Solid State Physics Program

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on behalf of the SSP Community

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Nuclear Solid State Physics “Birth”

1920

J. Gróh and G. V. Hevesy
Annalen der Physik 1920 vol 368, issue 17, pages 85-92
„Die Selbstdiffusionsgeschwindigkeit des geschmolzenen Bleis"

4. ***Die Selbstdiffusionsgeschwindigkeit des geschmolzenen Bleis; von J. Gróh und G. v. Hevesy.***

Der Begriff der Selbstdiffusion entstammt James Clark Maxwell.[1]) Er ergibt sich unmittelbar, sobald man die Diffusion als Ergebnis der Molekularbewegung betrachtet. Nimmt man z. B. einen mit Stickstoff gleichmäßig gefüllten Zylinder und bezeichnet die in einem Zeitpunkte an einem Ende des Zylinders befindlichen Moleküle rein fiktiv, d. h. ohne dabei ihre Masse und Radien zu beeinflussen, so kann man die Selbstdiffusion des Stickstoffs ähnlich verfolgen, wie man etwa die Diffusion des Stickstoffs in Sauerstoff mißt.

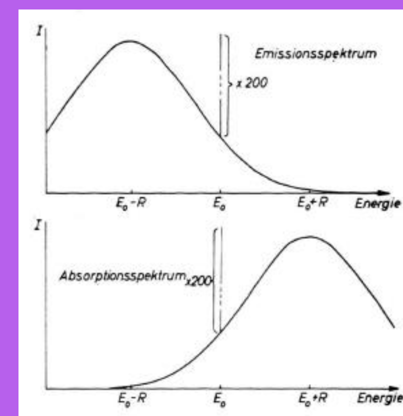
1975

ISOLDE Solid State Physics

H. Haas
„First results are described in the HMI-AR/1976. First conference contribution: HFI-IV in Madison (1977): ^{79}Kr/Zn,Cd,Sb.

1959

R.L. Mössbauer
Zeitschrift für Naturforschung 1959 vol 14a, pages 211-216
„Kernresonanzabsorption von γ-Strahlung in Ir^{191}"

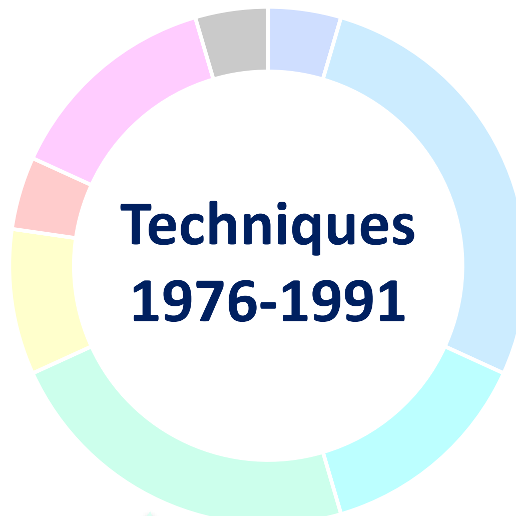


Diffusion
Thermal motion of particles

PL
Optical and electronic properties

ASPIC
Versatile system to study surfaces and interfaces

DLTS
Study concentration of electrically active defects /analyze the content of deep level defects in the material



PAC
EFG and BHF, charge symmetry from 10 to 1500 K

...and much more!
Hall effect, capacity-voltage, electrical conductivity, paramagnetic resonance spectroscopy

MS
EFG and BHF, charge symmetry, binding properties

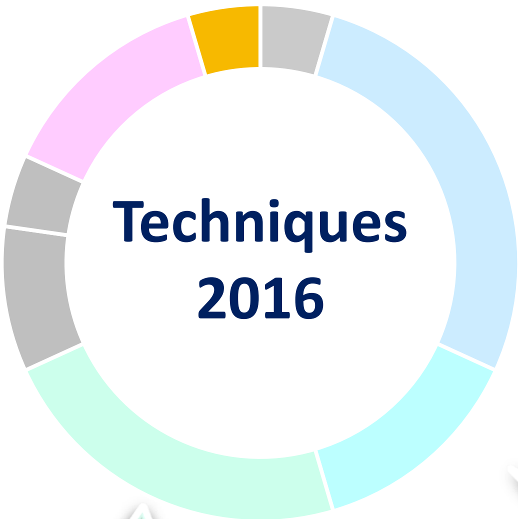
EC
Lattice location

Diffusion
Offline studies

PL
summer student project

ASPIC
Shipped to KU-Leuven: upgrade and maintenance

DLTS



PAC
GelbPAC

EC
^{123}Sn

MS
Using LED excitation

...and much more!

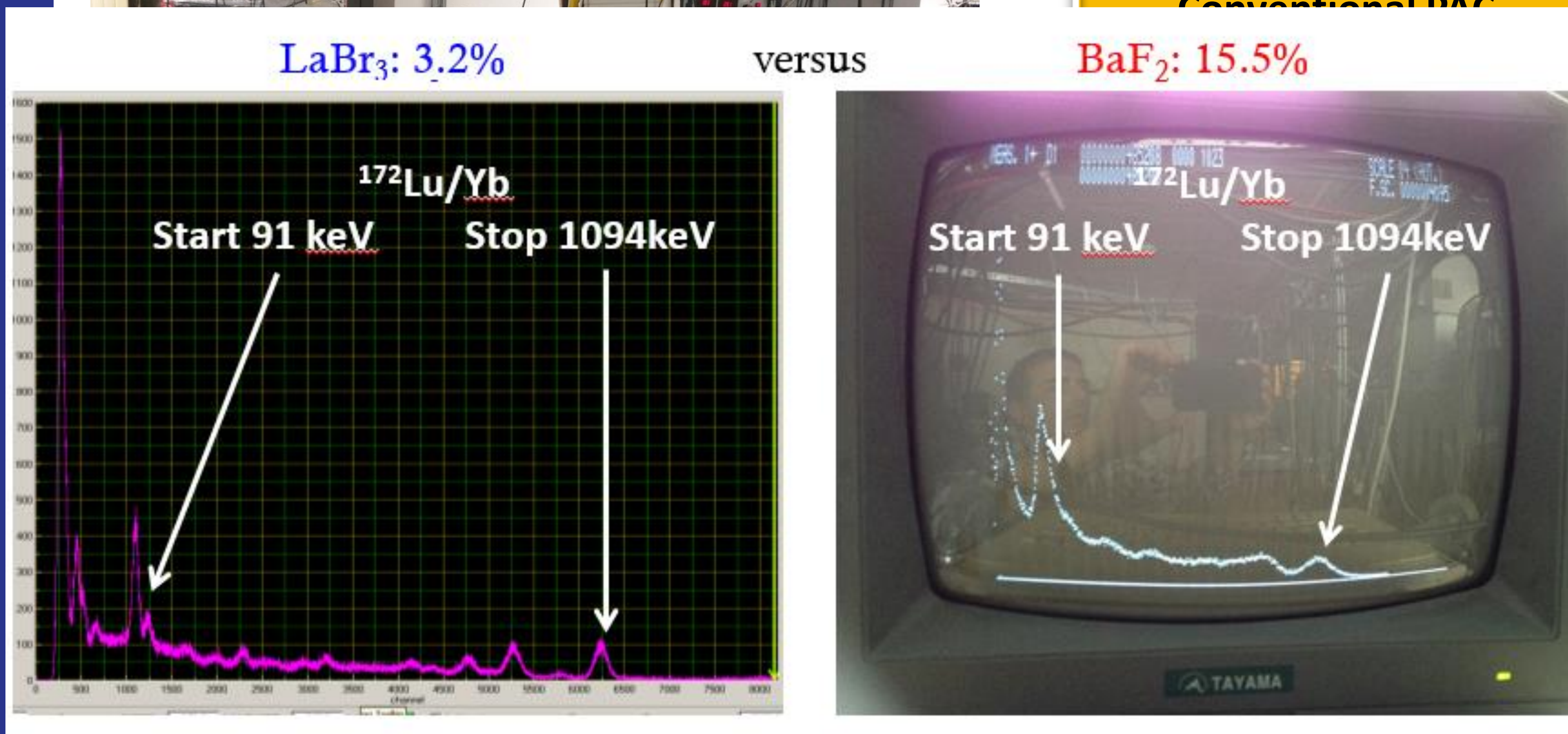
SSP infraestructure

Annealing room
Collaboration ISOLDE, BMBF, FCT, KU-Leuven

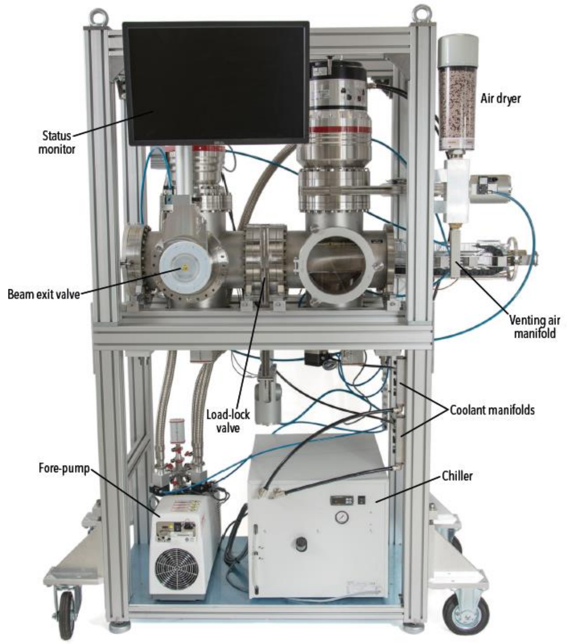
Digital PAC
Collaboration ISOLDE, BMBF

SSP infraestructure

Conventional PAC



Upgrades



The load-lock implantation chamber. The left side of the chamber is the permanently evacuated implantation part while the right section can be vented for sample changing.

The new implantation chamber at the GLM branch
BMBF Universität Göttingen
Nagl, Vetter, Hofsäss
Poster: Christoph Pohl

Perturbed Angular Correlations with Short-Lived Isotopes, the PAC-SLI setup
Poster: Abel Fenta & Manuel Silva

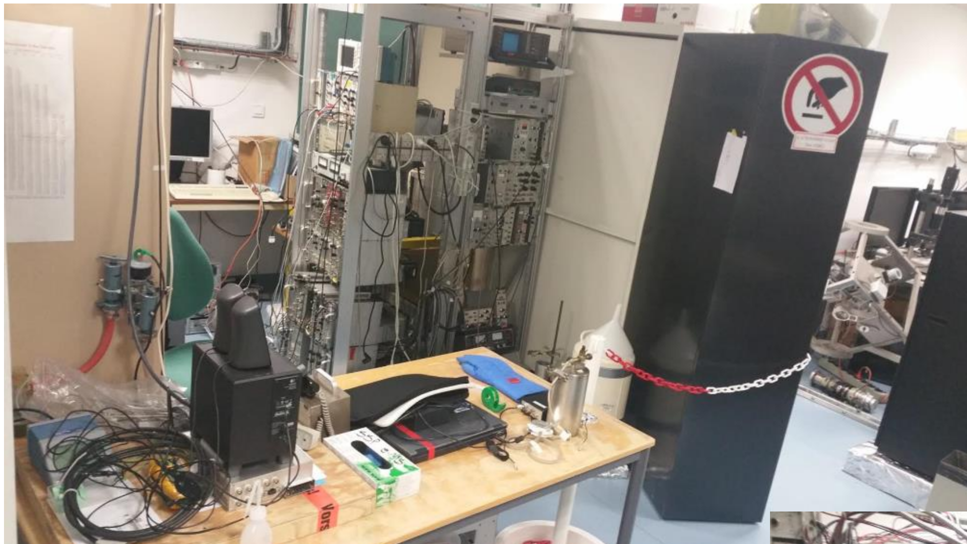
Emission Channeling with Timepix position sensitive dectectors
Poster: David Bosne

Upgrades: chemical lab

Chemical lab
Collaboration ISOLDE, BMBF, FCT, COPENHAGEN, KU-Leuven

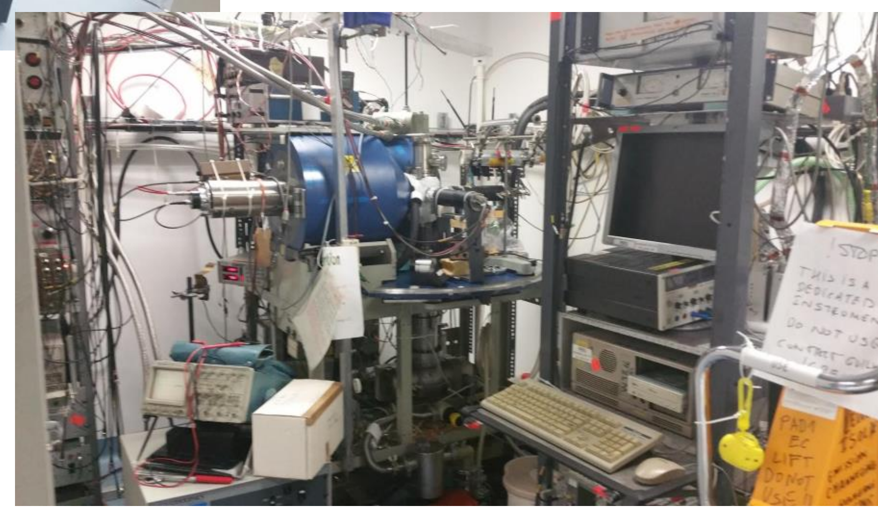
Evaporator
BMBF

SSP infraestructure



Mössbauer
Collaboration ISOLDE, BMBF, KU-Leuven, Mössbauer Collaboration

e-g PAC
Collaboration ISOLDE, BMBF, FCT

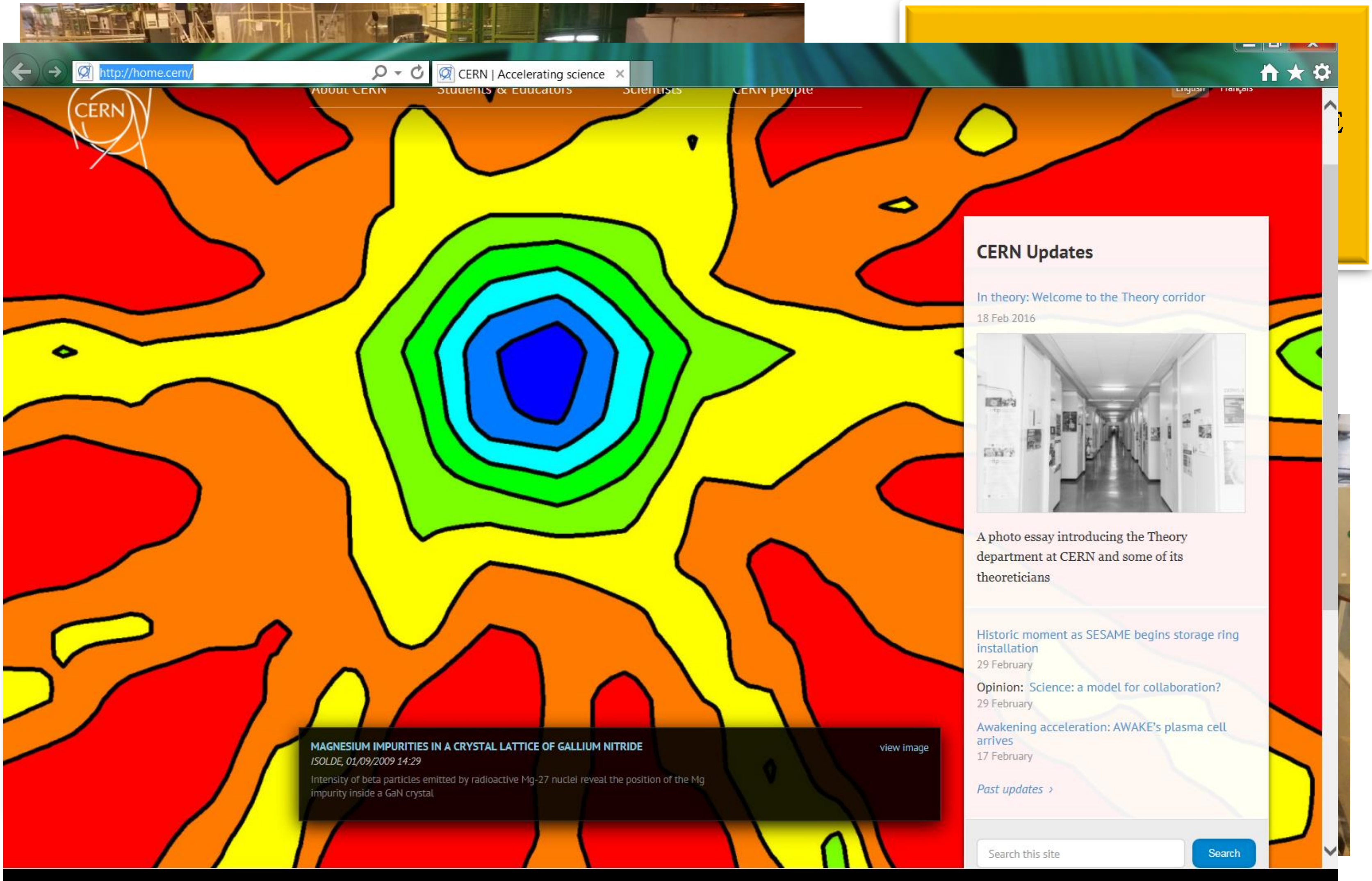


SSP infraestructure

Gamma Spectrometry
Collaboration ISOLDE, BMBF

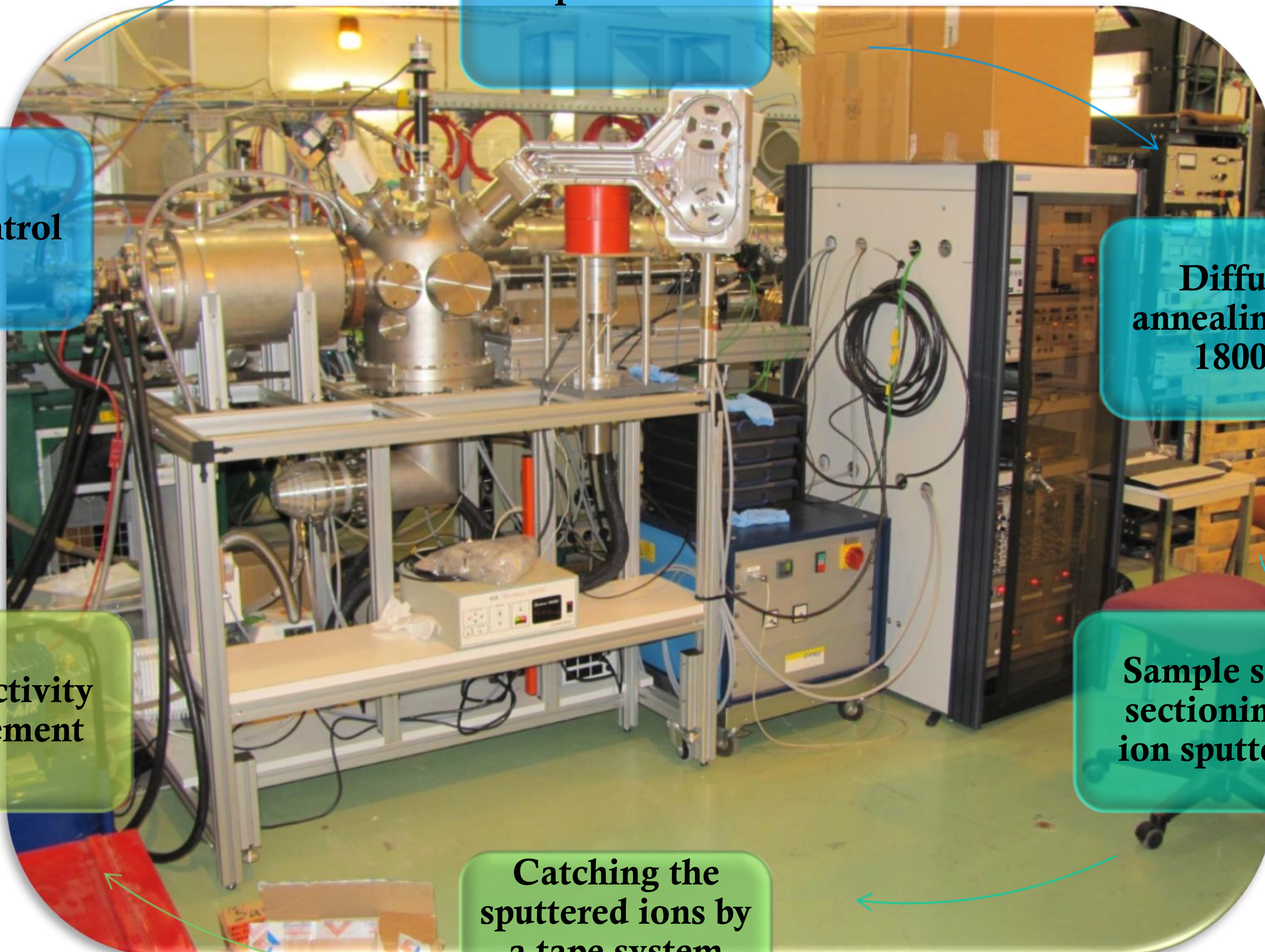
PL and offline diffusion
Collaboration ISOLDE, BMBF

SSP in the ISOLDE hall



On-line diffusion chamber

Courtesy: M. Deicher



Implantation

Diffusion annealing up to 1800 °C

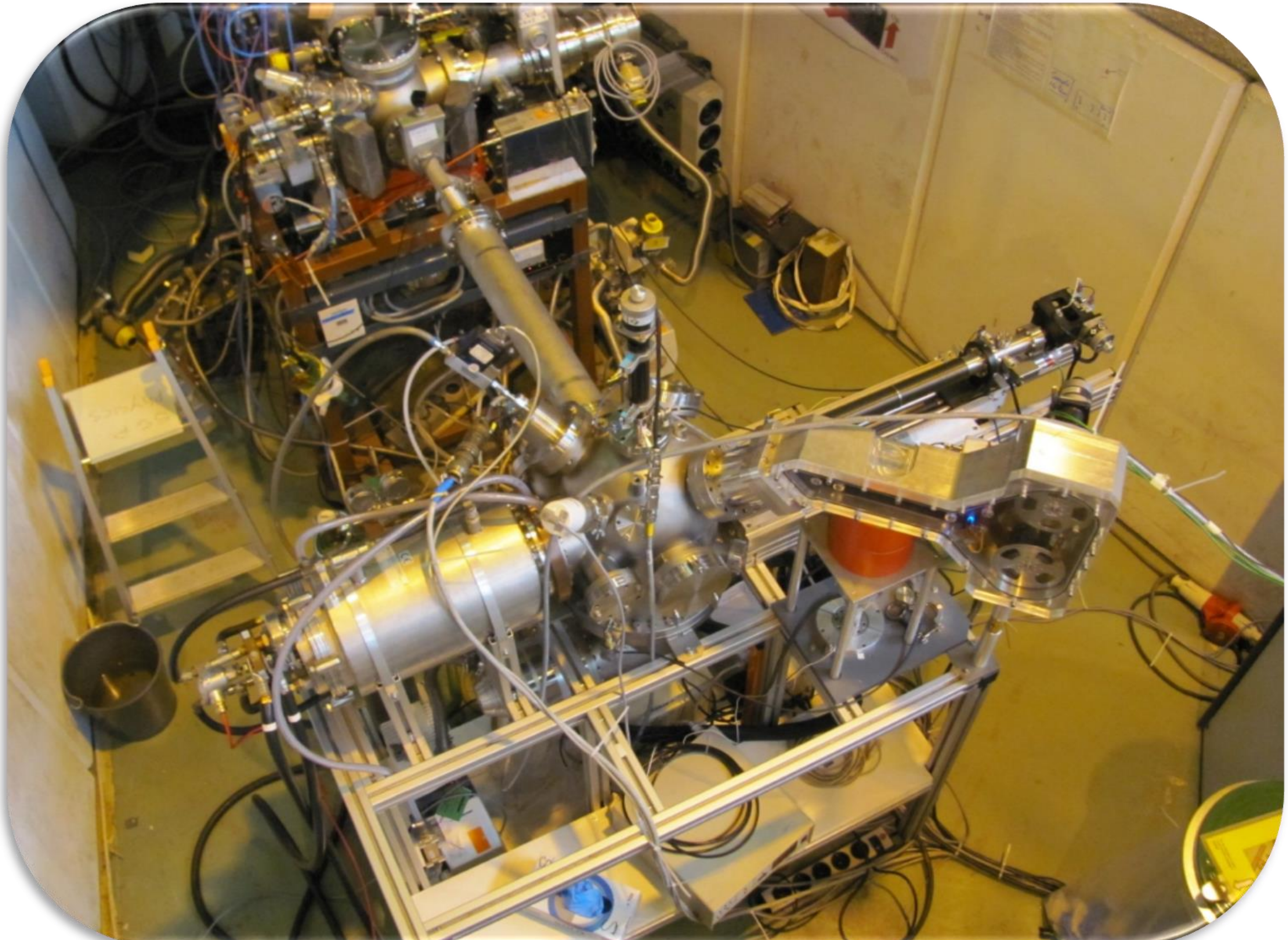
Sample serial sectioning by ion sputtering

Catching the sputtered ions by a tape system (allow $D < 10^{-19} m^2/s$)

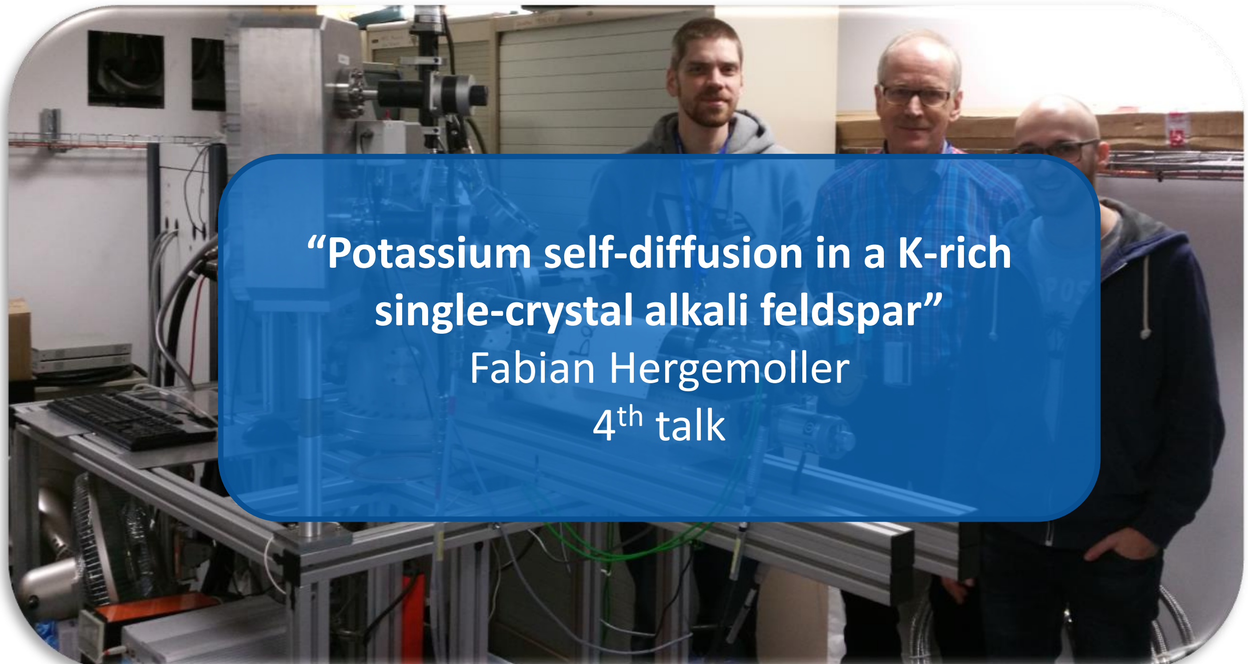
In situ activity measurement

Remote control

On-line diffusion chamber



People working with diffusion at ISOLDE in 2016



"Potassium self-diffusion in a K-rich single-crystal alkali feldspar"
Fabian Hergemoller
4th talk

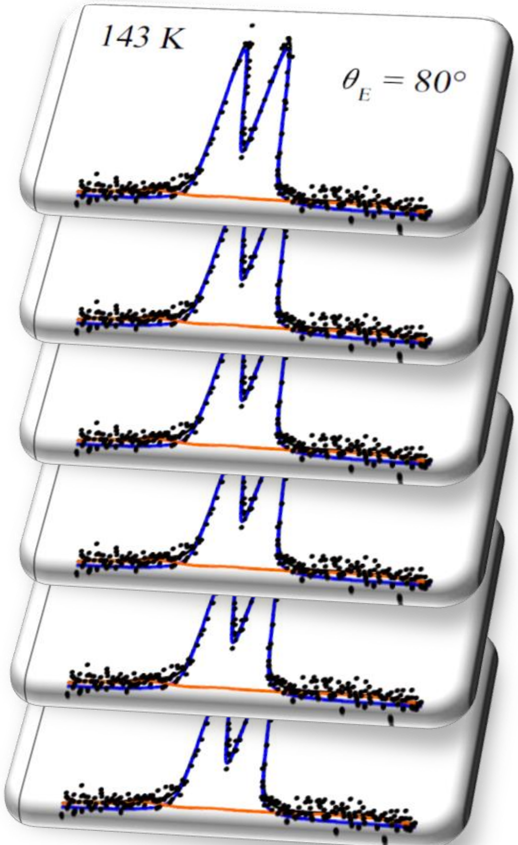
UNIVERSITÄT DES SAARLANDES

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

eMS at ISOLDE

Courtesy: H. P. Gunnlaugsson

Why Mössbauer at ISOLDE?



Valence state

Site symmetry/ interstitial/substitutional

Always two elements that play role:

^{57}Fe

Parent (^{57}Mn, 1.5 min) → daughter (^{57}Fe, 100 ns)

Parent (^{57}Co, 272 d) → daughter (^{57}Fe, 100 ns)

^{119}Sn

Parent (^{119}In, 2.1 min) → daughter ($^{119*}Sn$, 18 ns)

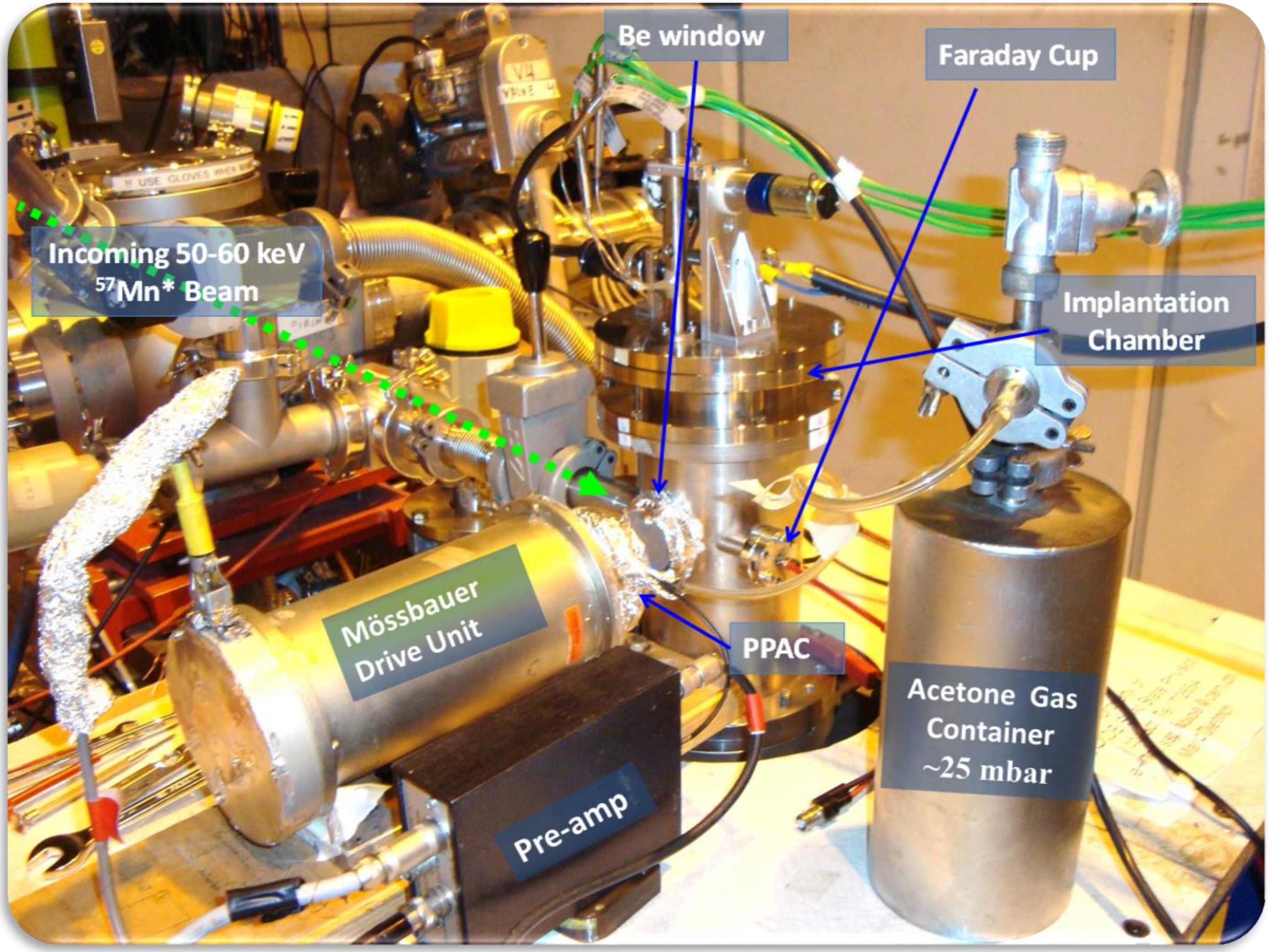
Distinguish ferro/para(magnetism)

Binding properties (through Debye Waller factor)

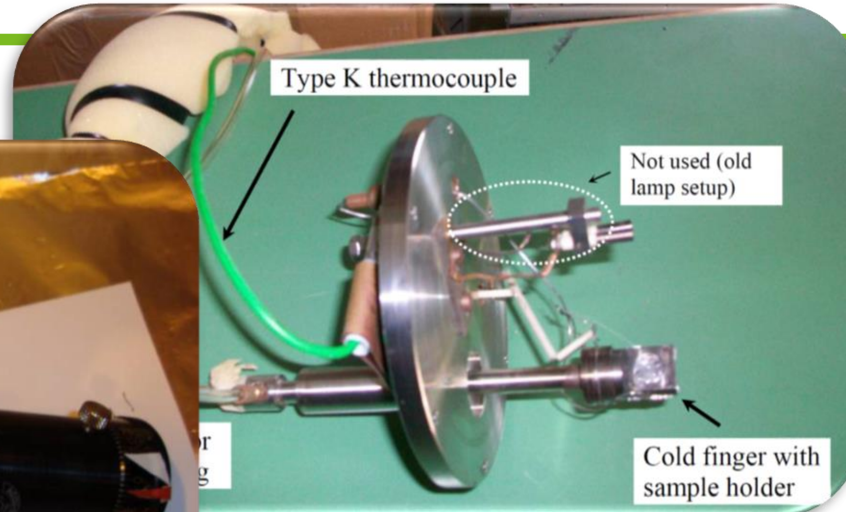
eMS: can measure low local concentrations (~10^{-4} at.%)

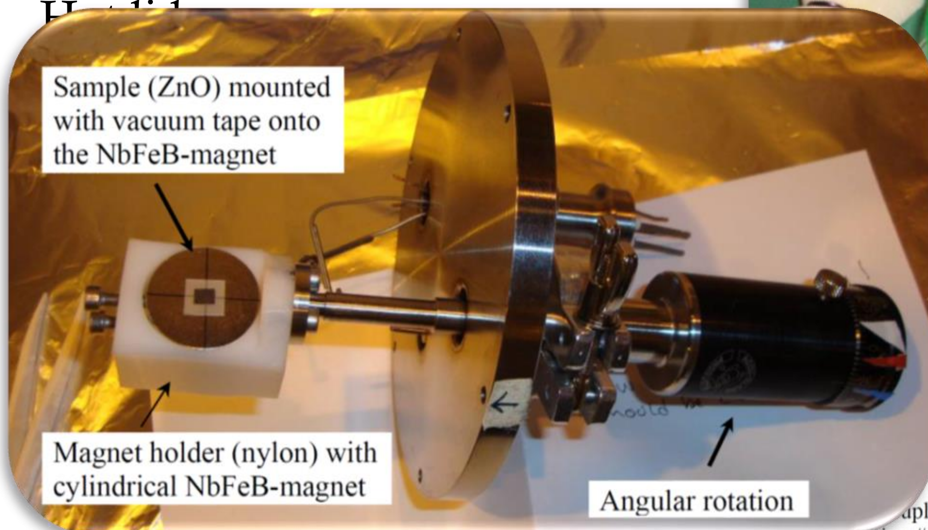
At ISOLDE/CERN we can measure spectrum in few minutes

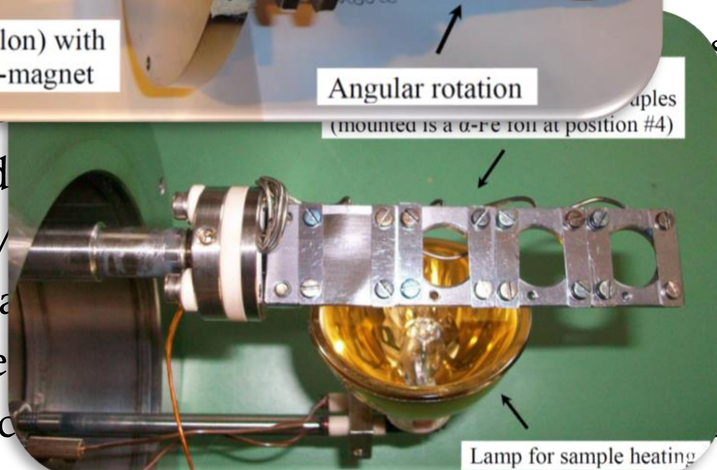
On-line setup: ^{57}Mn (1.5 min) ^{119}In (2.1 min)



Measurement Conditions







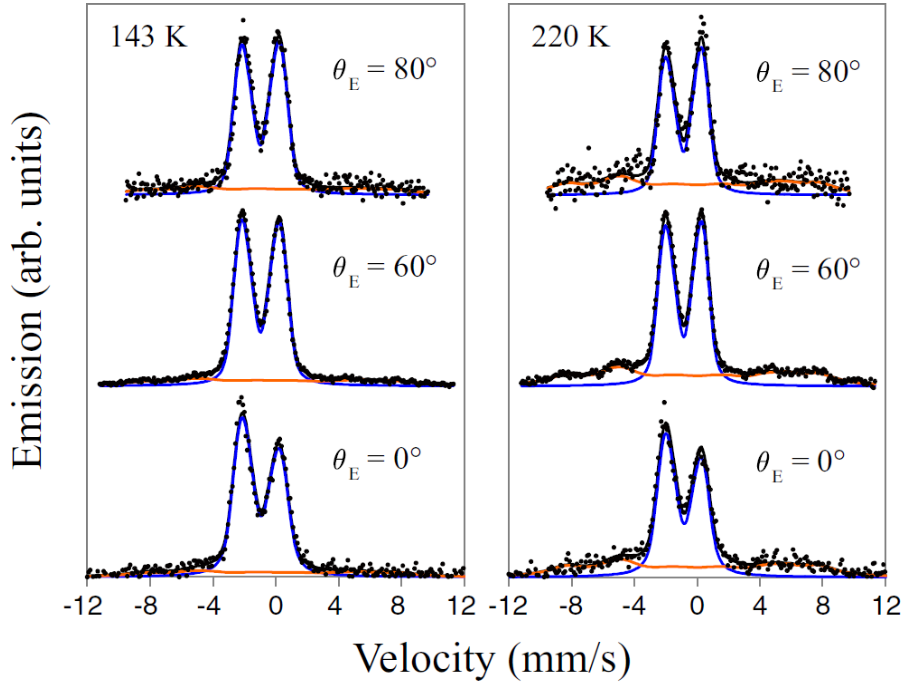
- ...sure under 60°
- Rotation lid
  - Implant/
  - Rotate sa
  - Measure
  - Sample c ... ample normal)
  - Heated to ~300°C (electrical) in $B < 0.3$ T

Quench

- Implantation/measurement at $T >$
- Sample quickly removed from vacu
- External measurement started (whi
  - Quenching: sample dropped in LN
  - External magnetic field
  - Laser illumination
  - ....
- First tested 2014 with moderate suc success, used in 2016 with huge suc

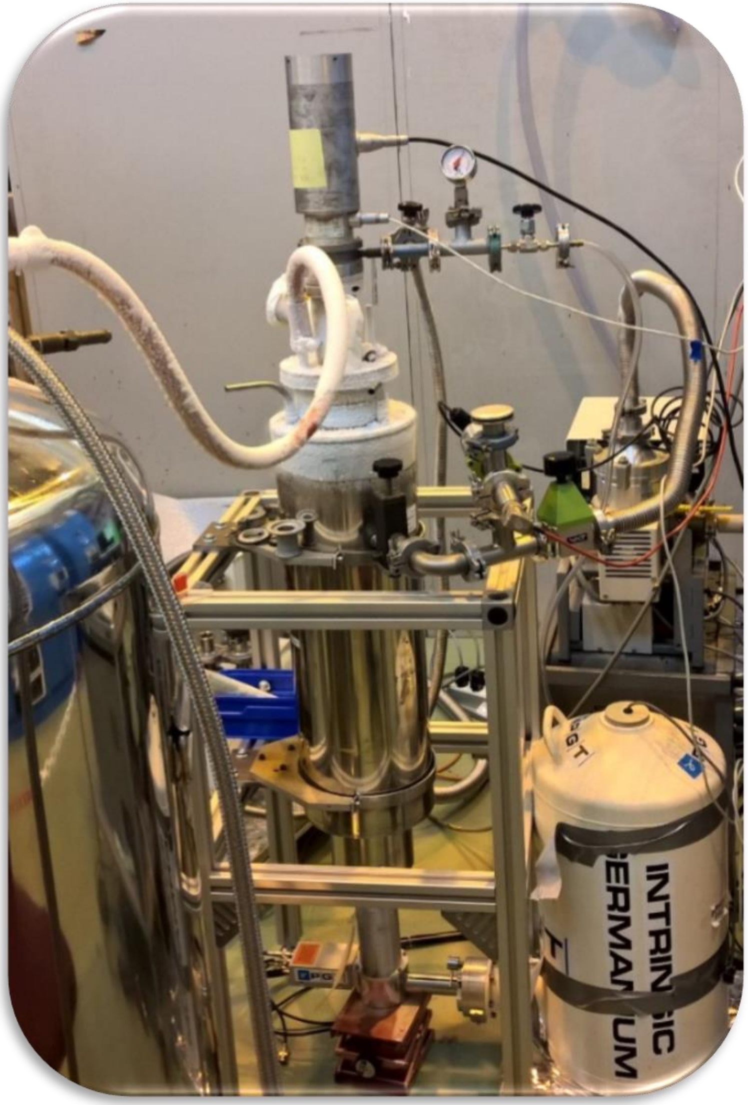
General Observations/methods

- Temperature series:
  - Implantation damage at low *T*'s
  - Incorporation on regular lattice sites at high *T*'s
  - Defect-probe complexes at intermediate *T*'s
- Angular dependent measurements
  - "Damage" without angular dependence
  - "Crystalline sites" with angular dependence (if not cubic material)



- ^{57}Mn implanted TiO_2
- Slight, but significant angular dependence
  - Not Fe in amorphous zones

Cold Source/absorber eMS



- Hg produced from spallation in a molten Pb target
- ^{197}Hg/^{197}Au (PAC) implanted into ice
- Biomolecules prepared and sample frozen

Isotopes used (since 2000)

MS Isot.	Parent	Lifetime	Recoil	Det.	Target/ion source	Yields (s^{-1})
^{57}Fe	^{57}Mn (β^-)	1.5 min.	M:93 eV	Res.	UCx/RILIS	few×10^8
	^{57}Co (EC)	272 d.	0.14 eV	Res.	ZrO/VADIS	~10^7
^{119}Sn	^{119}In (β^-)	2.1 min.	M:22 eV	Res.	UCx/RILIS	~10^9
	^{119m}Sn (IT)	291 d.	~0 eV	Res.	UCx/RILIS	~10^9 (?)
	^{119}Ag (β^-) →^{119}Cd (β^-) →^{119}In (β^-)	2.1 s. 2.2 min. 2.4 min.	M:102 eV	Res.	UCx/RILIS	~few×10^7
^{197}Au	^{197}Hg (EC)	64 h.	~0	Ge (LT)	Pb	~10^9
^{151}Eu	^{151}Dy (EC) →^{151}Tb (EC) →^{151}Gd (EC)	17.9 min. 17.6 h. 123.9 d.	~0	Ge	Ta	~10^9

MS Collaboration


2011


2014


2015


2016

Perturbed Angular Correlations

by J. Schell & G. Correia

PAC: a method to probe hyperfine interaction in matter

Strengths

- Sample's morphology is very flexible: Solids, liquids, molecules…
- Efficiency is almost independent of temperature
- Its a differential time measurement ranging from ns to µs

Weaknesses

Needs radioactive nuclei with:

- suitable decay cascades, nuclear moments, half-lives
- *"complicated"* analyzing software
- interpretation is not direct

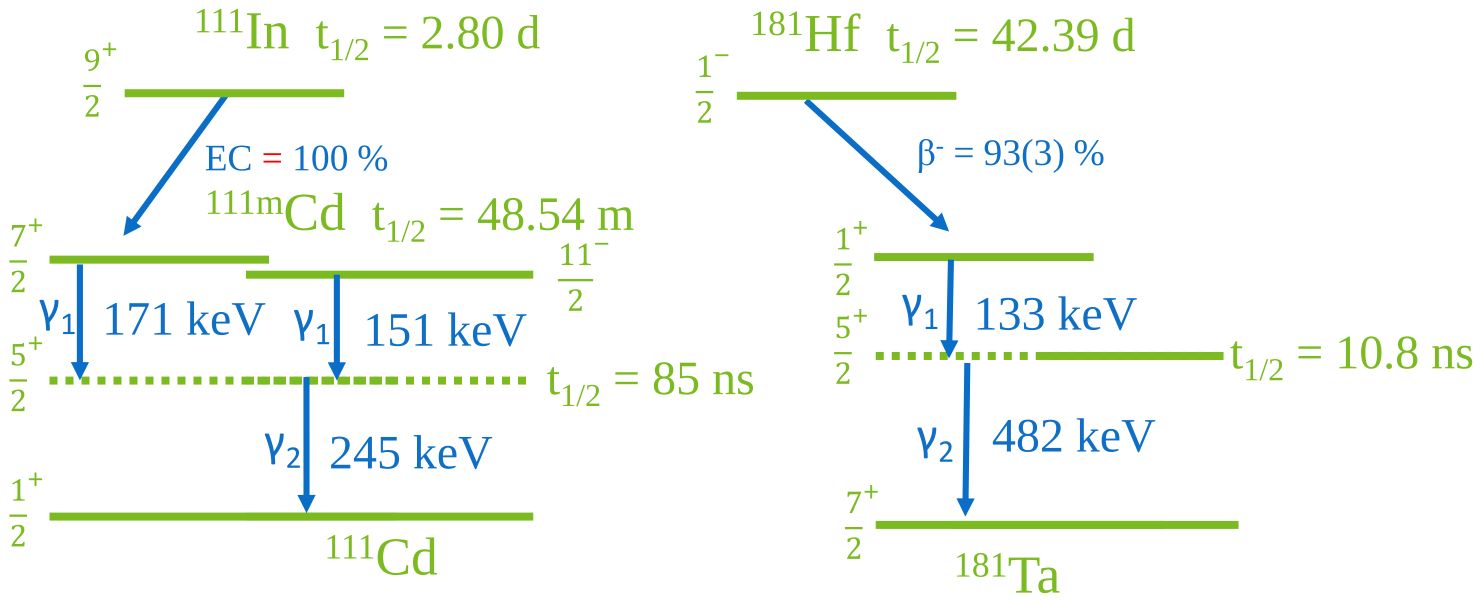
Opportunities

- Facilities like ISOLDE provide many "new" PAC probes
- Synchrotron radiation can make available more probe elements
- New DFT and Cluster models offer great progresses on interpretation
- New detection methods offer greater efficiency and handling of data (LaBr3 detectors, digital)
- **e-gamma, gamma-gamma and beta-gamma should be exploited TOGETHER providing new data and exciting new physics**

Threats

- Access to large scale facilities depends on appropriate funding
- Training and know-how (in applied nuclear physics) is vanishing from educational programs
- Traditional European groups are disappearing where deep knowledge of the method was accompanied by a regular production of good work.

Why only conventional PAC ISOTOPES?



	Q (b)	μ (μ_N)	A_{22}	I
^{111m}Cd	+0.765(15) (*)	-0.766(3)	0.1786	$5/2^+$
^{181}Hf (**)	+2.35(6)	+3.29(3)	-0.3185(11)	$5/2^+$
	+2.16(37)	+0.669(16)	-0.392(8)	2^+

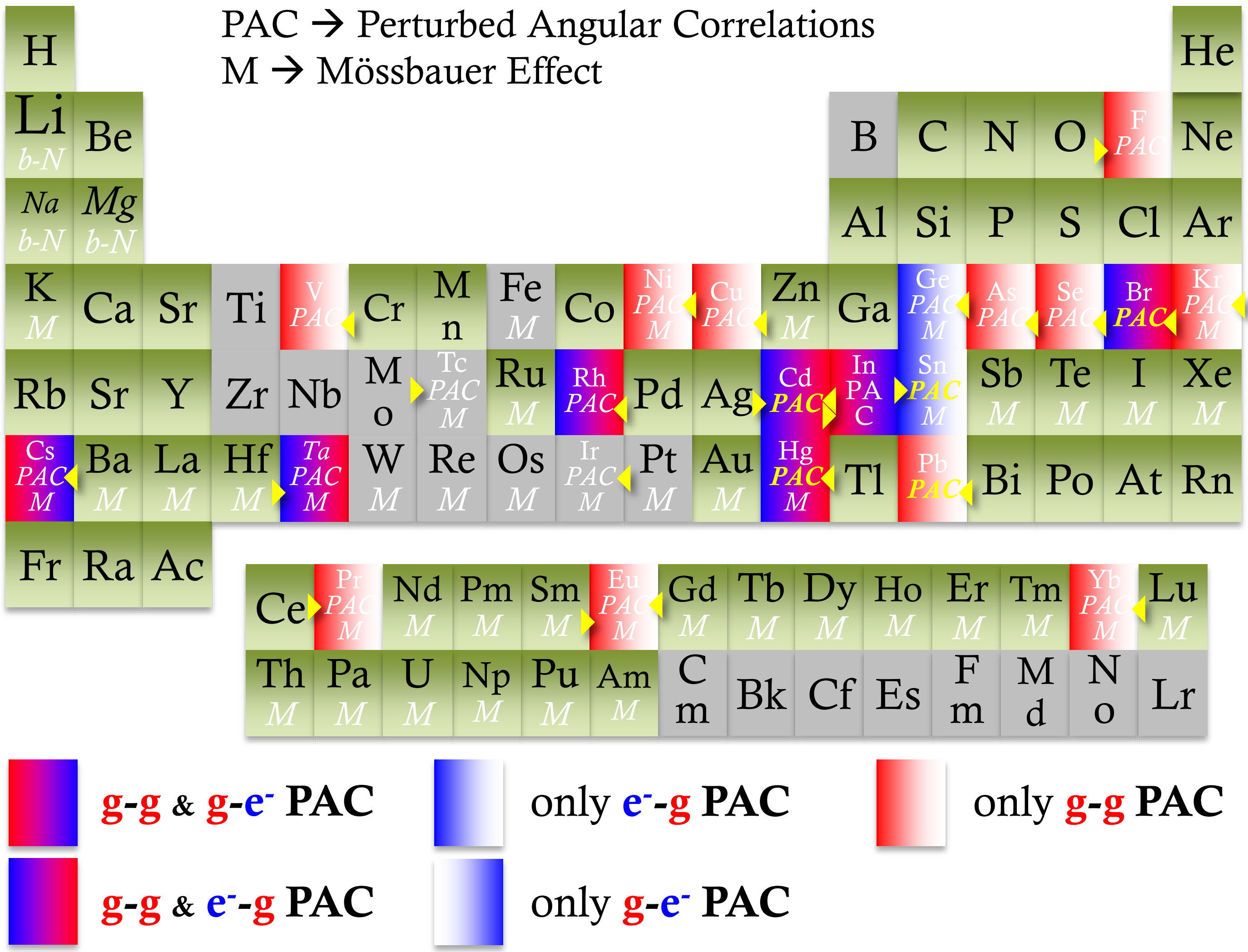
(*)**Haas, H.** and **Correia J. G.**, Hyp. Int. 198, 133-137, 2010.
(**)**Singh, B.,** Nuclear Data Sheets, 199 **& Tuli J.K.**, Academic Press Inc., 1995.

Probe elements

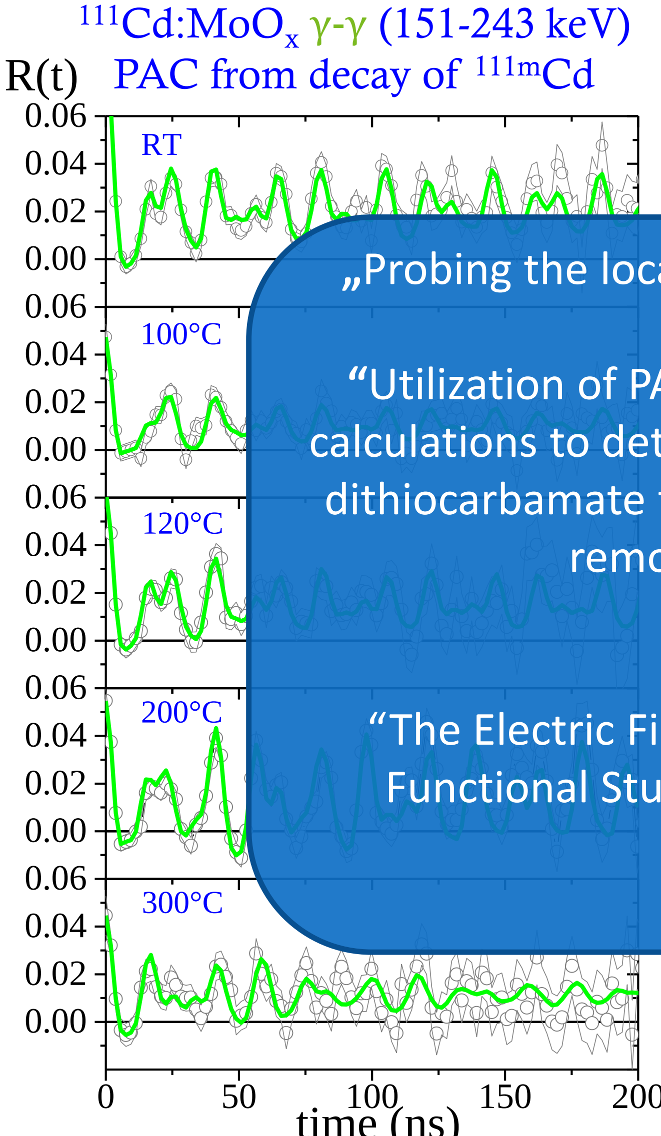
Available at ISOLDE

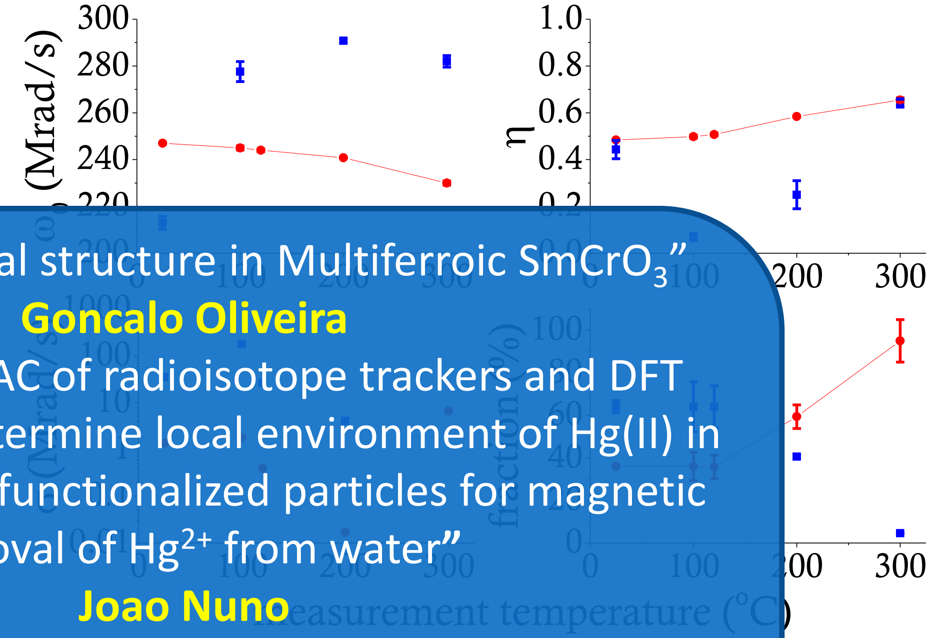
NOT available at ISOLDE

PAC → Perturbed Angular Correlations
M → Mössbauer Effect



PAC RESULTS: dopant incorporation (Cd)





„Probing the local structure in Multiferroic $SmCrO_3$"

Goncalo Oliveira

"Utilization of PAC of radioisotope trackers and DFT calculations to determine local environment of Hg(II) in dithiocarbamate functionalized particles for magnetic removal of Hg^{2+} from water"

Joao Nuno

Friday

"The Electric Field Gradient: A systematic Density Functional Study for Hg adatoms on Graphene"

Abel Fenta

Friday

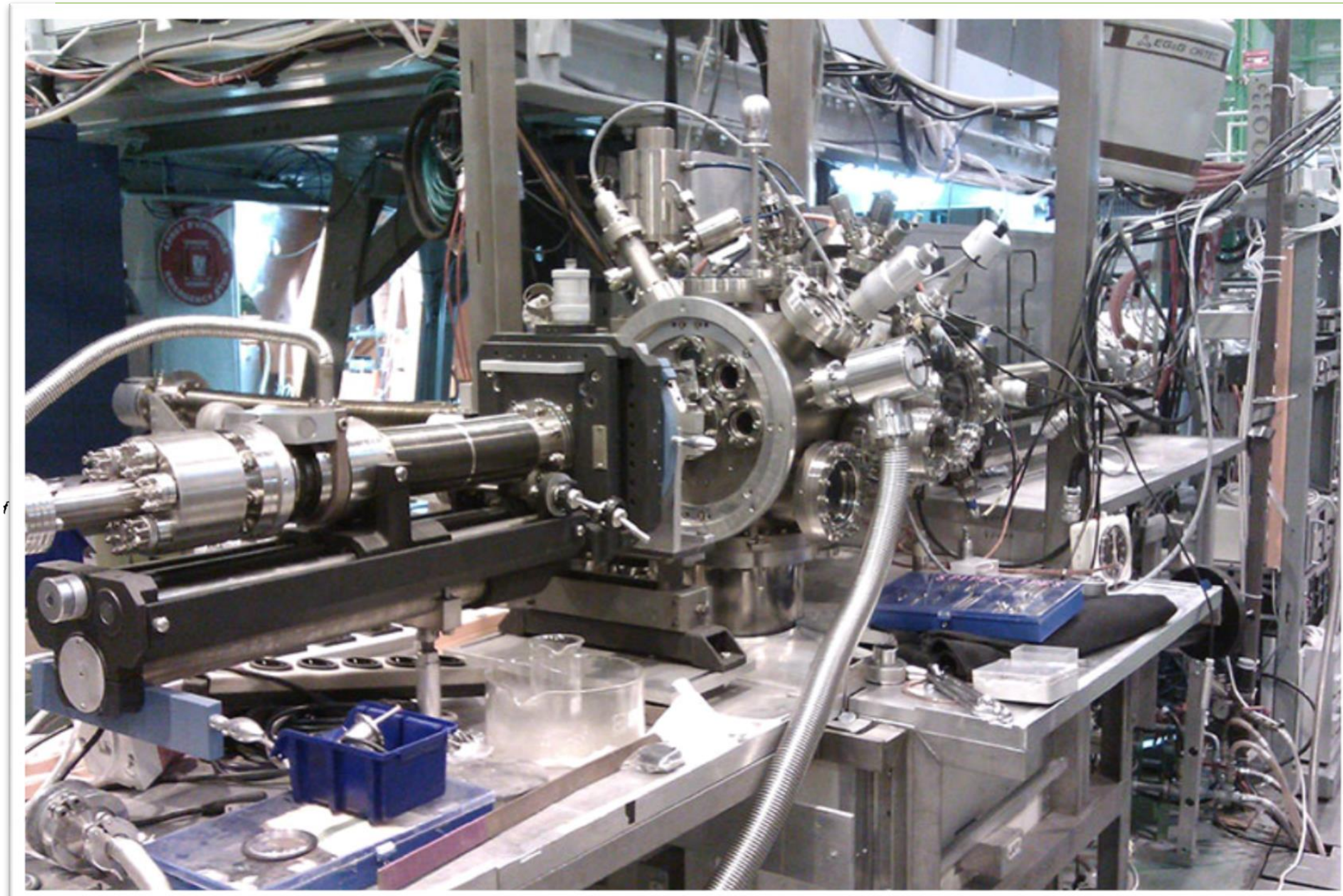
- the temperature reversability of the EFG_1, EFG_2 fractions hint an electronic excitation at the dopant Cd. *(to be continued, e.g., with … e^--γ PAC)*

Apparatus for surface Physics at ISOLDE CERN (1991)

Apparatus for Surface Physics and Interfaces at CERN (2003)

(ASPIC)

Apparatus for Surface Physics and Interfaces at CERN



on a Cu

ot only)

EC

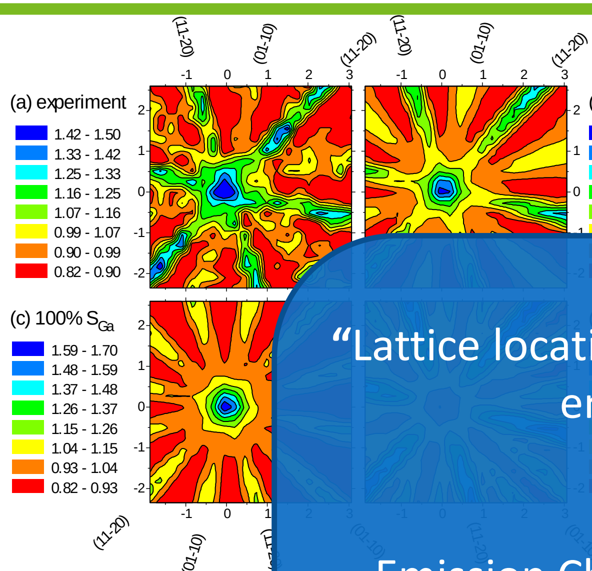
euven

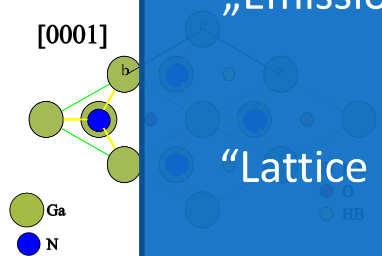
CERN-ISC-91-10

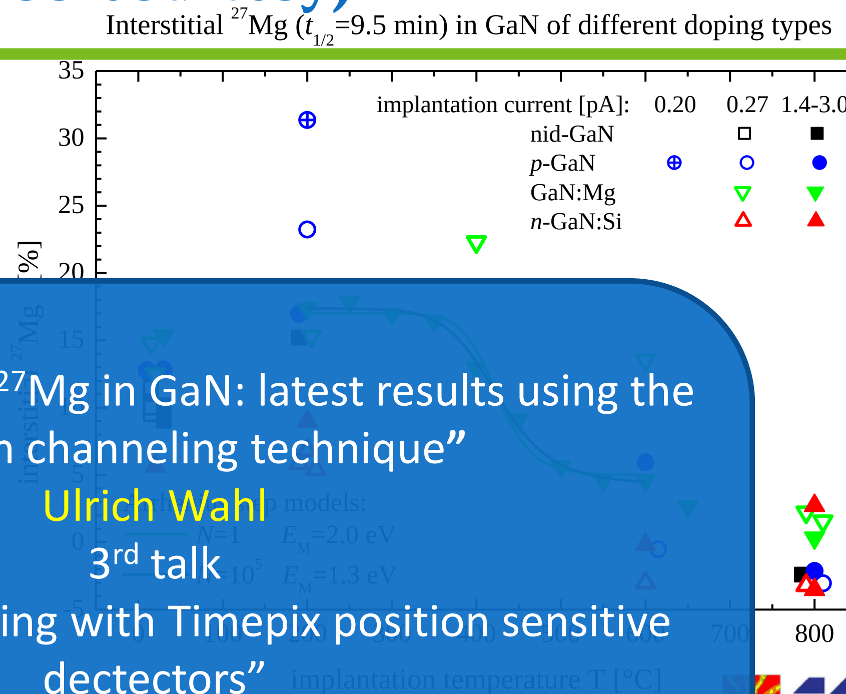
Offline and on-line emission channeling

Courtesy: L. Pereira and U. Wahl

Lattice sites of ^{27}Mg in different pre-doped GaN (IS453 courtesy)







"Lattice location of ^{27}Mg in GaN: latest results using the emission channeling technique"

Ulrich Wahl

3rd talk

„Emission Channeling with Timepix position sensitive dectectors"

David Bosne (poster)

"Lattice location of implanted transition metals in 3C-SiC"

Ângelo Costa (Friday)

- Electron emission channeling patterns show mix of substitutional + interstitial ^{27}Mg

- Interstitial Mg fraction highest in *p*-GaN:Mg
- Lowest in *n*-GaN:Si

– Direct evidence for amphoteric character of Mg that is coupled to the doping type

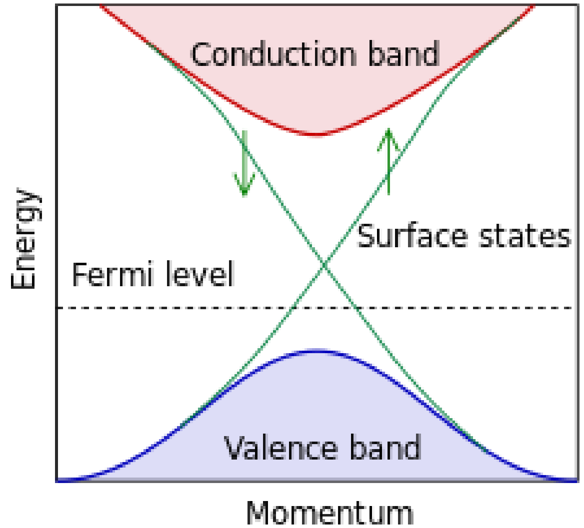
- Site change interstitial - substitutional Mg_{Ga}

⇒ Activation energy for migration of interstitial Mg: E_M » 1.3 - 2.0 eV

Extra topic: topological insulators (IS612 courtesy)

Semi-metalic surface states originating from non-trivial topology of the electronic band structure in the bulk (insulator)

(spintronics, quantum computation...)



Nature Physics **8**, 800 (2012)
Phys. Rev. Lett. **112**, 186801 (2014)
Nature Materials **13**, 178 (2014)
Nature Communications **3**, 982 (2012)

Topological crystalline insulators (IS612 courtesy)

Rhombohedral distortion: breaking crystal mirror symmetry

PbTe

↓

(Pb,Sn)Te

↓

SnTe

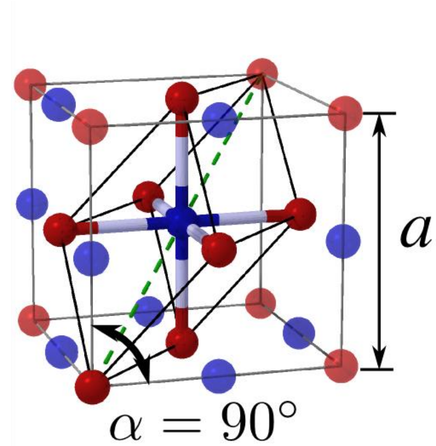
↓

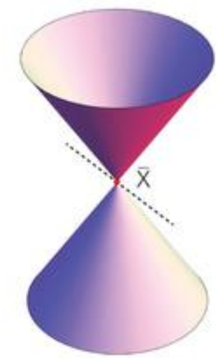
(Ge,Sn)Te

↓

GeTe

cubic



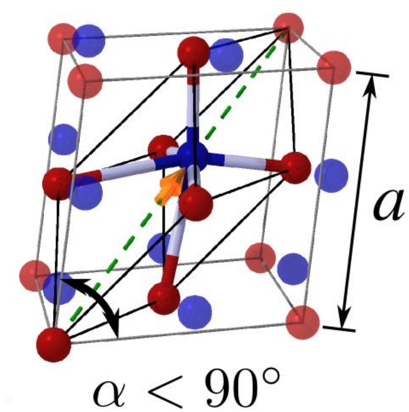


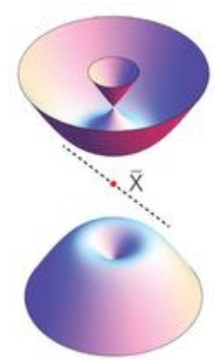
topological crystalline insulator (TCI)

Pb, Sn or Ge ●

Te ●

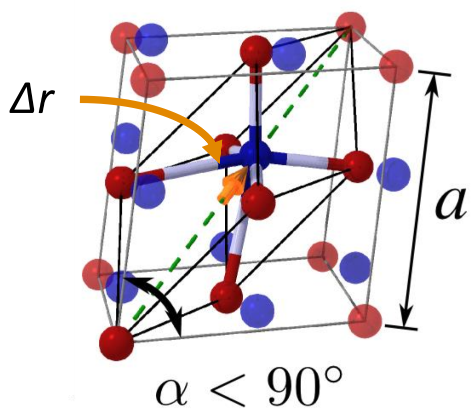
rhombohedral

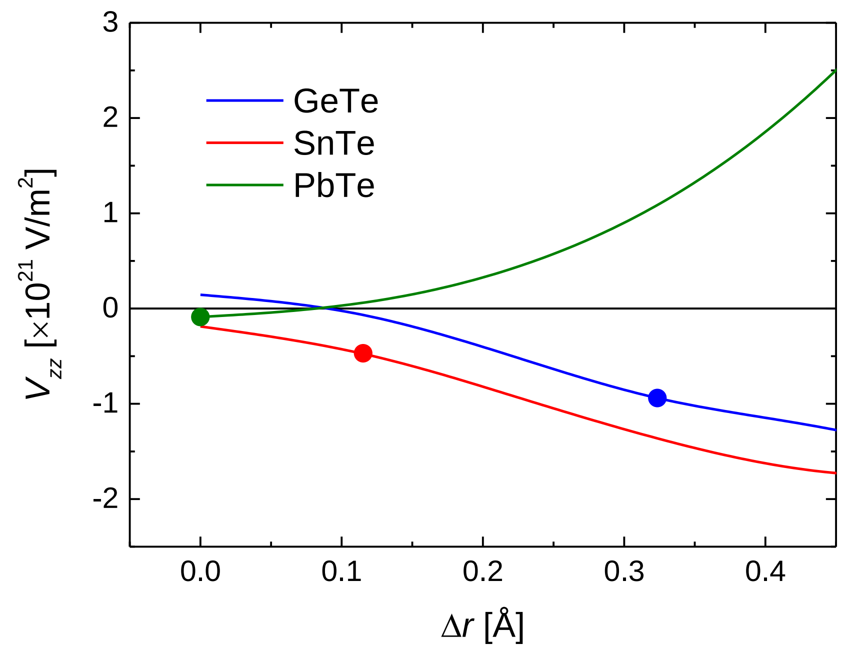




ferroelectric Rashba semiconductor (FERS)

…with hyperfine interactions (IS612 courtesy)





$$\omega_Q \text{ or } \Delta E_Q \propto Q\, V_{zz}$$

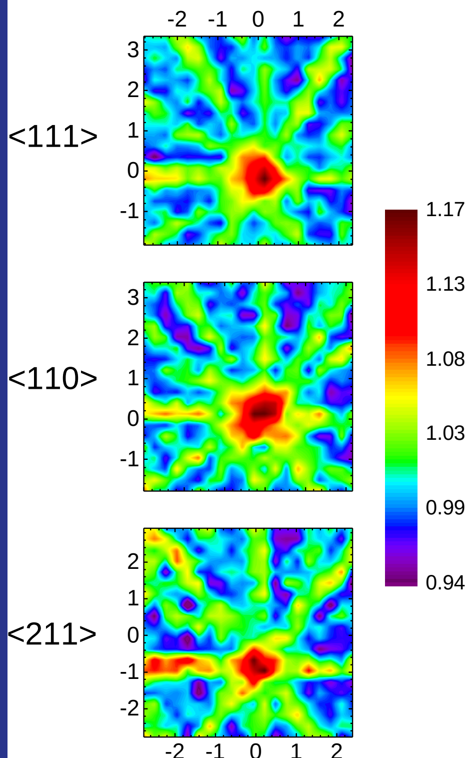
	technique	parent	$t_{1/2}$	Q [b]
Pb	PAC	^{204m}Pb	67 min	0.44
Sn	e-MS	^{119}In ^{119m}Sn	2.4 min 293 d	0.094
Ge	PAC	^{73}As	80 d	0.70

density functional theory calculations

to establish relation between measured HFI parameters and structural parameters

EC-SLI (IS580)
Emission Channeling with Short-Lived Isotopes (online)

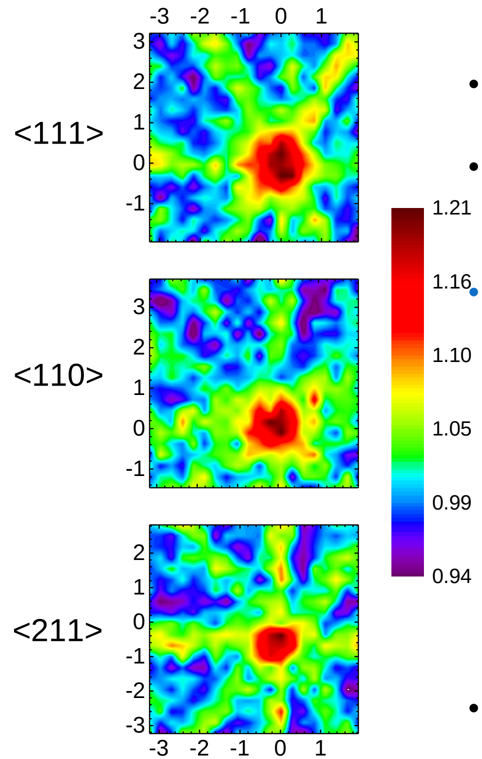
Successful emission channeling measurements on topological insulators



example spectra:
Mn-doped PbTe, implanted at 100 °C

^{56}Mn (2.6 h)

- Mn as magnetic dopant
- magnetic properties depend on Mn lattice site (e.g. substitutional *versus* intersititial)
- EC is used to determine the lattice location



example spectra:
Sn-doped PbTe, implanted at 200 °C

^{123}Sn (40 min)

- parent: ^{123}In
- *isotope used for first time for EC*
- doping with Sn induces a rhombohedral distortion; **the topological state** (e.g. topological insulator, Rashba semiconductor, or trivial) **depends on the magnitude of this distortion**
- EC is used to characterize the distortion

"For the greatest benefit to mankind"
Alfred Nobel

2016 NOBEL PRIZE IN PHYSICS
David J. Thouless
F. Duncan M. Haldane
J. Michael Kosterlitz

David J. Thouless

Prize share: 1/2

F. Duncan M. Haldane

Prize share: 1/4

J. Michael Kosterlitz

Prize share: 1/4

"for theoretical discoveries of topological phase transitions and topological phases of matter"

Source: "The Nobel Prize in Physics 2016". *Nobelprize.org.* Nobel Media AB 2014. Web. 4 Dec 2016. <http://www.nobelprize.org/nobel_prizes/physics/laureates/2016/>

Acknowledgements

BMBF

Bundesministerium für Bildung und Forschung

Erforschung kondensierter Materie mit Großgeräten

Ausbau und Unterhalt der Einrichtungen an ISOLDE/CERN

Germany, contracts: 05K13TSA, 05K16PGA

M. Deicher, D. Lupascu, J. Schell

ISOLDE Solid State Physics

SPONSORED BY THE

Federal Ministry of Education and Research

FCT

Fundação para a Ciência e a Tecnologia

Caracterização de Materiais com Técnicas Nucleares Radioativas - sinergia e complementaridade aplicadas ao treino e desenvolvimento.

Portugal, Project: CERN-FIS-NUC-0004-2015

J.G. Martins Correia

FCT Fundação para a Ciência e a Tecnologia

MINISTÉRIO DA CIÊNCIA E DA TECNOLOGIA

KU-Leuven

Katholieke Universiteit Leuven

Lino Pereira

KATHOLIEKE UNIVERSITEIT LEUVEN

Acknowledgements

Thank you very much for your attention!

... to colleagues and collaborators!

Specially the SSP in-house group!