE, meV	5	0.7	0.06
Δθ, urad	**3.4**	**0.3**	**0.02**
R,%	80	73	22

SR beam divergence:
10-20 urad

2 steps of collimation:

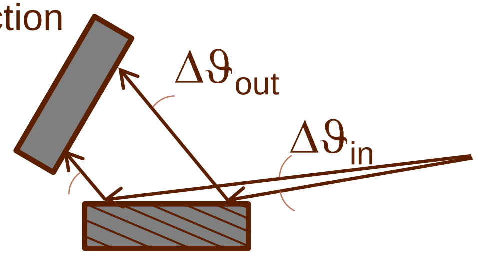
1. Compound refractive lenses



from 10-20 μrad to 2-5 μrad

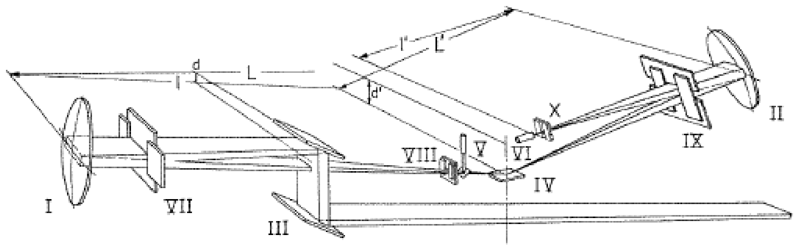
2. Asymmetric reflection

$$b = \frac{\Delta\vartheta_{in}}{\Delta\vartheta_{out}} \approx 10 \div 20$$



Backscattering Monochromators

Burkel, Rep. Prog. Phys. 63(2000)171



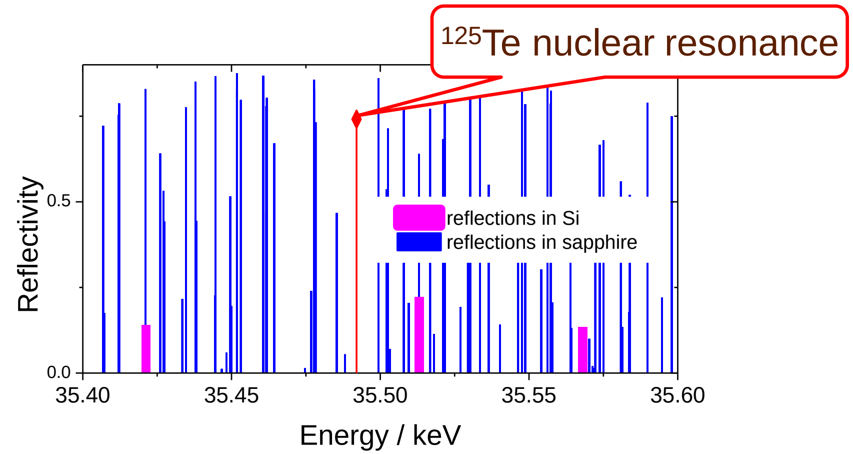
Si reflections with Bragg angle = 90º

Si reflection	7 7 7	12 12 12	17 17 17
E, keV	13.8	23.7	33.6
ΔE, meV	5	0.7	0.06
Δθ, urad	**970**	**320**	**83**
R,%	80	73	22

Energy is defined by Si crystal lattice

Y.V. Shvyd'ko and E. Gerdau, Hyp. Interact. 123 (1999)

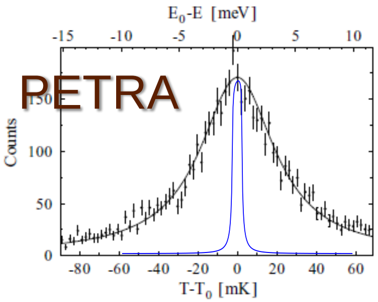
Crystal with low symmetry (sapphire, quartz)



At least 2 reflections in 150-300K
for any E > 20keV

Sapphire backscattering monochromator

PETRA



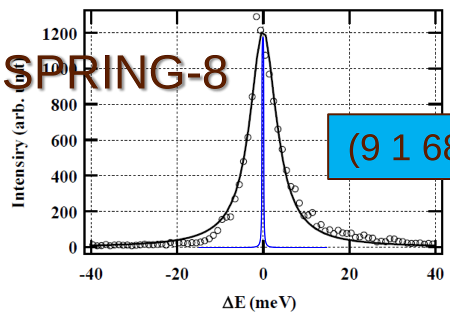
Shvyd'ko et al., EPL 56(2007)309

(3 2 52) @ 25.51 keV

ΔE_{th} = 0.8 meV
ΔE_{exp} = 8 meV

I. Sergueev, H.-C. Wille, R. P. Hermann, D. Bessas, Yu. V. Shvyd'ko, M. Zajac and R. Rüffer, J. Synchrotron Rad. 18(2011)

SPRING-8

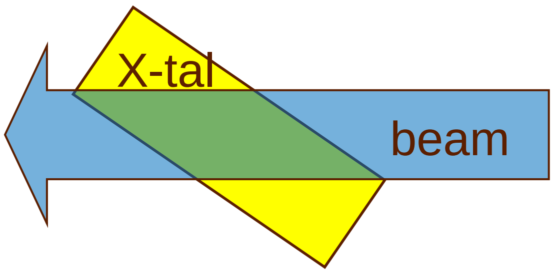


Imai et al., Proc. SPIE, 2007

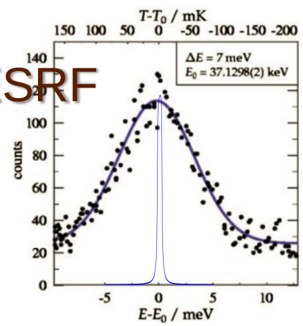
(9 1 68) @ 35.49 keV

ΔE_{th} = 0.4 meV
ΔE_{exp} = 8 meV

Traditional approach:



ESRF

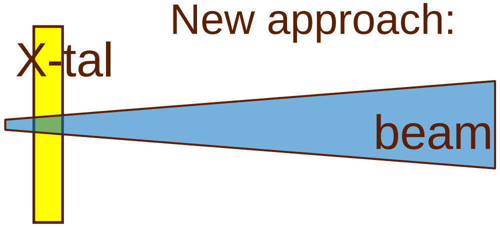


Wille et al., EPL 74(2006)170

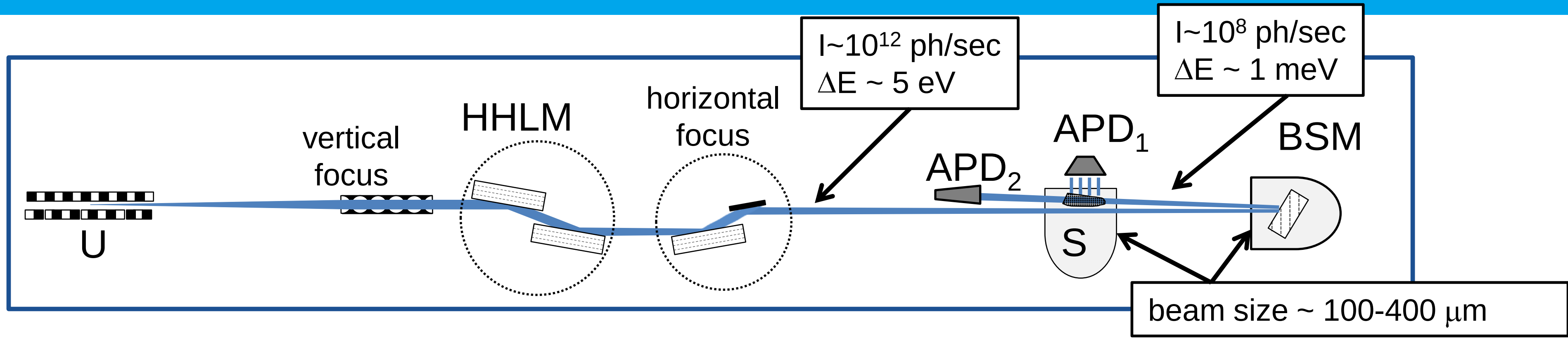
(15 13 14) @ 37.13 keV

ΔE_{th} = 0.4 meV
ΔE_{exp} = 7 meV

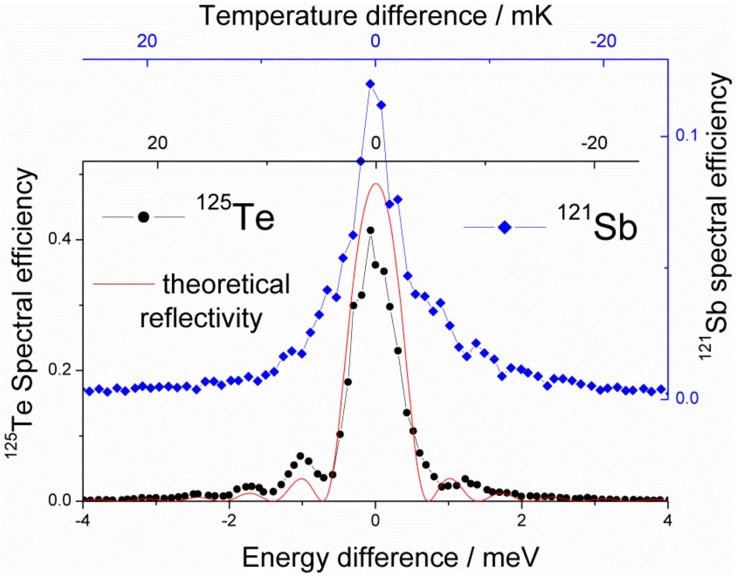
New approach:



Experimental Setup and Instrumental Functions



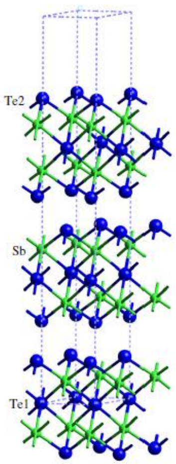
	^{121}Sb	^{125}Te	^{119}Sn	^{129}Xe
E/ keV	37.13	35.49	23.88	39.58
Reflection	(8 16 40)	(9 1 68)	(4 4 45)	(5 17 54)
T / K	237	220	193	291
Angle / degree	59	24	26	49
ΔE_{th} / meV	**0.4**	**0.7**	**1.0**	**0.5**
ΔE_{exp} / meV	**0.7**	**0.7**	**1.0**	**0.9**



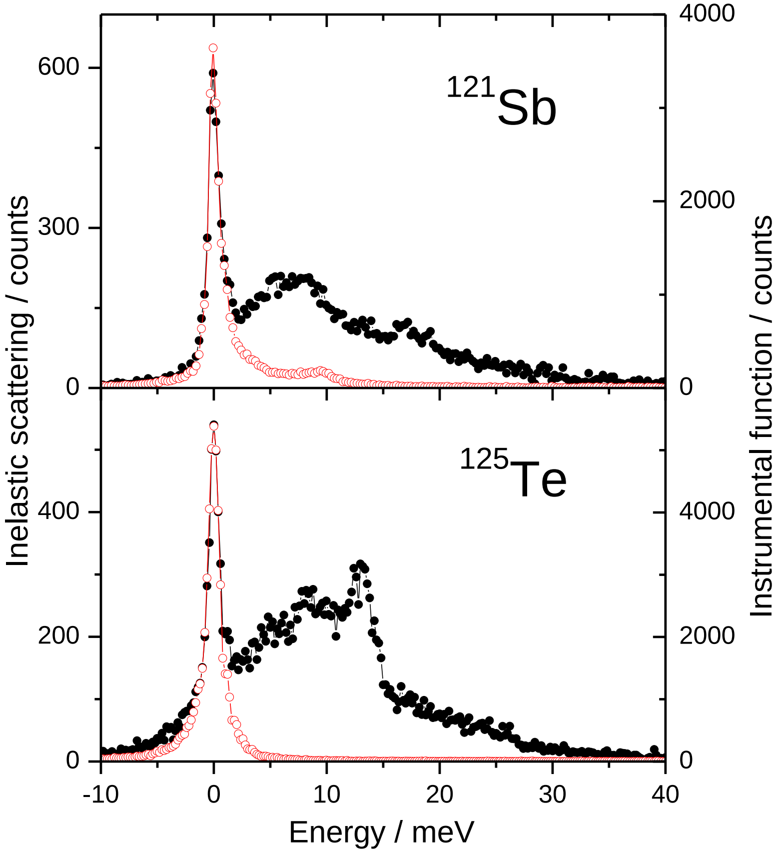
Energy band width ~0.7 meV,

$\Delta E / E = 2 \cdot 10^{-8}$

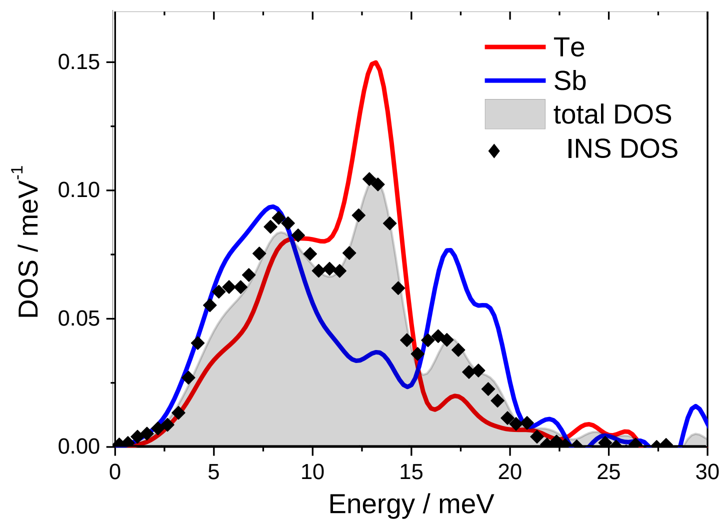
Application. Phonons in Sb_2Te_3



Inelastic spectra



Phonon DOS

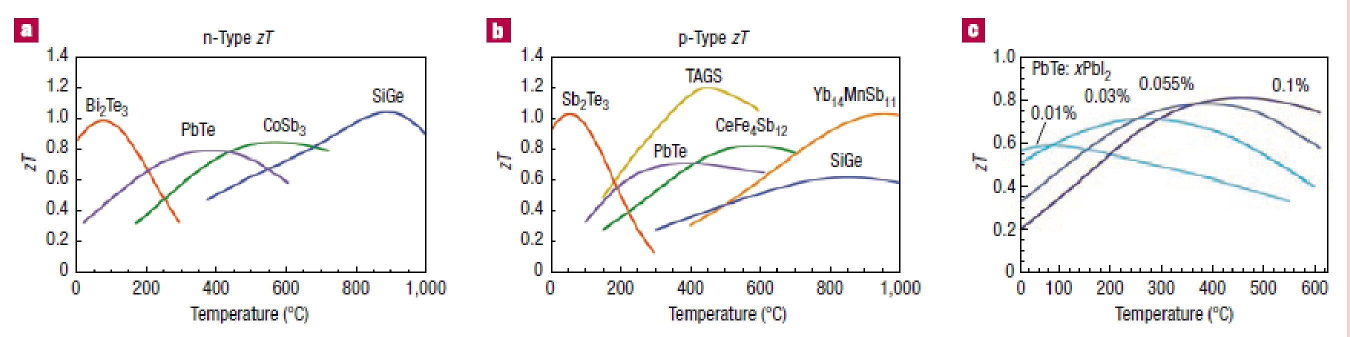


Inelastic neutron scattering on $Sb(Bi)_2Te(Se)_3$

Rauh et al., J. Phys. C 14(1981)2705

Thermoelectrics.Current trends

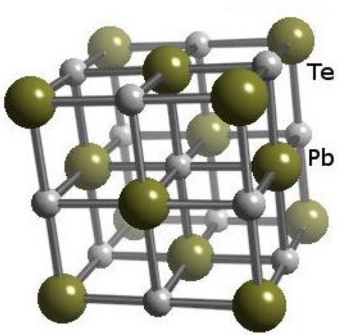
Commercial materials



Snyder and Toberer, Nature Mat. 7(2008)

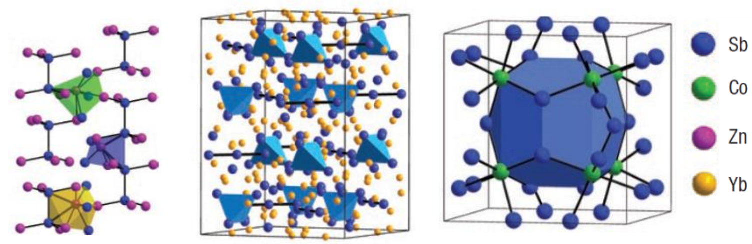
Search for “phonon glass, electron crystal”

From simple

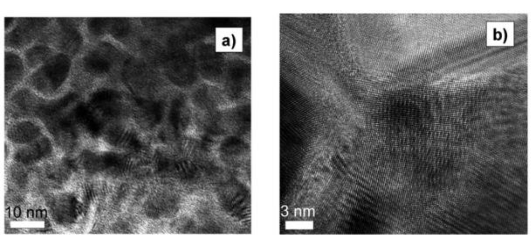


PbTe

To complex structure



To nanostructured materials

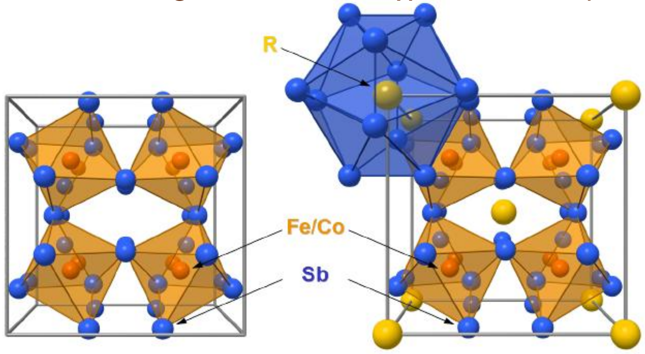


TEM images of a $Si_{80}Ge_{20}$ nanocomposite
Wang et al., Appl. Phys. Lett., 93 (2008).

DESY

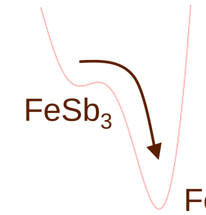
Thermoelectrics. Skutterudites

$CoSb_3$ $R_x(Co,Fe)_4Sb_{12}$



Is $CoSb_3$ a good reference for filled skutterudite lattice dynamics?

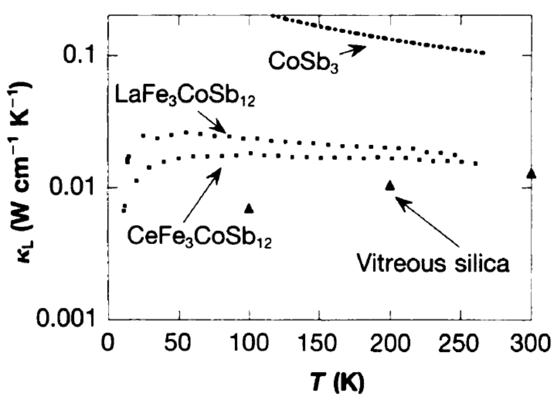
$FeSb_3$ is thermodynamically unstable.



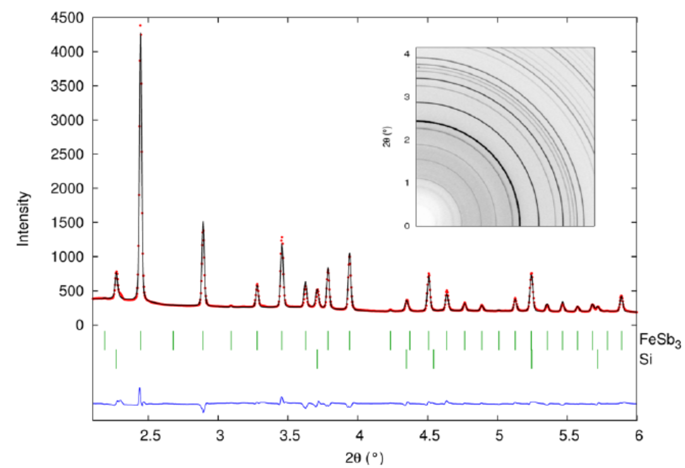
Synthesis of Metastable $FeSb_3$ using multilayer precursors (Hornbostel et al., J. Am. Chem. Soc. 1997, 119, 2665)

→ 1-1.5 μm films of **$FeSb_3$**

Lattice thermal conductivity



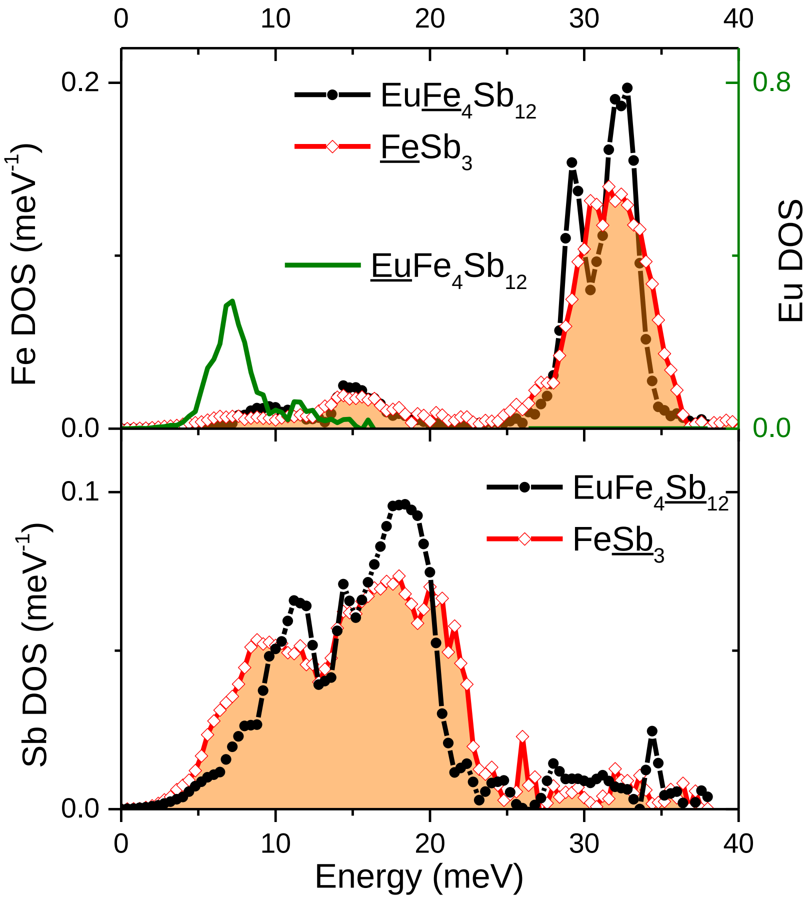
Sales et al., Science, 272(1996)

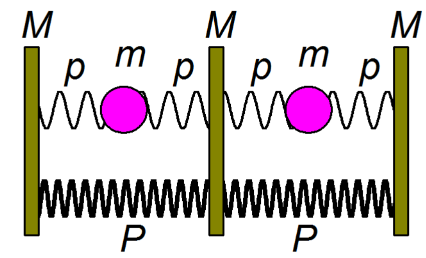


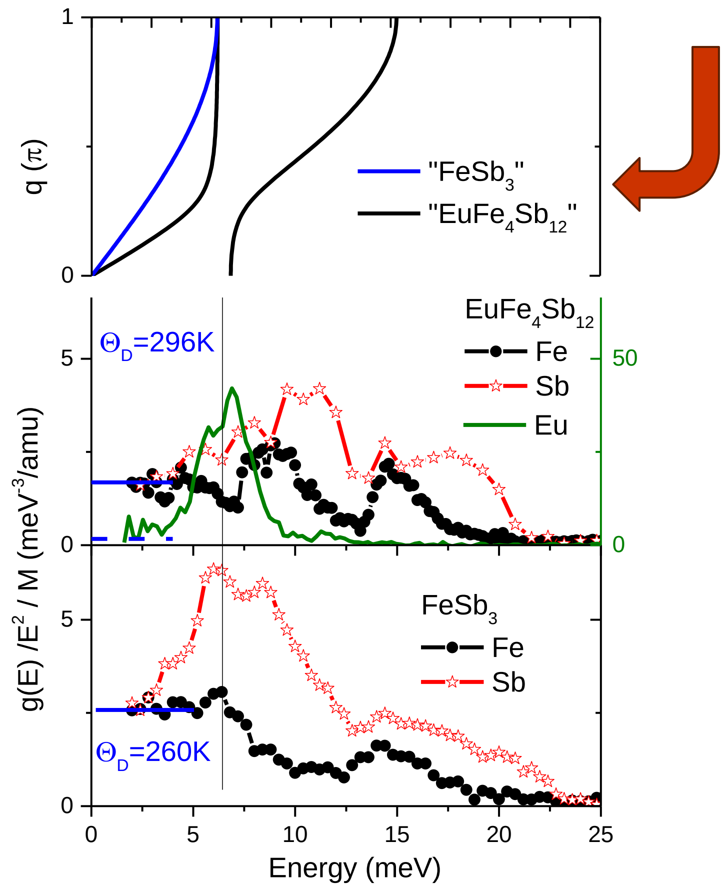
Möchel et al, Phys. Rev. B, 84(2011)064302

Phonons in skutterudites. $EuFe_4Sb_{12}$ vs $FeSb_3$

Nuclear Inelastic Scattering at
^{151}Eu, ^{57}Fe, ^{121}Sb nuclear resonances



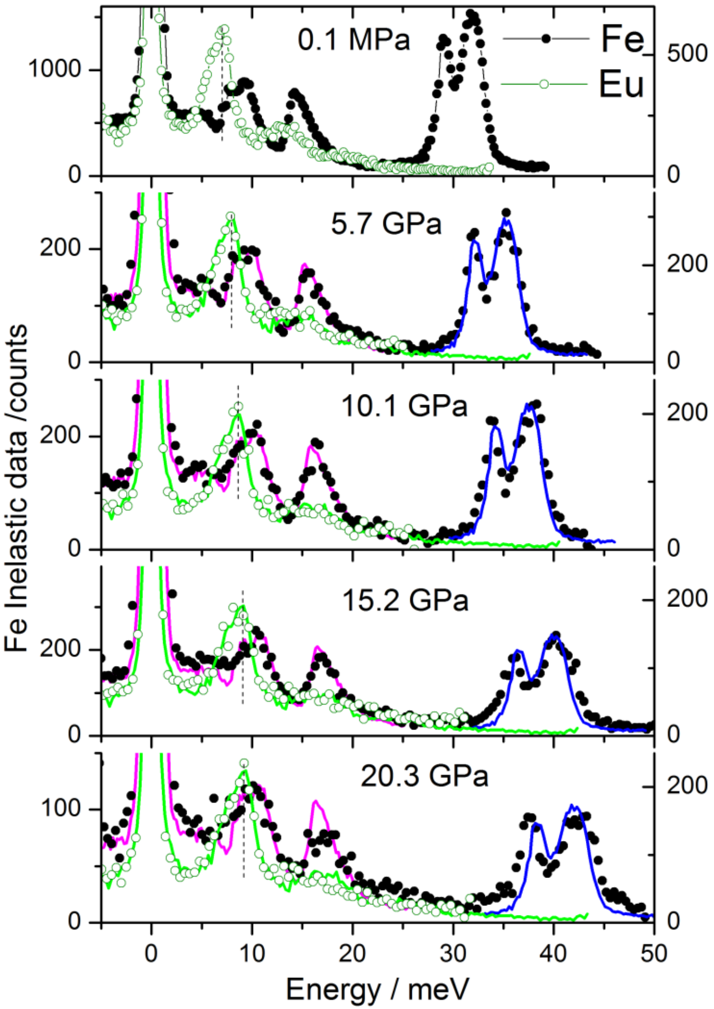




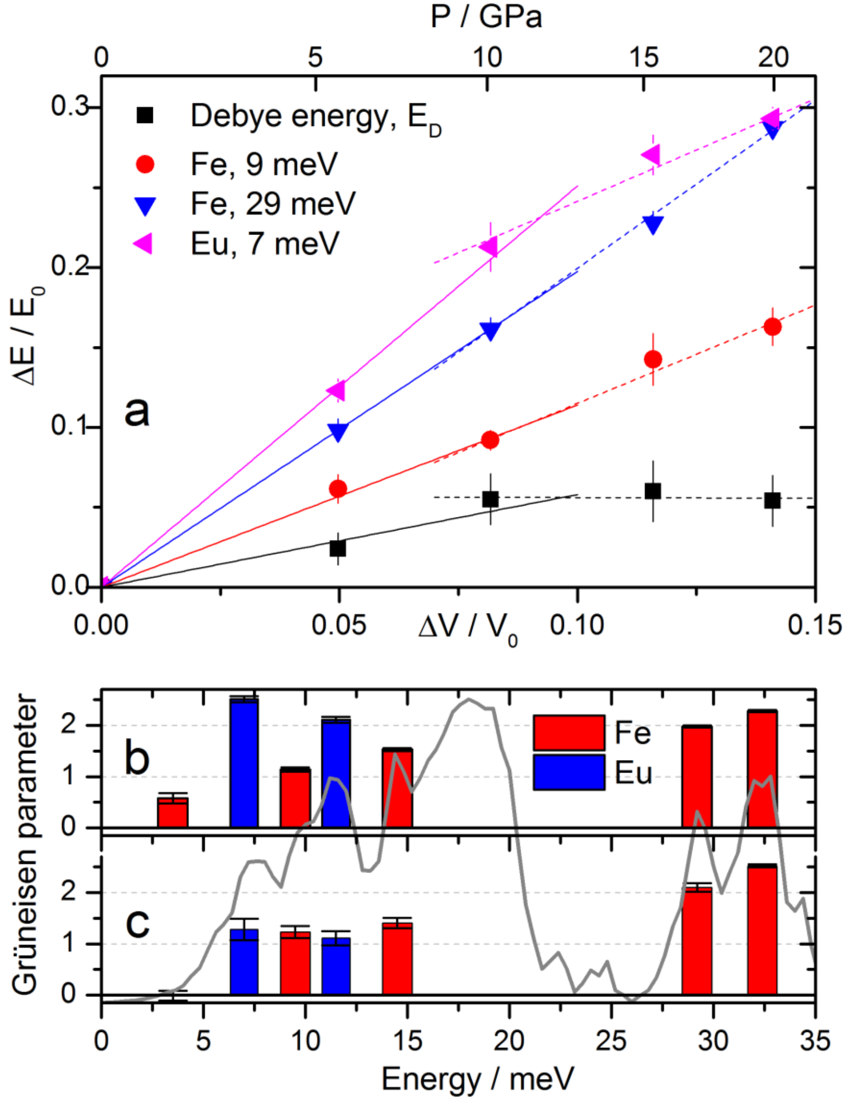
Möchel et al, Phys. Rev. B, 84(2011)064302
I. Sergueev, in prep.

Phonons in skutterudites. High pressure study

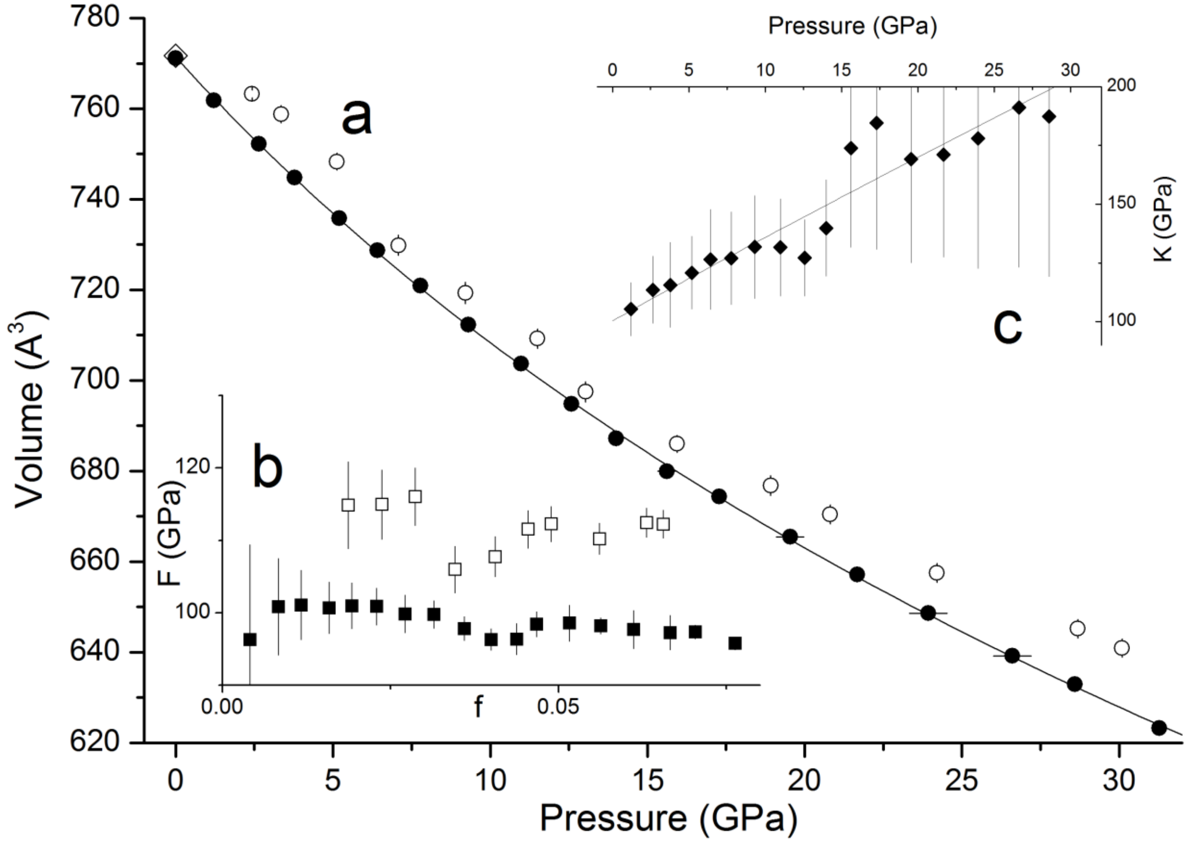
Experiment.



Grüneisen parameter



High pressure diffraction



Sapphire monochromator. Perspectives

Improvement of the sapphire quality

at 35 keV

thickness	ΔE / meV
1 mm	0.7
2 mm	0.3
5 mm	0.1

at 50 keV

thickness	Refl-ty / %
1 mm	2
2 mm	7
5 mm	30

Resolution to measure:

- phonon line broadening
- mean sound velocity

<u>New elements:</u>

^{183}W 46.5 keV
^{189}Os 36.2 keV
^{238}U 44.9 keV
^{240}Pu 42.8 keV

Sapphire ultraoptics for synchrotron radiation

Helmholtz-Russia Joint Research Group HRJRG-402

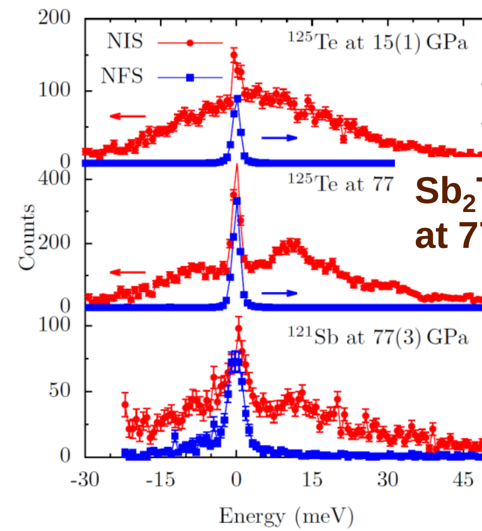
<u>Partners:</u>

Russia - RAS Shubnikov IC, Moscow
Germany – Forschungszentrum Jülich, DESY, ANKA

Apply for extreme conditions (high P):

Feasibility high pressure study:

R.Simon et al., Semicond. Sci. Technol. 00 (2014)



Sb_2Te_3
at 77 Gpa, RT

Requires setup to perform
low T/ high pressure
measurements

Acknowledgment

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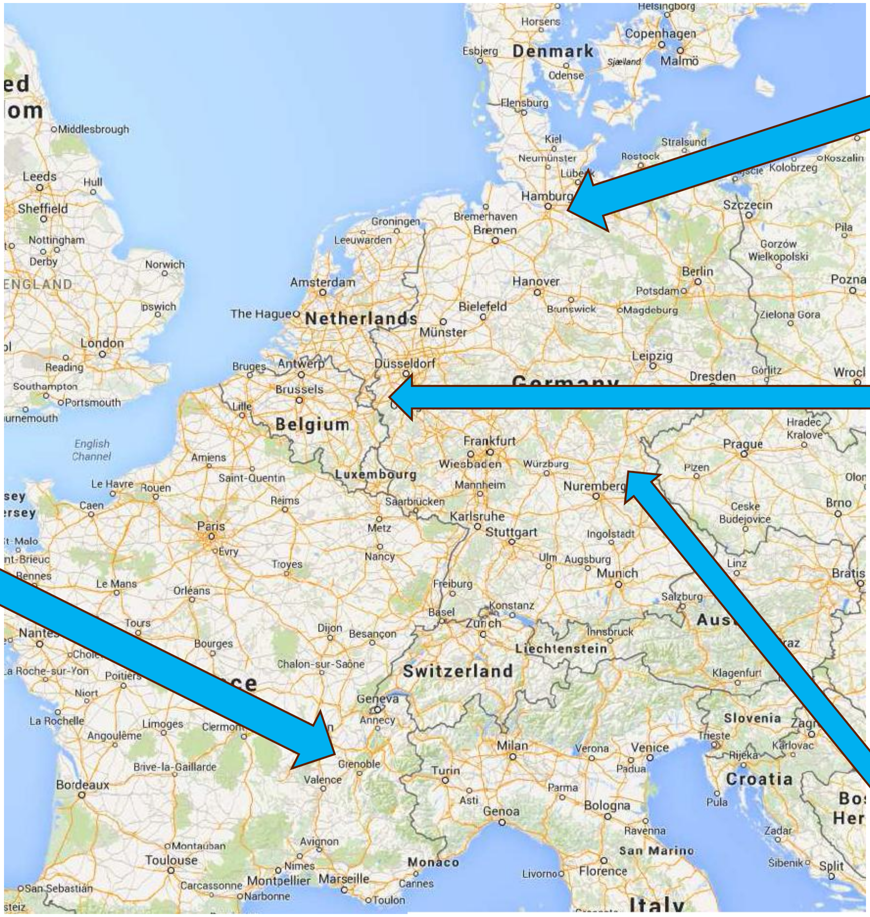
DESY, PETRA III

P01

Hans-Christian Wille,
Pavel Alexeev



Forschungszentrum Jülich

JCNS-2

Raphael Hermann,
Anne Hounen, Benedict Klobes, Ronnie Simon, Atefeh Jafari

ESRF

Nuclear Resonance Group

Rudolf Rüffer, Alexander Chumakov, Jean-Philippe Celse, Cornelius Strohm, Thanh Hai Deschaux-Beaume, Marcin Zajac, Vasily Potapkin, Dimitrios Bessas

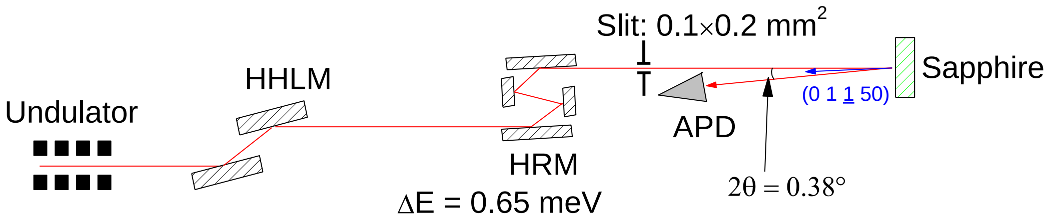
Bayerisches Geoinstitut

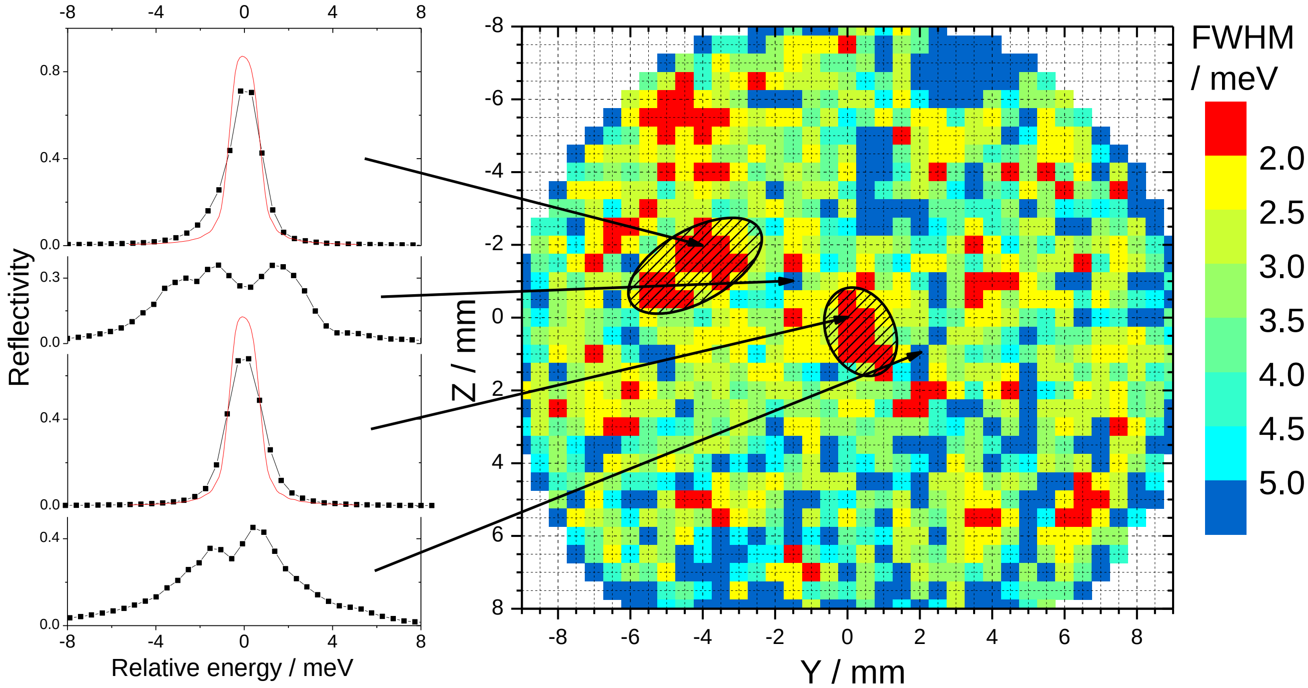
Leonid Dubrovinsky

Спасибо за внимание

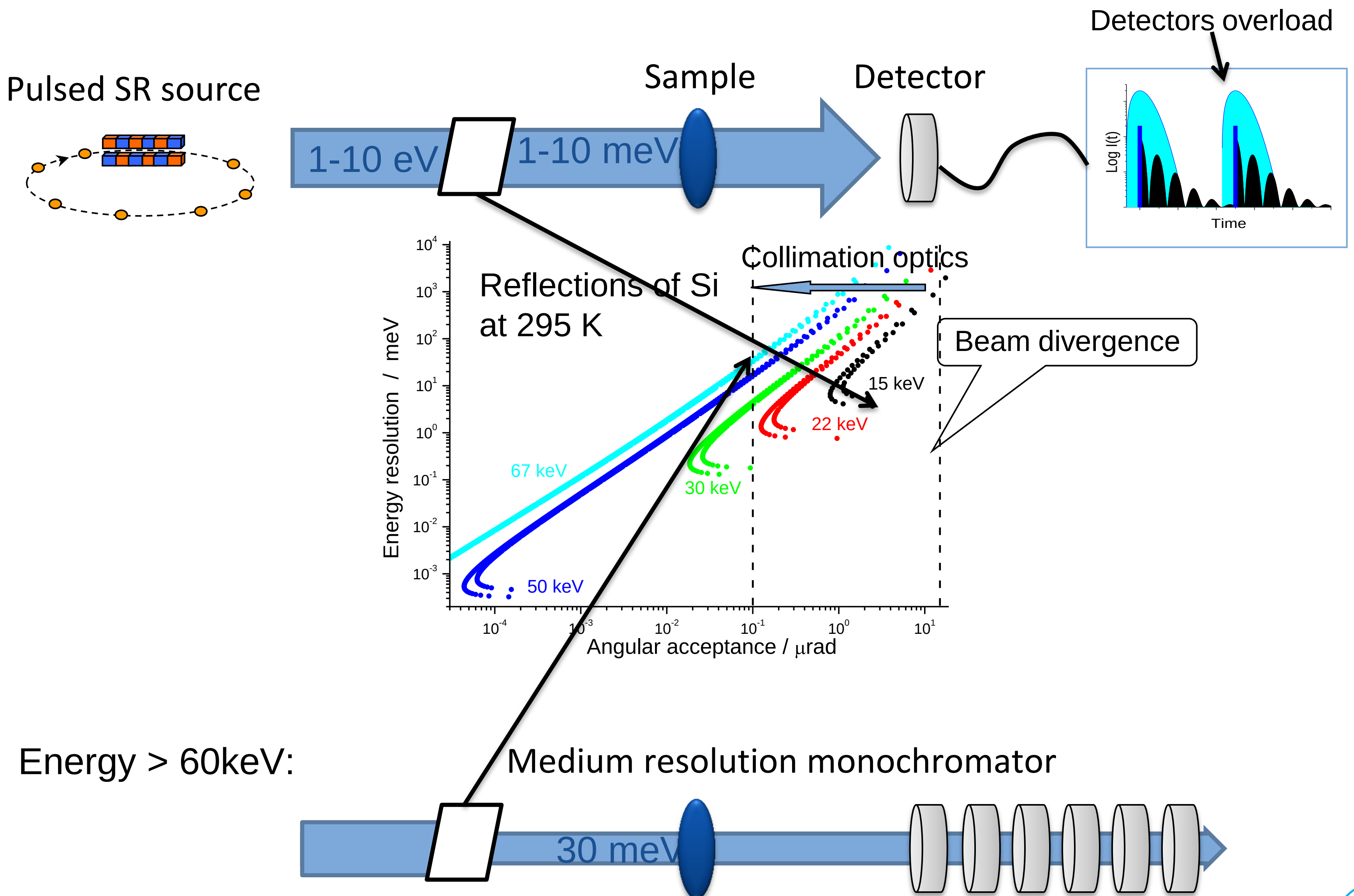
ФИЗФАК- ЧЕМПИОН!

Quality of sapphire crystals

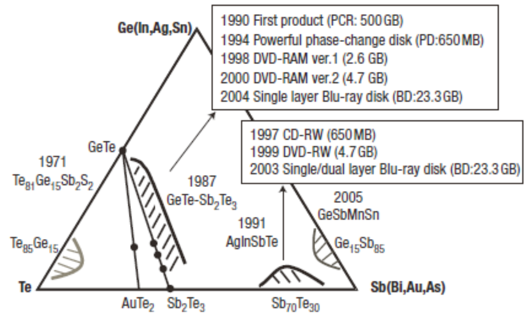




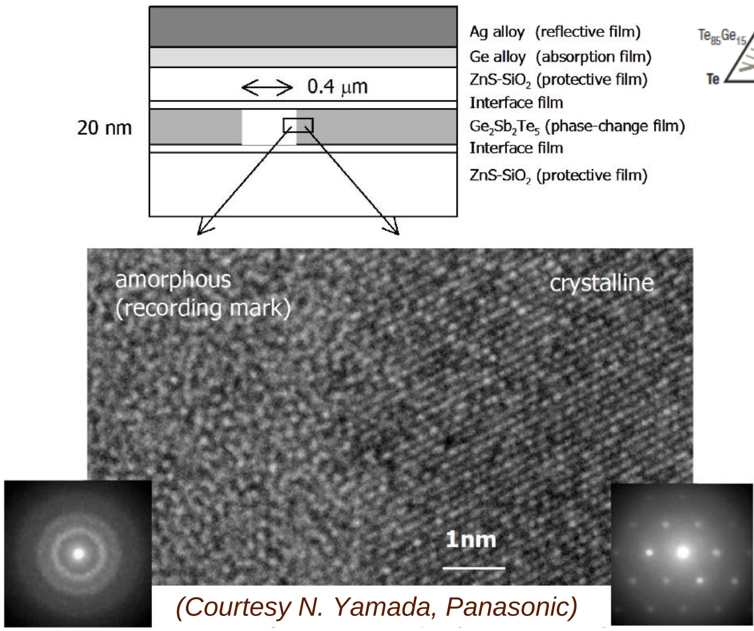
Time Mössbauer spectroscopy above 60 keV



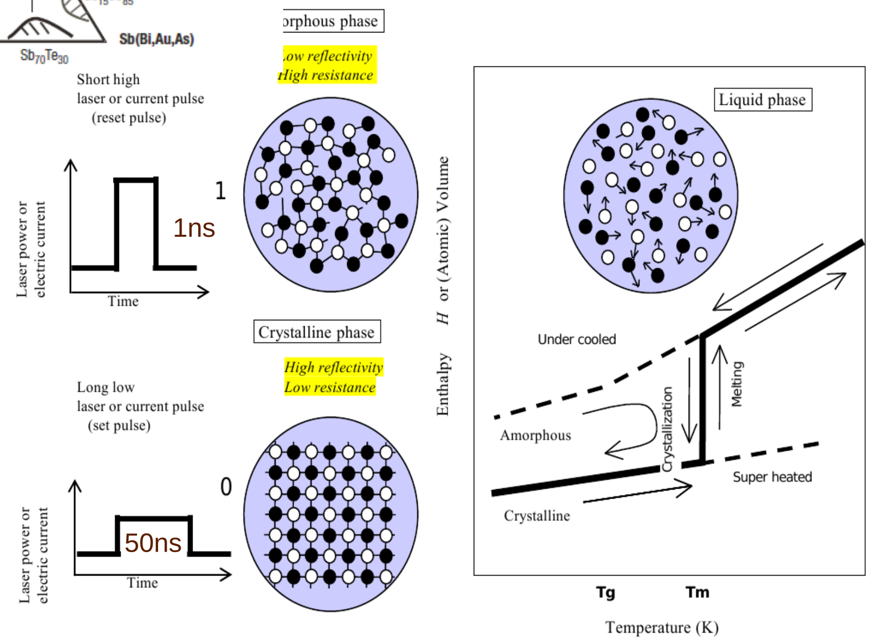
Phase change materials for storage devices



Wuttig and Yamada, Nature Mat. 6(2007)824



(Courtesy N. Yamada, Panasonic)



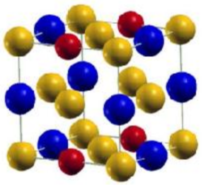
Candidate for
memory materials:

- Fast – ~10 ns
- Dense – ∅ << 50nm
- Stable – several years /bit
- Long-lived – 10^{12} cycles

Today: optical contrast: storage media, DVD, Blu-Ray.
Future: resistivity contrast: fast non volatile memory!

Elastic properties of $Ge_2Sb_2Te_4$

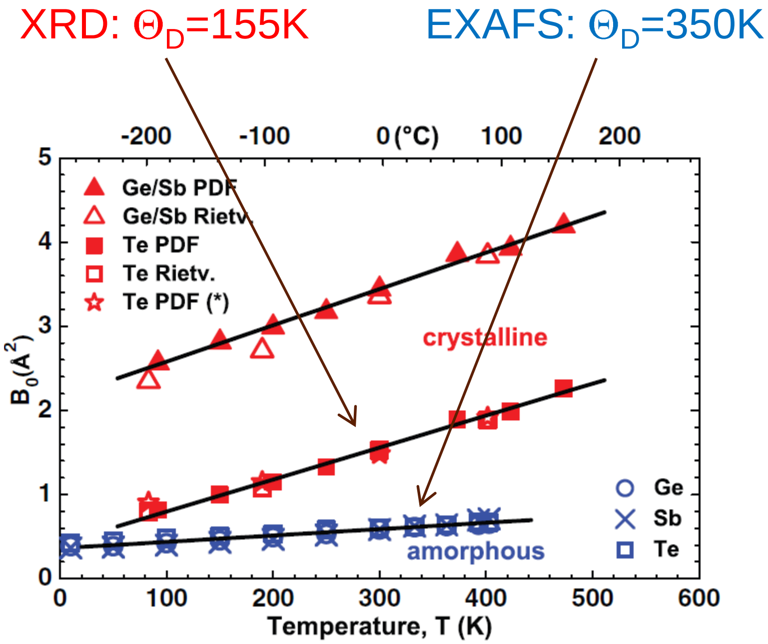
Hardening upon crystallization



	Amorphous	Crystalline
C_{11}	31 GPa	48 GPa
V_L	2280 m/s	2770 m/s
C_{44}	10 GPa	16 GPa
V_T	1300 m/s	1600 m/s
V_{Debye}	1440 m/s	1770 m/s

Blachowicz et al., J. Appl. Phys. ***102****, 093519 (2007)*

Softening upon crystallization



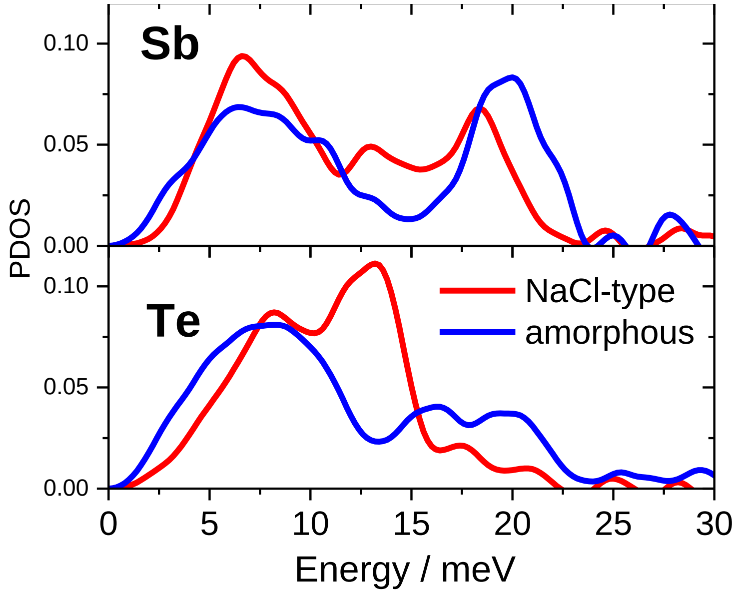
Matsunaga et al., Adv. Funct. Mater. 21(2011)2232

How we can reconcile this?

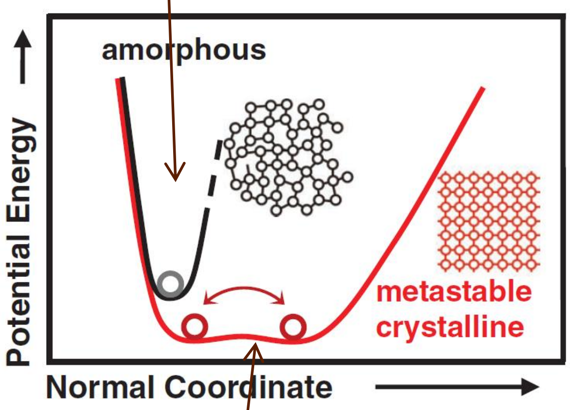
Amorphous and crystalline state of $Ge_2Sb_2Te_4$

Matsunaga et al., Adv. Funct. Mat., 21(2011)2232

Sample: ~1 μm film deposited on Al, T=20 K



Amorphous:
Strong covalent bonding



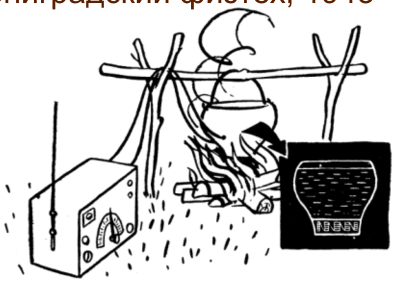
Crystalline:
Weak “resonance” bonding

	Sb		Te	
	B, Å^2	F, N/m	B, Å^2	F, N/m
Amorphous	0.184(2)	97(4)	0.198(2)	84(4)
NaCl	0.166(2)	72(4)	0.160(2)	68(4)

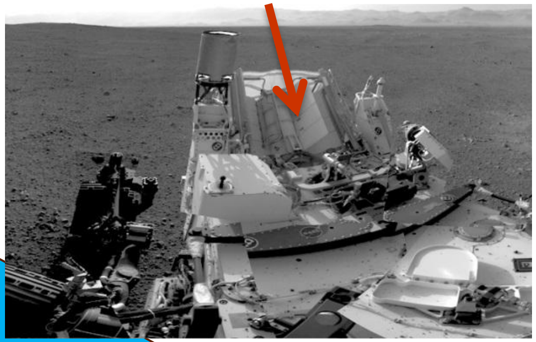
Combination of NIS on ^{125}Te and ^{121}Sb and INS (IXS) ⇒ Ge PDOS

Thermoelectrics. Applications

ТГ-1,«партизанский котелок»
Юрий Маслаковец,
Ленигрaдский физтех, 1943



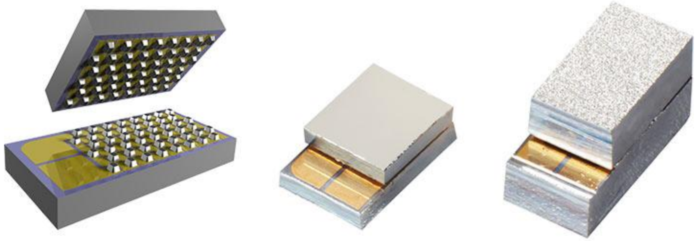
Radioisotope Thermoelectric Generator,
Mars Science Laboratory
https://solarsystem.nasa.gov/rps/rtg.cfm



Thermoelectric stations for gas pipe lines
http://www.telgen.ru/

Recovery of thermal waste
BMW TEG

Peltier Coolers
http://www.micropelt.com



http://biolitestove.com/products/campstove/