Spicing up solid state physics with radioactive isotopes: recent highlights from ISOLDE

Karl Johnston, CERN

Xth tastes of physics 2020

- Introduction to some aspects of solid state physics
- Why use radioactive isotopes?
- Techniques
- Examples of recent results

Thanks to Juliana Schell, Guilherme Correia, Georg Marschick and all groups in SSP@ISOLDE

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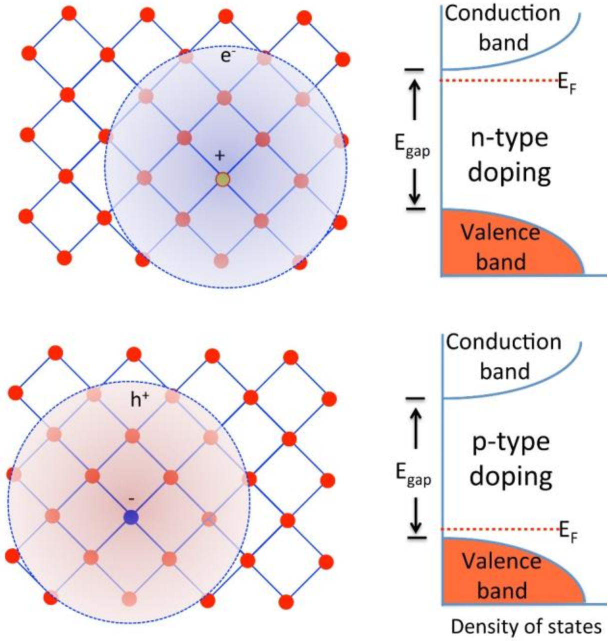
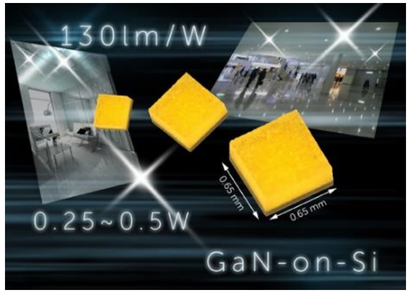
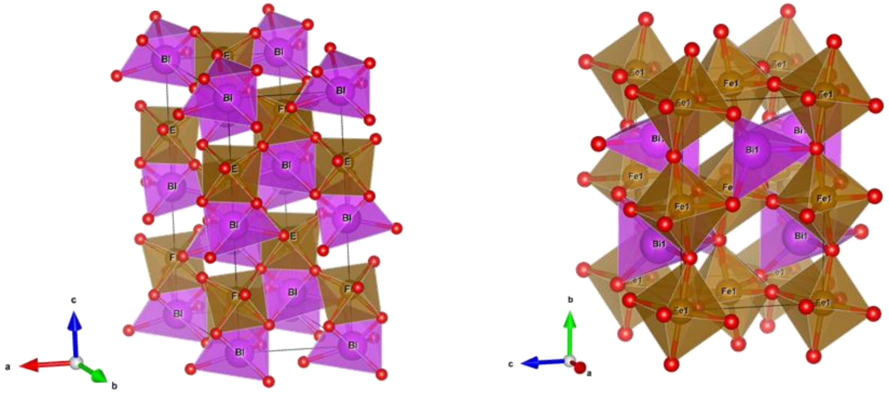
Some aspects of solid state physics





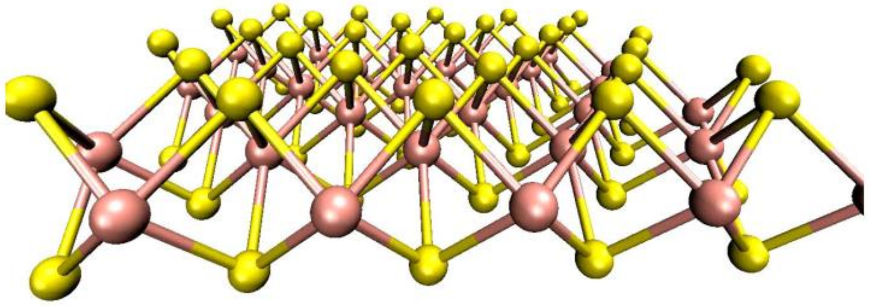
Doping in semiconductors

What causes doping (element, or defect)?
Where does it sit in the lattice?



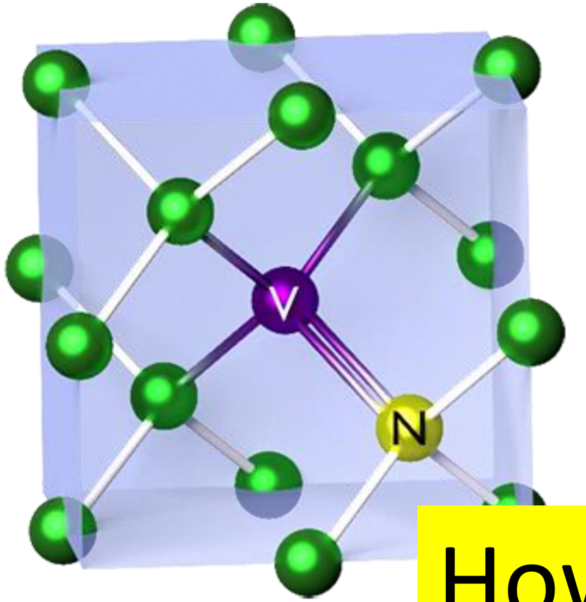
Multiferroics e.g. BiFeO3

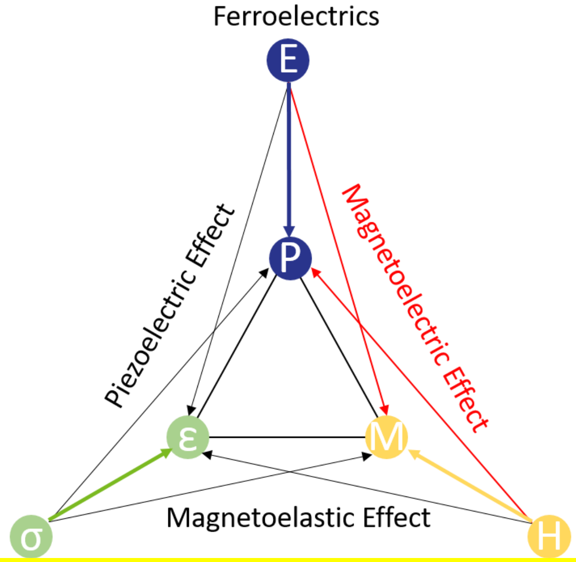
What form of material produces a particular effect?

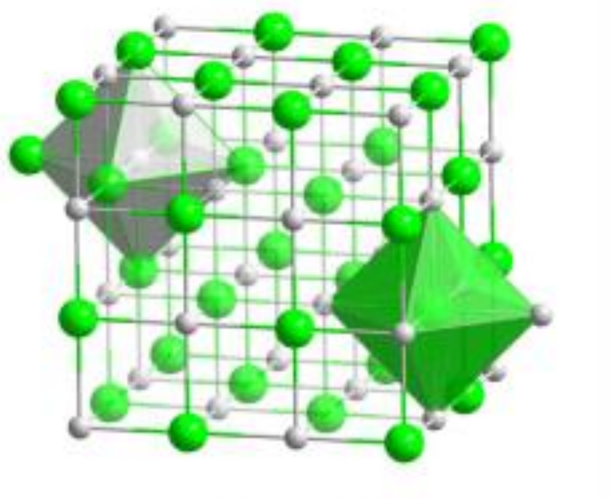


Surface studies of low dimensional materials…

Current “hot” topics





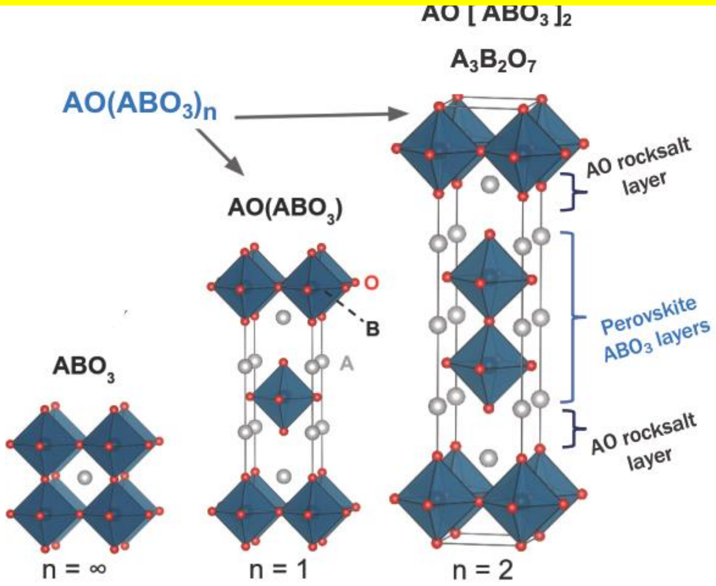


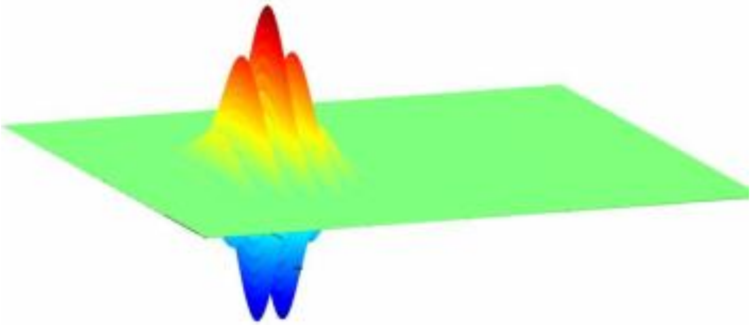
How can radioactive ion beams help?

K

Defect … mond

Quantum bits:
control and application

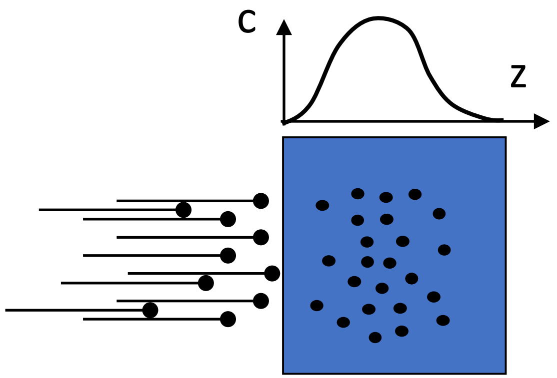


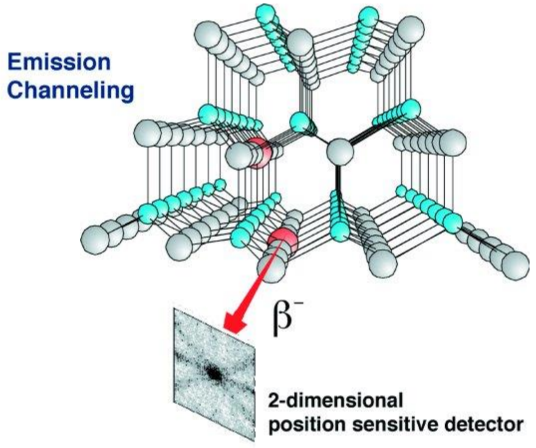


Spin or superconducting fluctuations

Unique features of radioactive probe atoms for SSP applications

- **Chemically selective and isotope specific**
- **Extremely good detection limit**
  - among the most sensitive methods, no reaction cross section limitation
    - 10^{15} - 10^{18} probes/cm^3
    - 10^{11} - 10^{12} probe atoms
- **Depth distribution and concentration control**
  - Ion energy and ion fluence control
  - Circumventing solubility and diffusion limits
- **Highly local Information**
  - Nucleus-size sensors for **local** magnetic and electric fields
    Electric Field Gradient ~ r^{-3}
    Emission channeling: ~ 0.02 nm position resolution



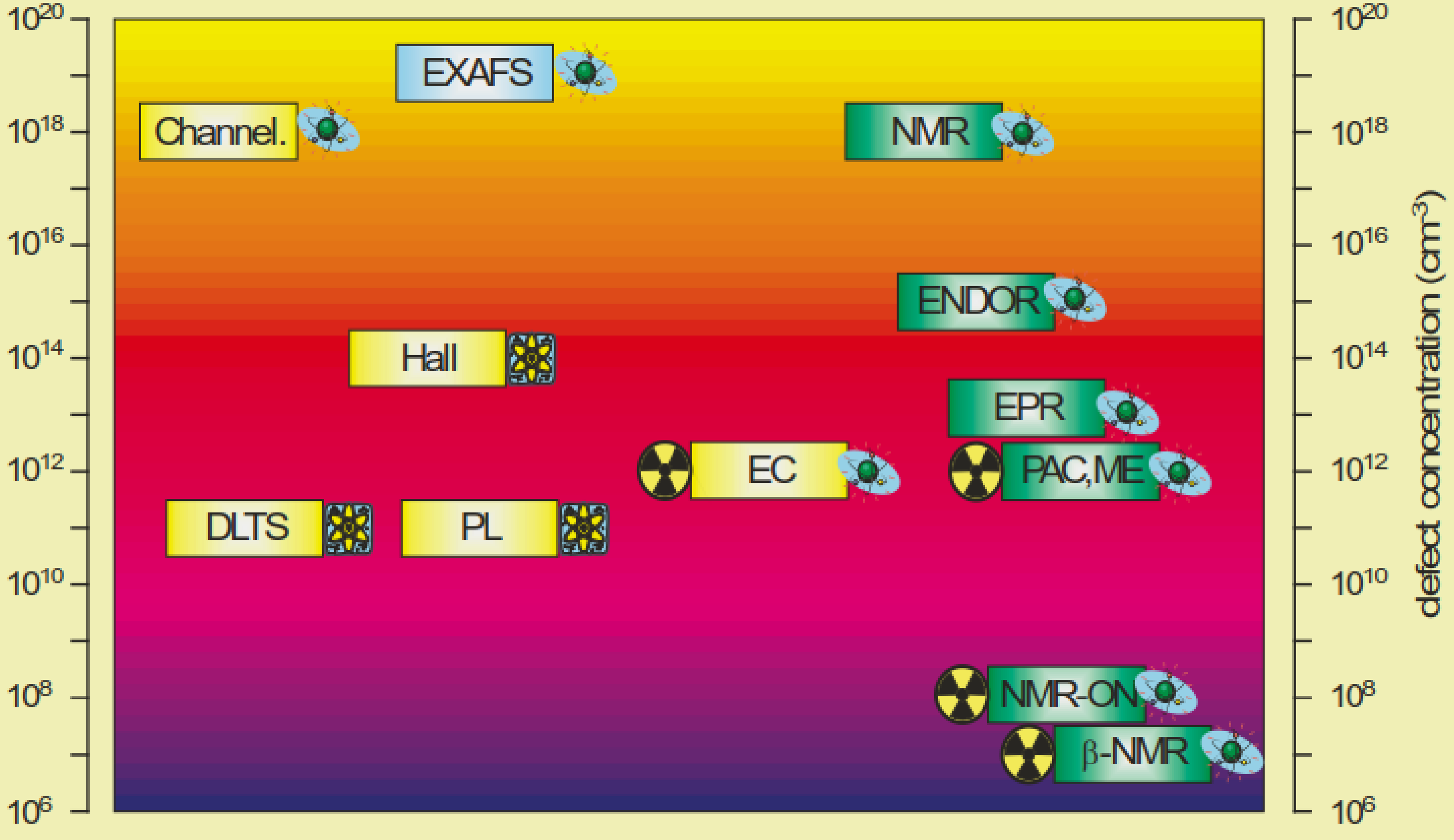


Why radioactive probes ? Sensitive – Selective - Controllable – Local
Often relatively easy isotopes for RIB facilities to produce (not always a good thing…)

Semiconductor Spectroscopy

sensitive to chemical nature or electronic properties

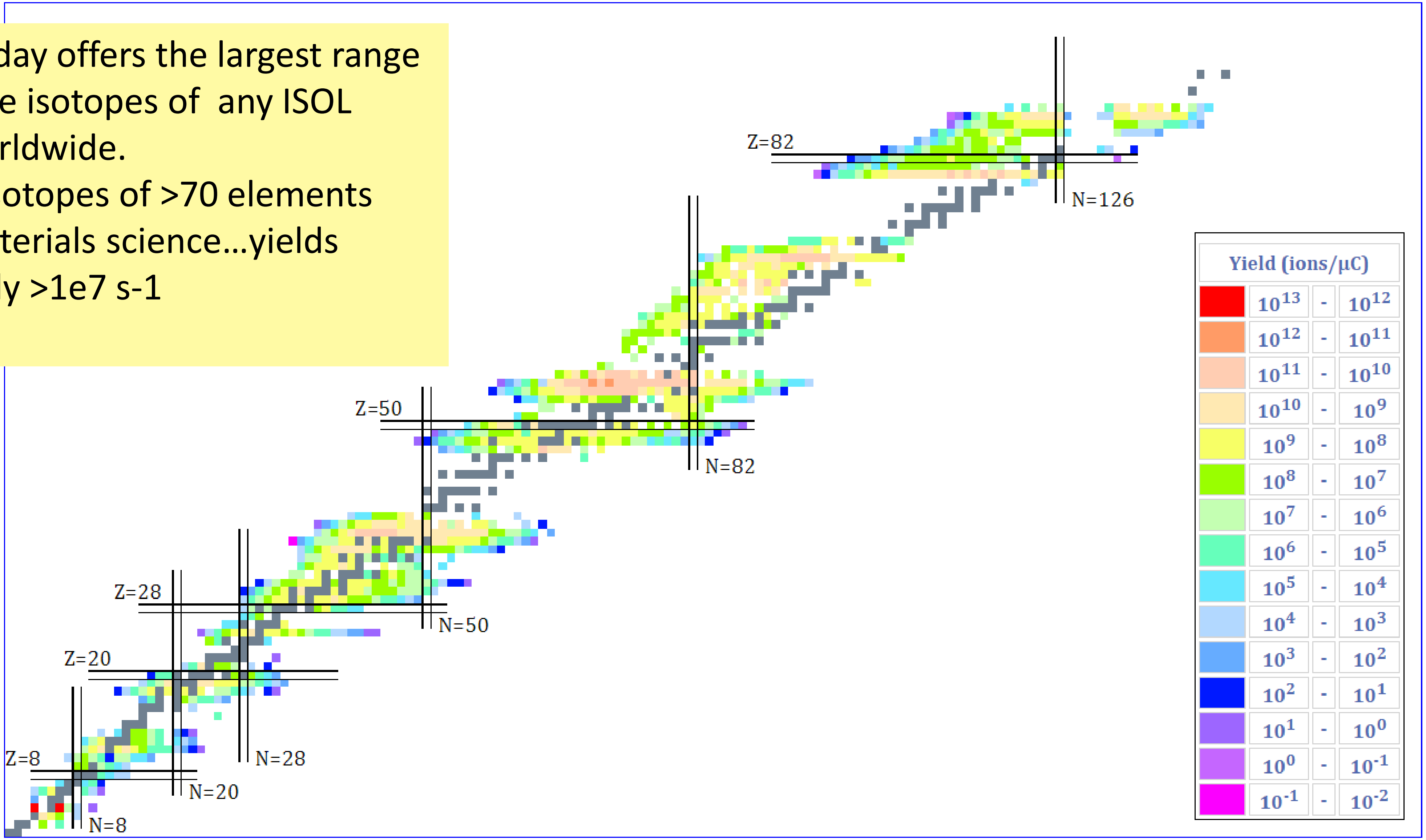
(some require radioactive istopes)



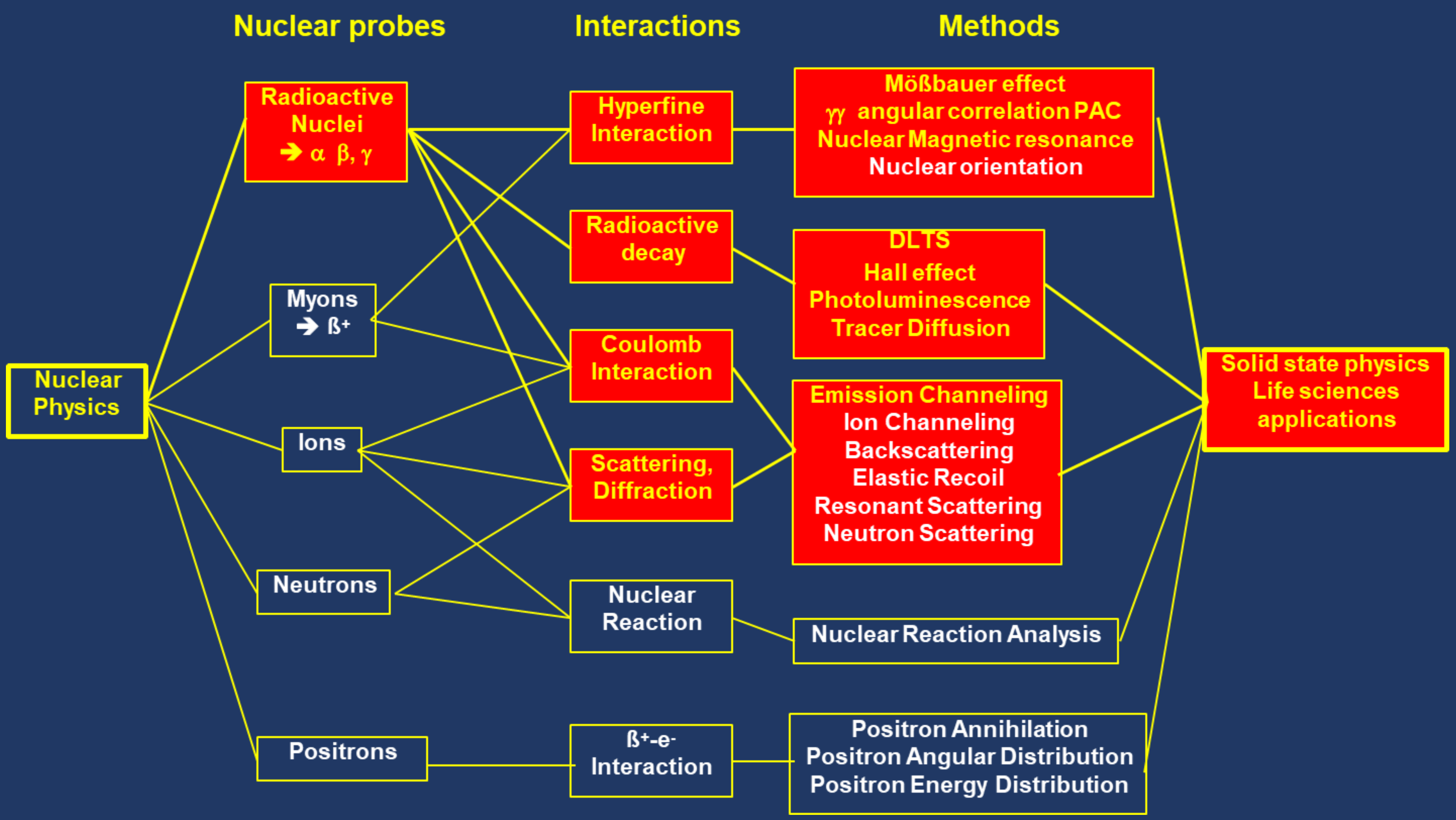
Nuclear chart for ISOLDE

ISOLDE today offers the largest range of available isotopes of any ISOL facility worldwide.

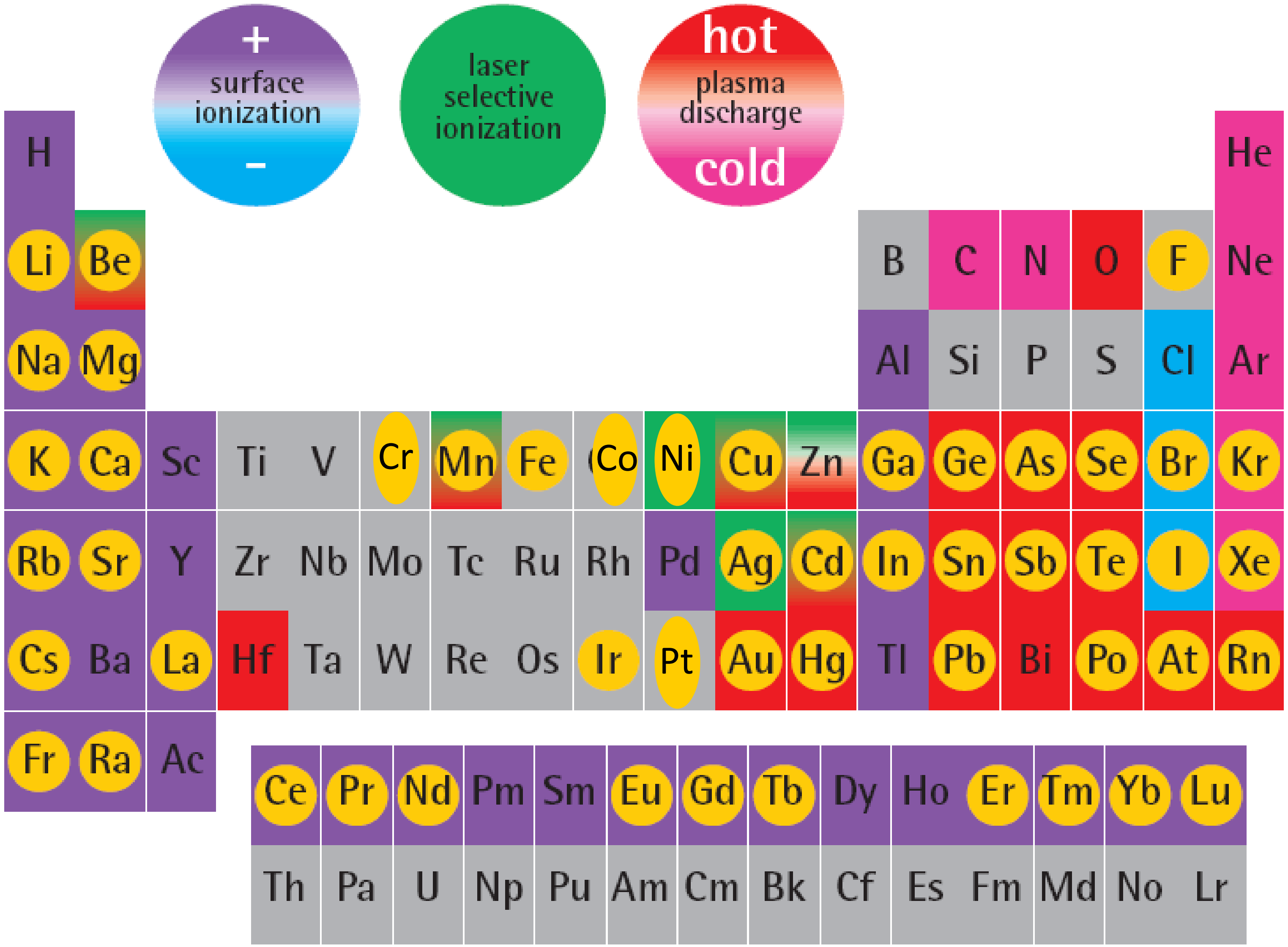
- 1000 isotopes of >70 elements
- For materials science…yields typically >1e7 s-1



Applying radioactivity to solid state physics/biophysics



ISOLDE table of elements



Workhorse probes:

^{111}Cd, ^{199}Hg, ^{117}Cd, ^{57}Mn, ^{73}As

New promising probes:

^{68}Cu, ^{149}Gd, ^{172}Lu, ^{151}Gd, ^{197}Hg

Isotopes of this element used for solid state physics or life science

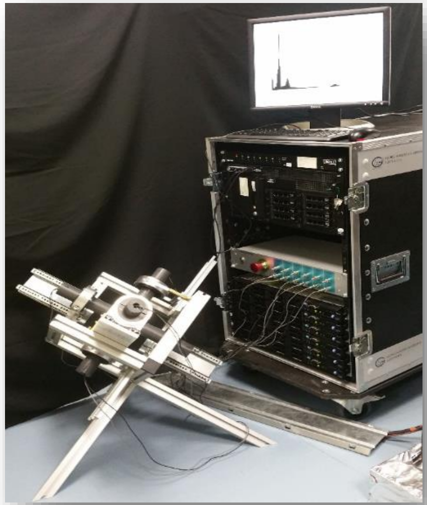
Solid state demands have been a driver in the development of new beams at ISOLDE

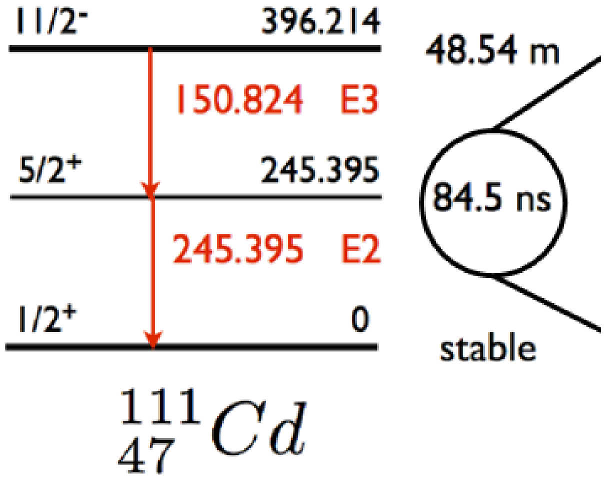
Overview of techniques for «applied» nuclear physics I: local probes/channelling

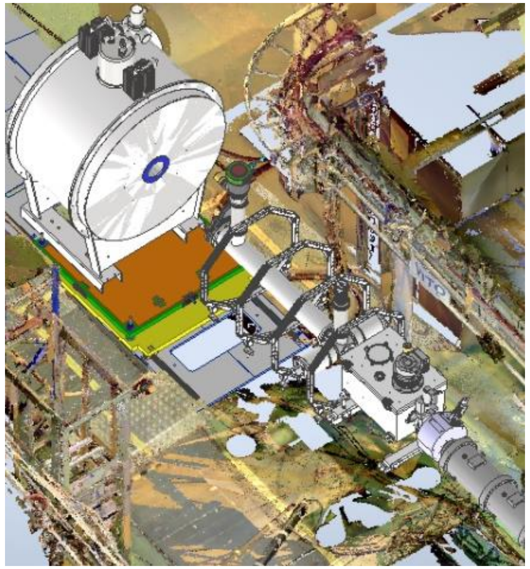
Perturbed angular correlation

Mossbauer effect

Beta-NMR





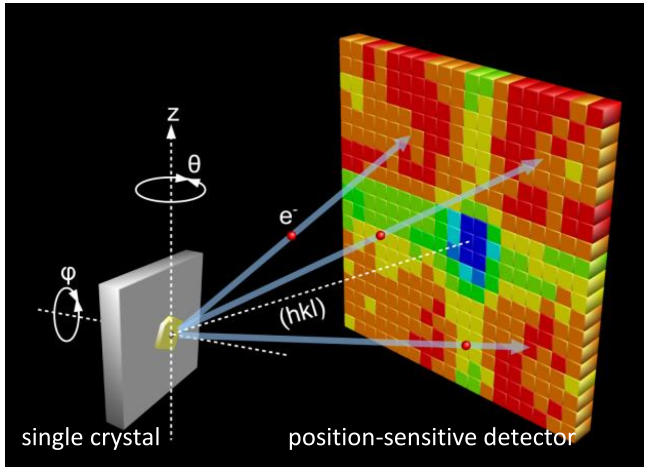


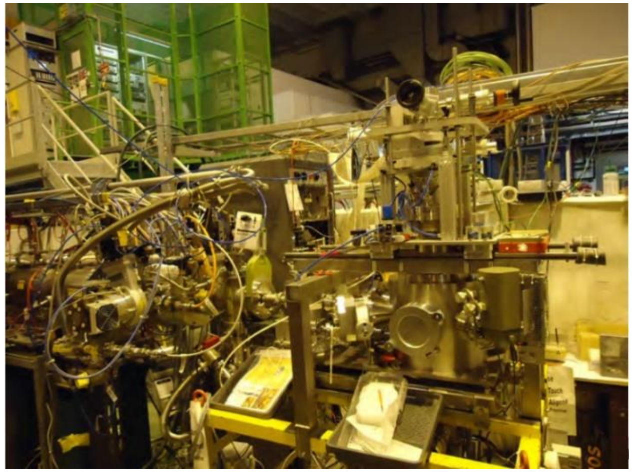
Very sensitive probes to the local environment of a material/protein etc, **magnetic interactions**, dynamical processes. Very intense (and often unique) beams available at ISOLDE

Emission channelling:

Almost unique to ISOLDE. 4 orders of magnitude more sensitive than RBS.

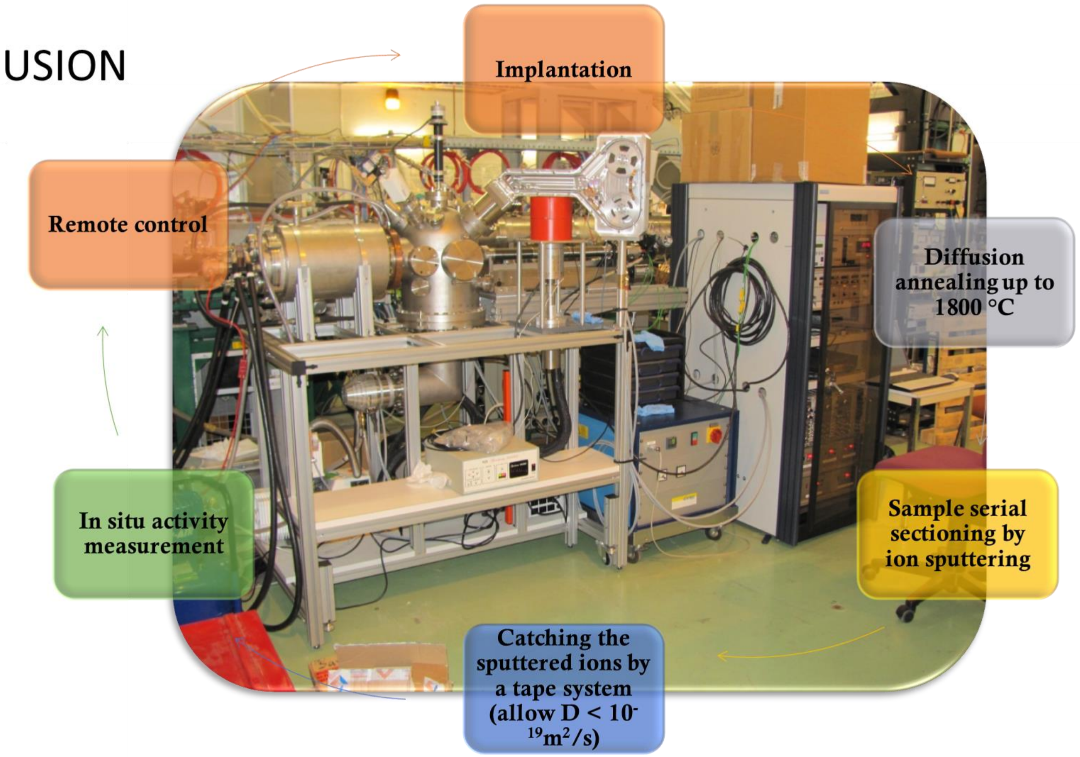
Ability to utilise low concentrations to determine position: increasingly important…





Overview of techniques for «applied» nuclear physics II: Tracer methods

DIFFUSION



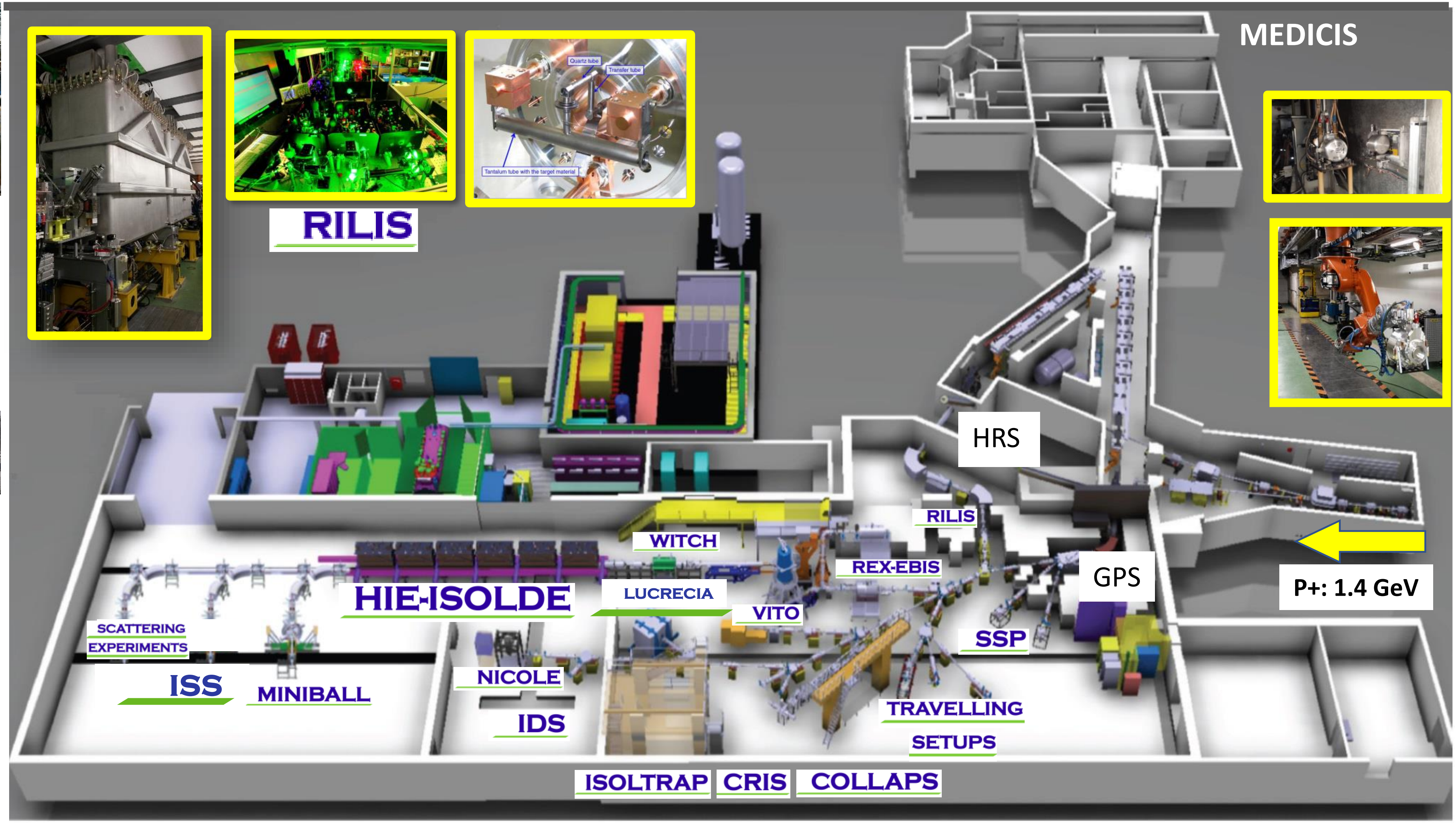
Photoluminescence spectroscopy

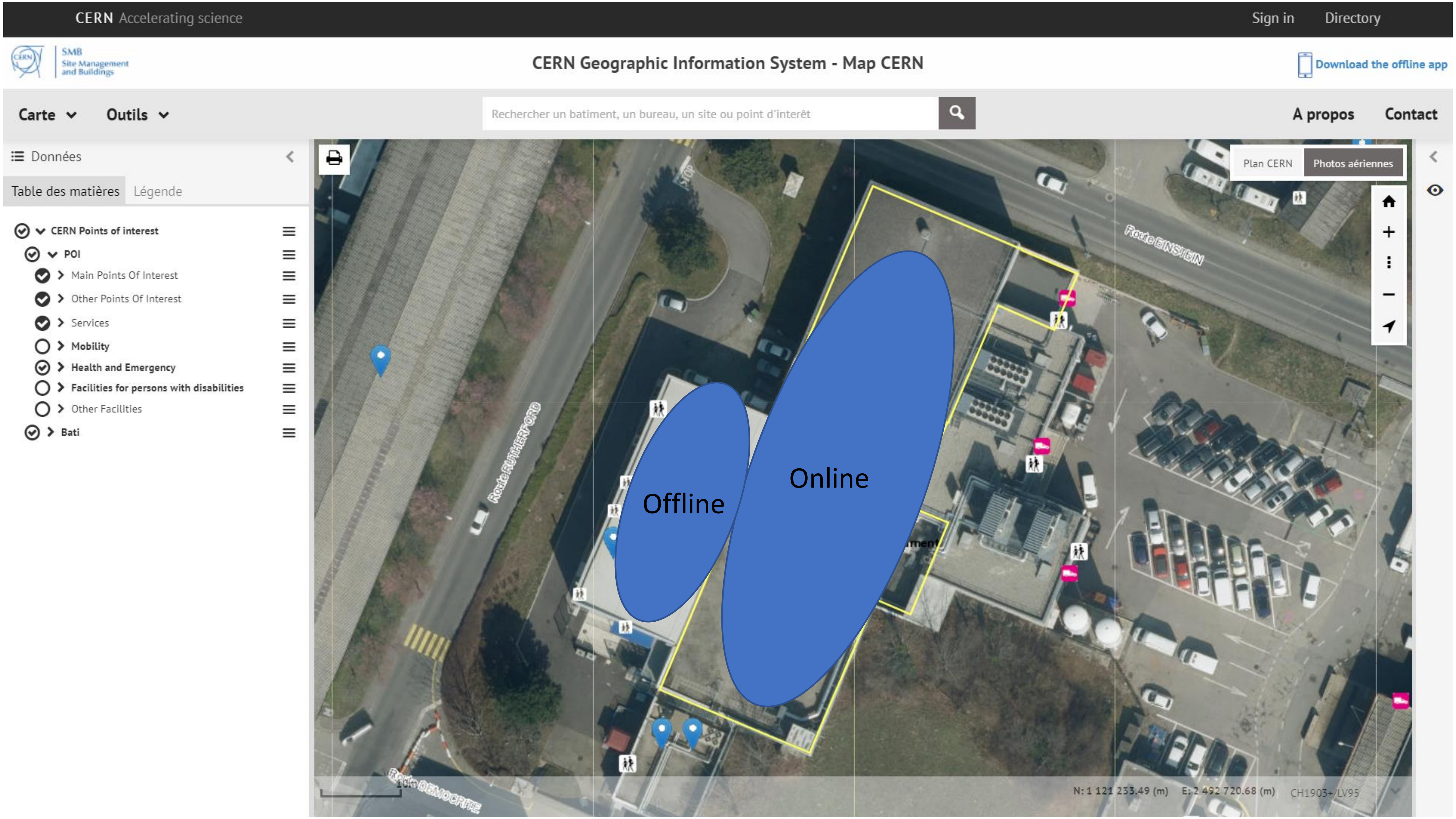
Most general approach….tracking half-life of implanted isotopes or their daughters

Can be applied to almost any «typical» laboratory technique: offers unique sensitivity

ISOLDE

Belgium | CERN | Denmark | Spain | Finland | France | Germany | Greece | Italy | Norway | Romania | Sweden | S. Africa | Slovakia | U. Kingdom | Poland

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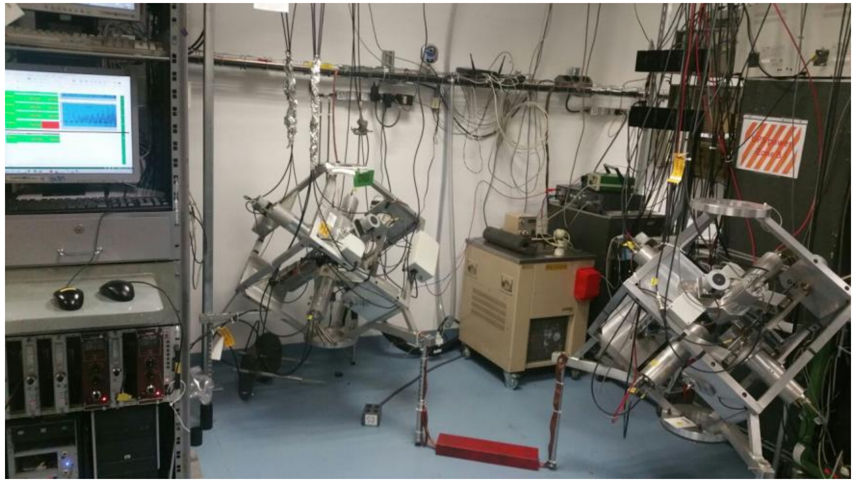
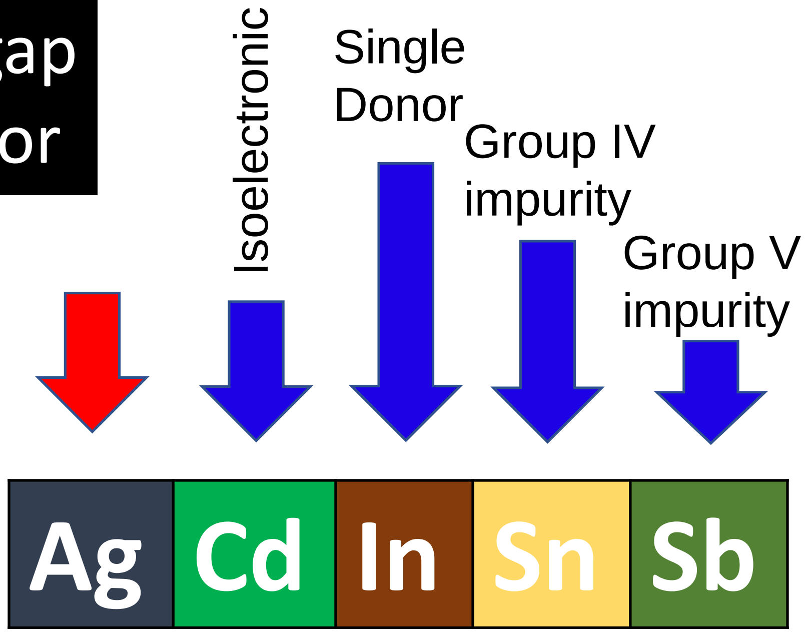
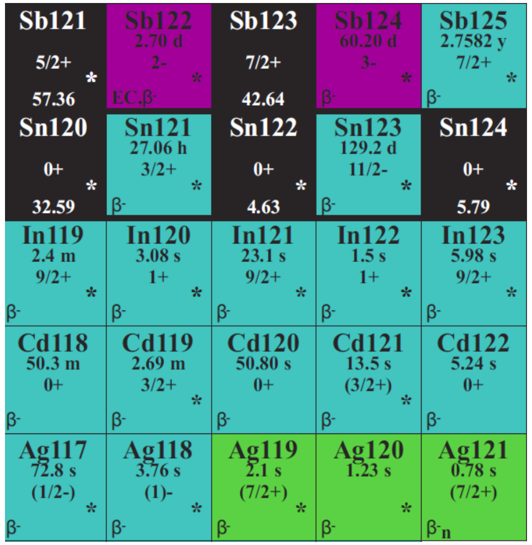
Offline labs at ISOLDE: chemistry; spectroscopy; characterisation

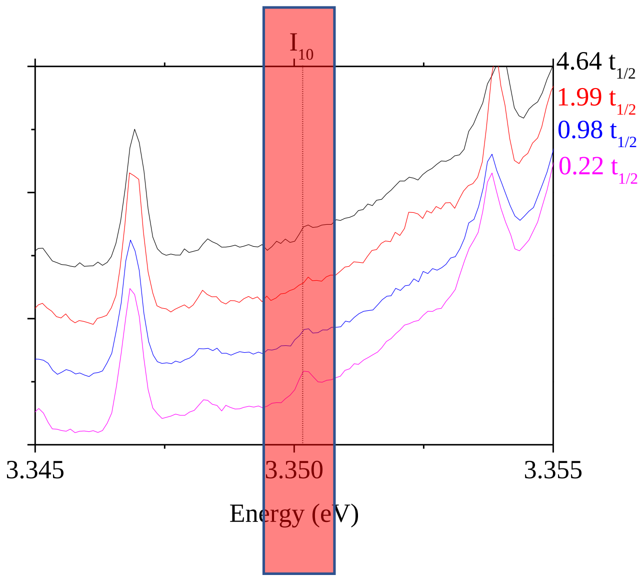


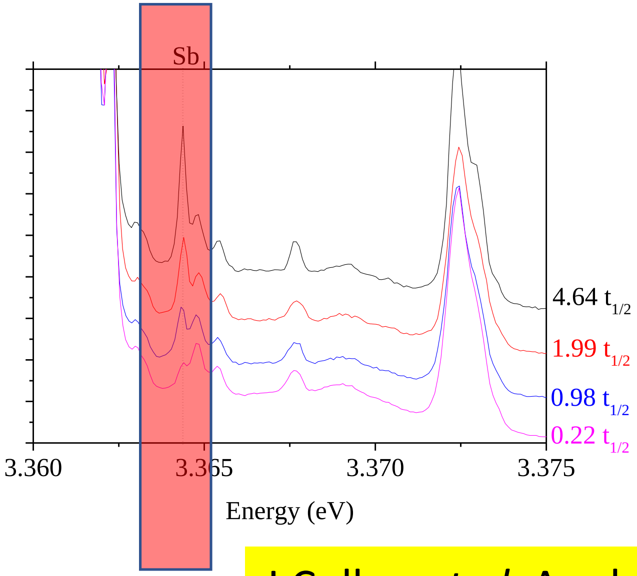
ZnO: wide band gap semiconductor

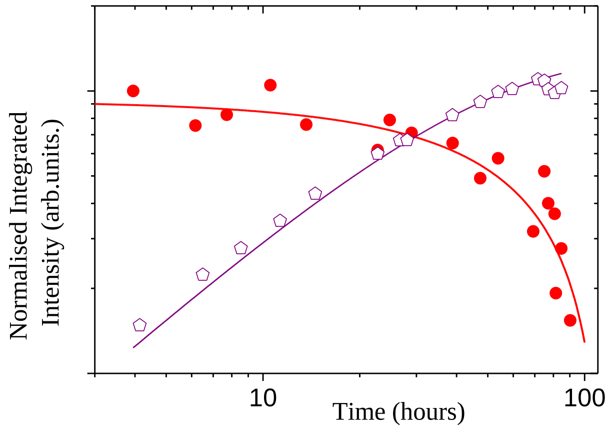
Radiotracer PL











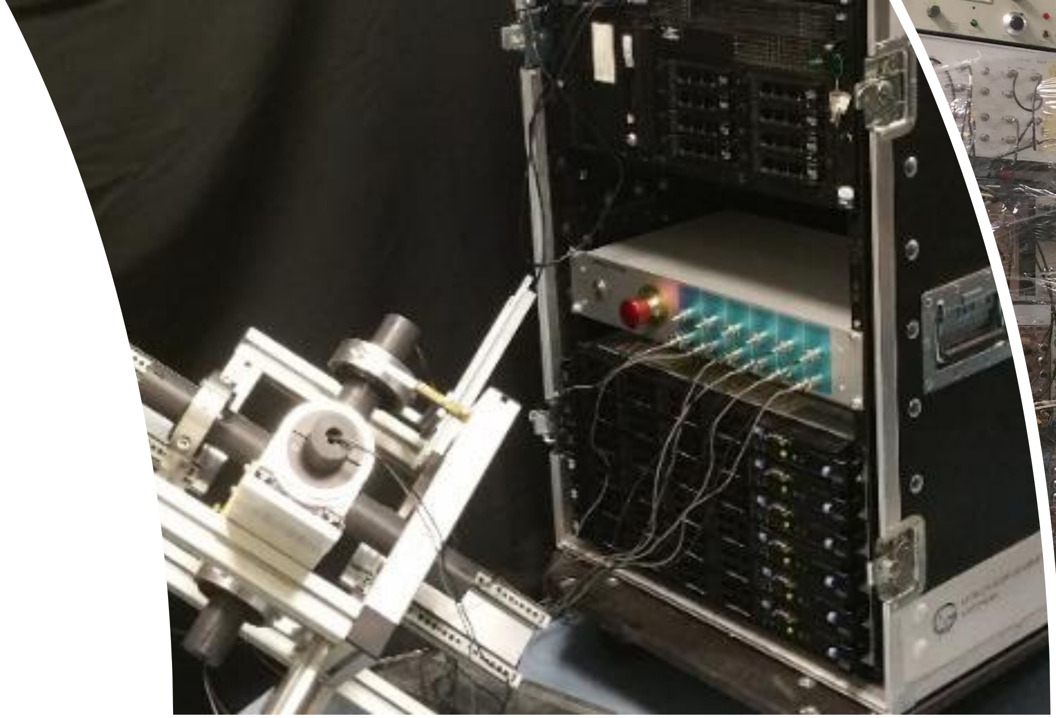
J Cullen *et al* Appl. Phys. Lett. **102** 192110 (2013)

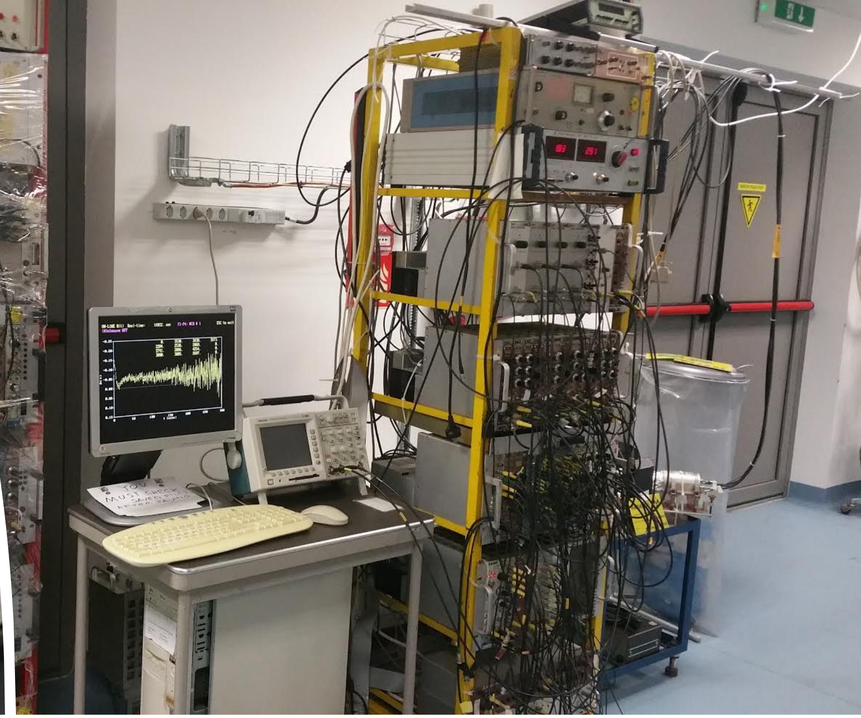
Perturbed angular correlation @ ISOLDE

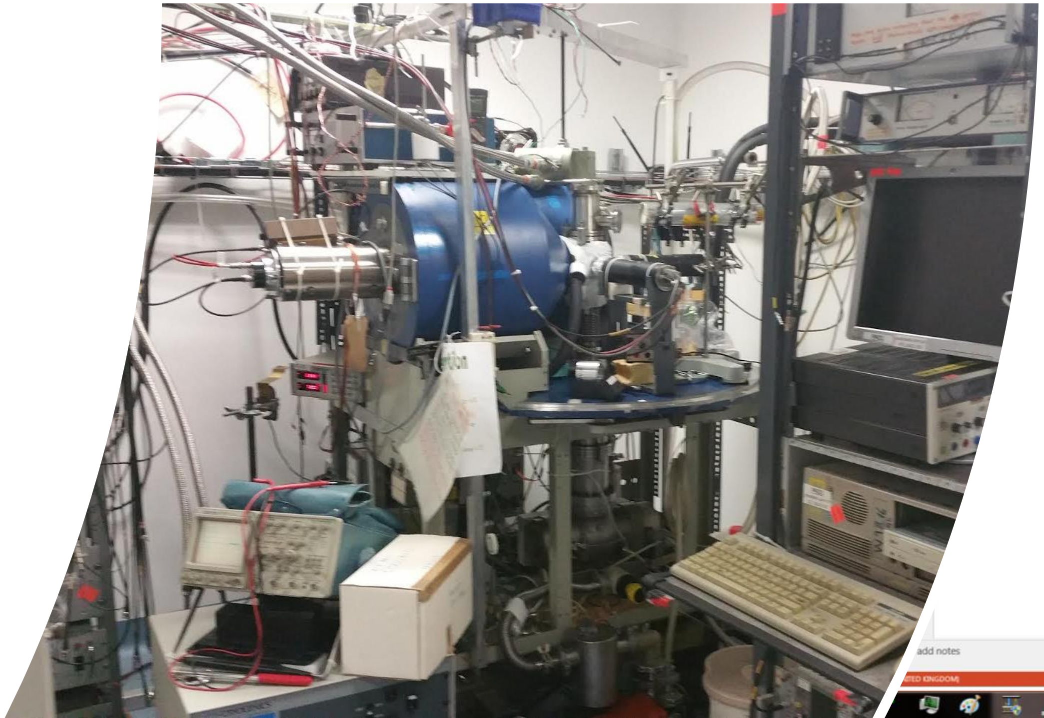
- Most established technique at ISOLDE: benefitting from upgrade of spectrometers in recent years and improved relation to theory.

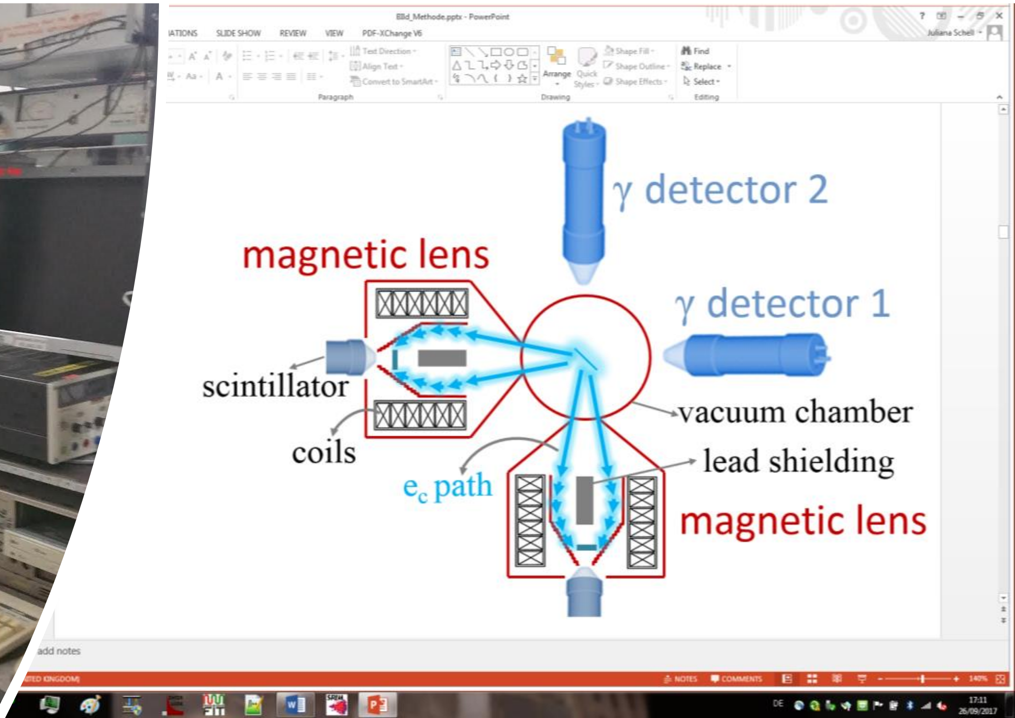
- Electron gamma unique to ISOLDE.

- Range of novel isotopes also only useable at ISOLDE: allows for varied programme in materials physics, biophysics and beyond

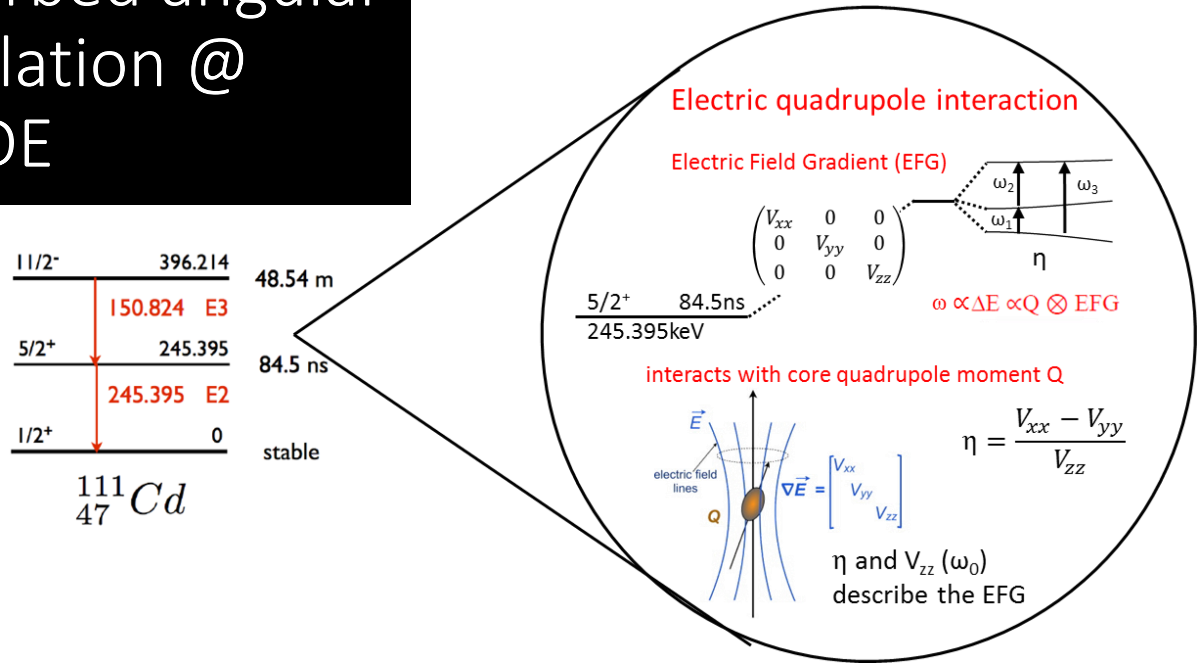


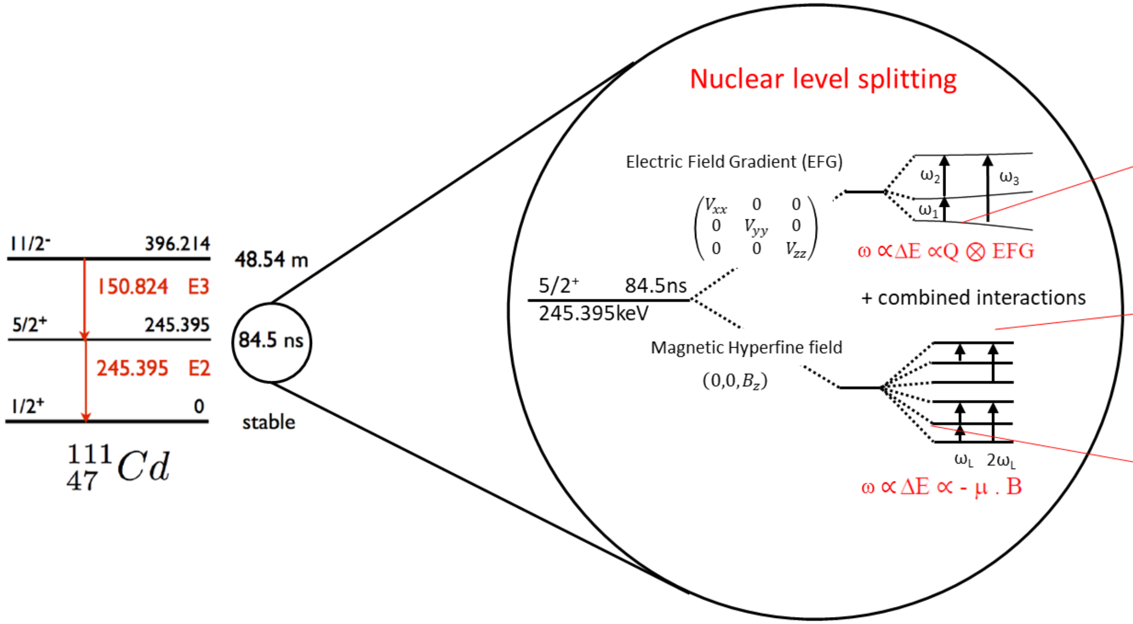


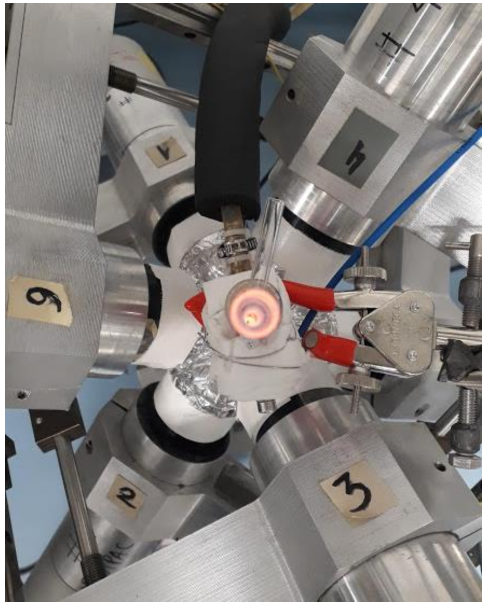


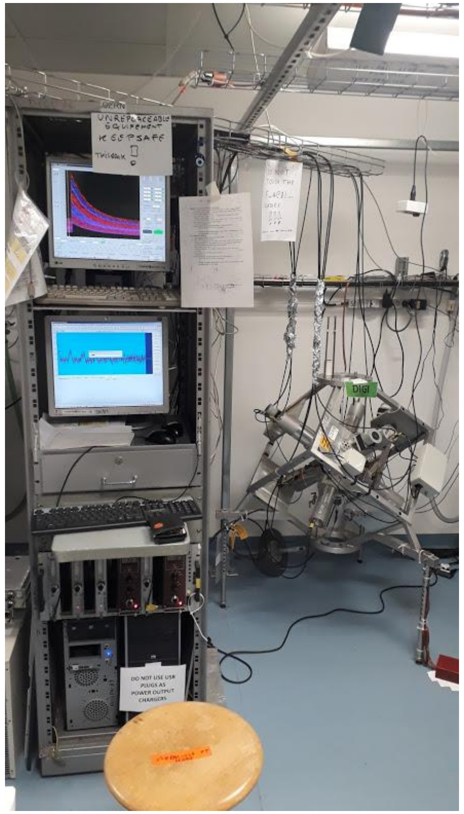


Perturbed angular correlation @ ISOLDE



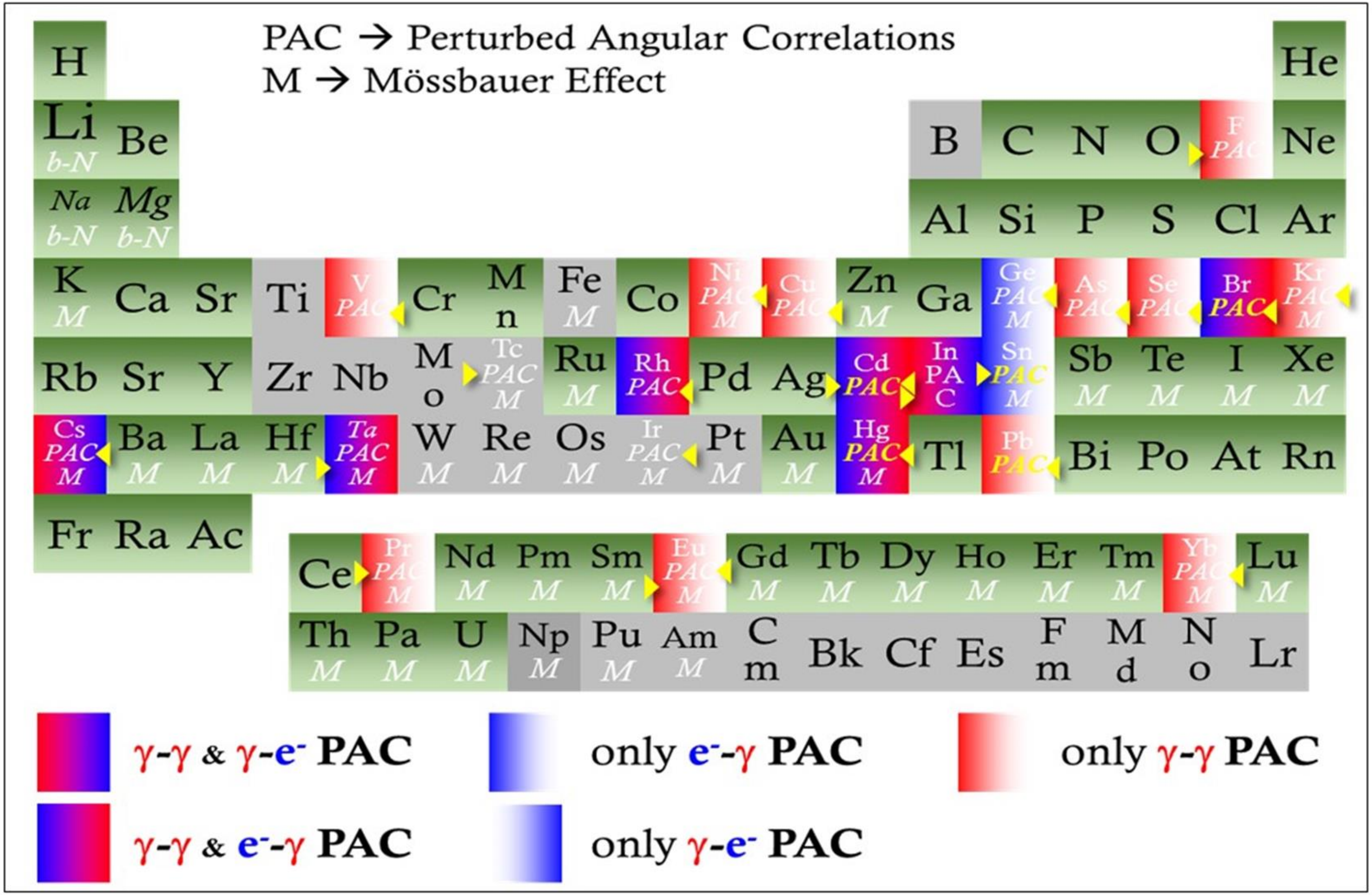






PAC: not sensitive to chemical shift, but more flexible than Mossbauer for temperature and environment in which can be measured.

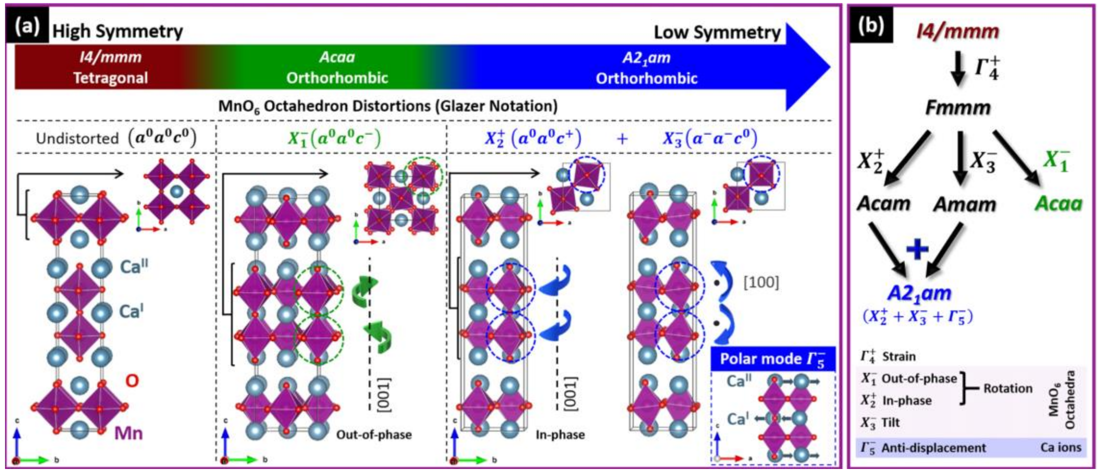
New setups to measure in magnetic field and for surface science on horizon

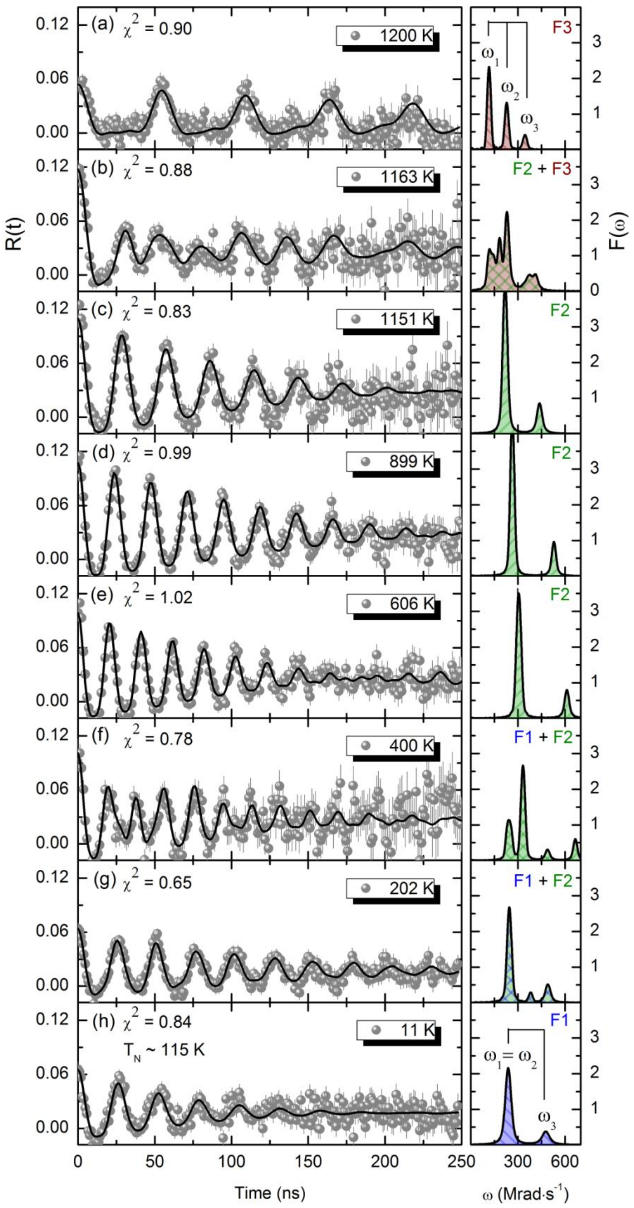


PAC → Perturbed Angular Correlations
M → Mössbauer Effect
H He
Li b-N Be B C N O F PAC Ne
Na b-N Mg b-N Al Si P S Cl Ar
K M Ca Sr Ti V PAC Cr Mn Fe M Co Ni PAC M Cu PAC Zn M Ga Ge PAC M As PAC Se PAC Br PAC Kr PAC M
Rb Sr Y Zr Nb Mo Tc PAC M Ru M Rh PAC Pd Ag Cd PAC In PAC Sn PAC M Sb M Te M I M Xe M
Cs PAC M Ba M La M Hf M Ta PAC M W M Re M Os M Ir PAC M Pt M Au M Hg PAC M Tl Pb PAC Bi Po At Rn
Fr Ra Ac
Ce Pr PAC M Nd M Pm M Sm M Eu PAC M Gd M Tb M Dy M Ho M Er M Tm M Yb PAC M Lu M
Th M Pa M U M Np M Pu M Am M Cm Bk Cf Es Fm Md No Lr
γ-γ & γ-e⁻ PAC
only e⁻-γ PAC
only γ-γ PAC
γ-γ & e⁻-γ PAC
only γ-e⁻ PAC

PAC: hyperfine studies of multiferroics

$Ca_3Mn_2O_7$ structural path unraveled by atomic-scale properties: A combined experimental and *ab initio* study





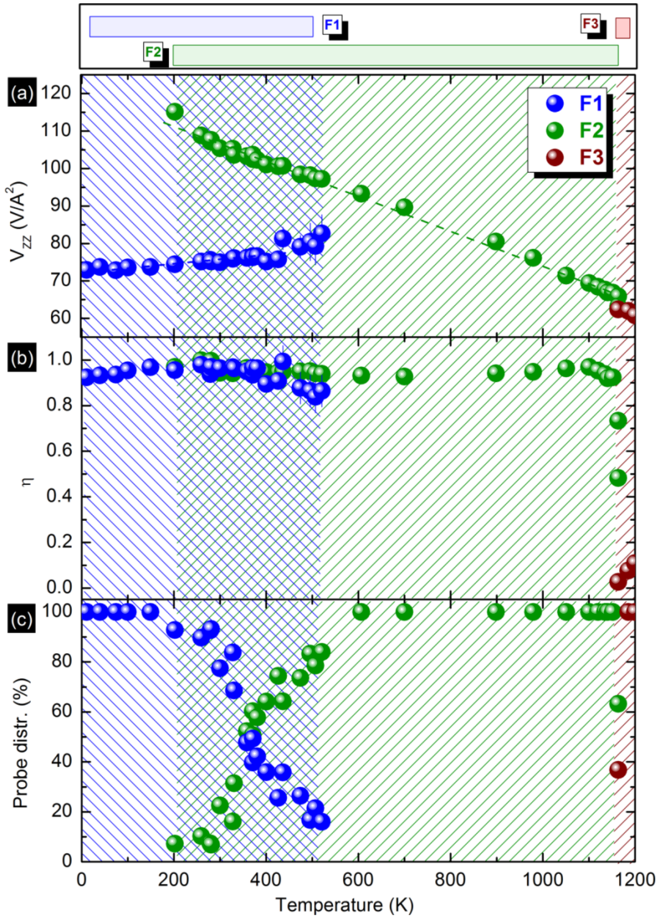


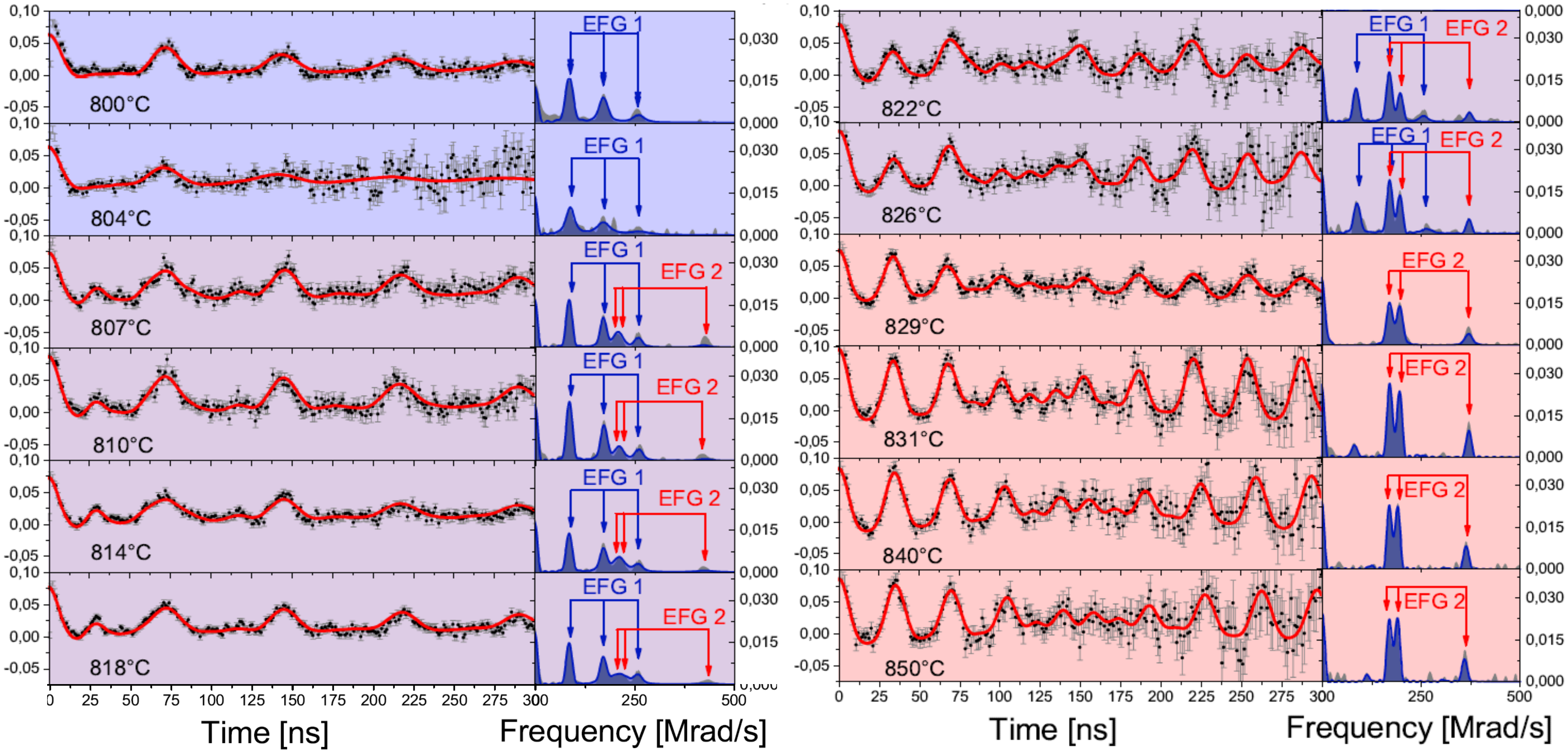
FIG. 3. Experimental EFG tensor at ^{111}Cd probe for the $Ca_3Mn_2O_7$ sample. (a) Principal component $|V_{zz}|$; (b) asymmetry parameter η; (c) probe distribution. The dashed lines are a guide for the eyes.

PHYSICAL REVIEW B **101**, 064103 (2020)

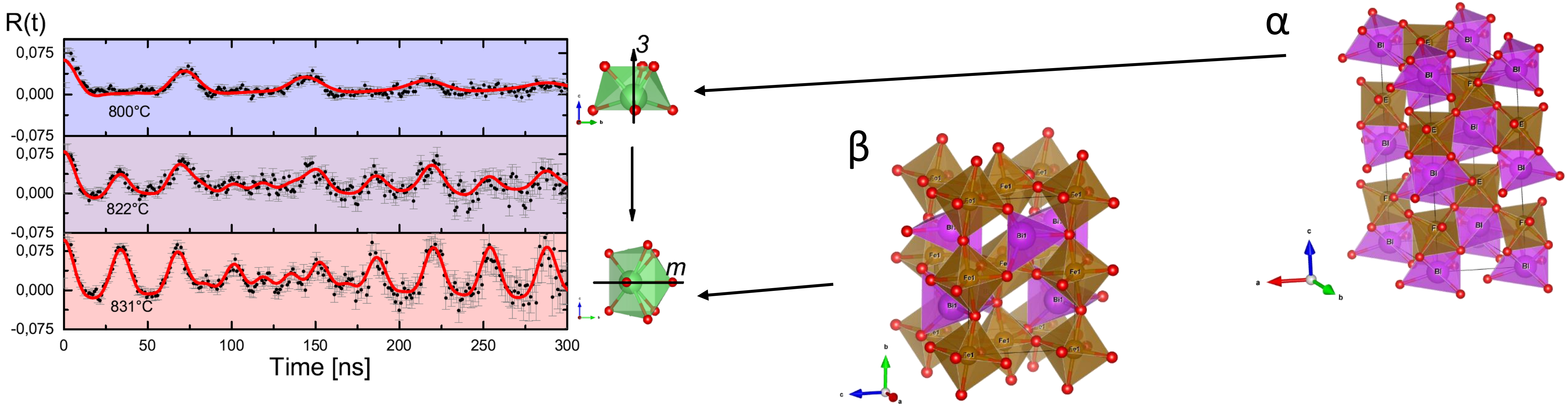
Probing multiferroic materials with PAC on the atomic scale: revealing the atomic changes behind the transitions from polar to ferroelectric behaviour

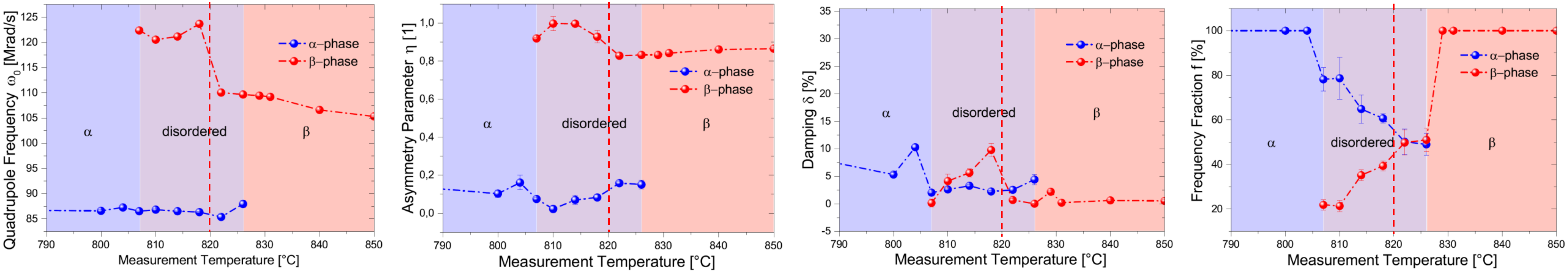
Persistence of polar – phase clusters up to 500C

Results in BiFe03



Results in BiFe03

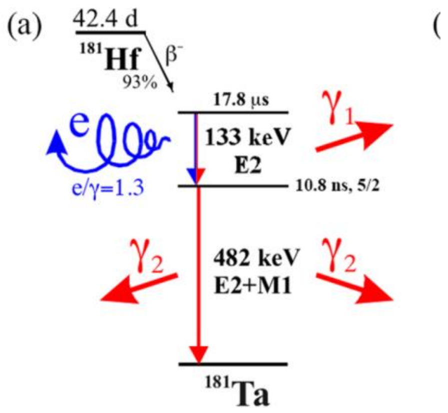


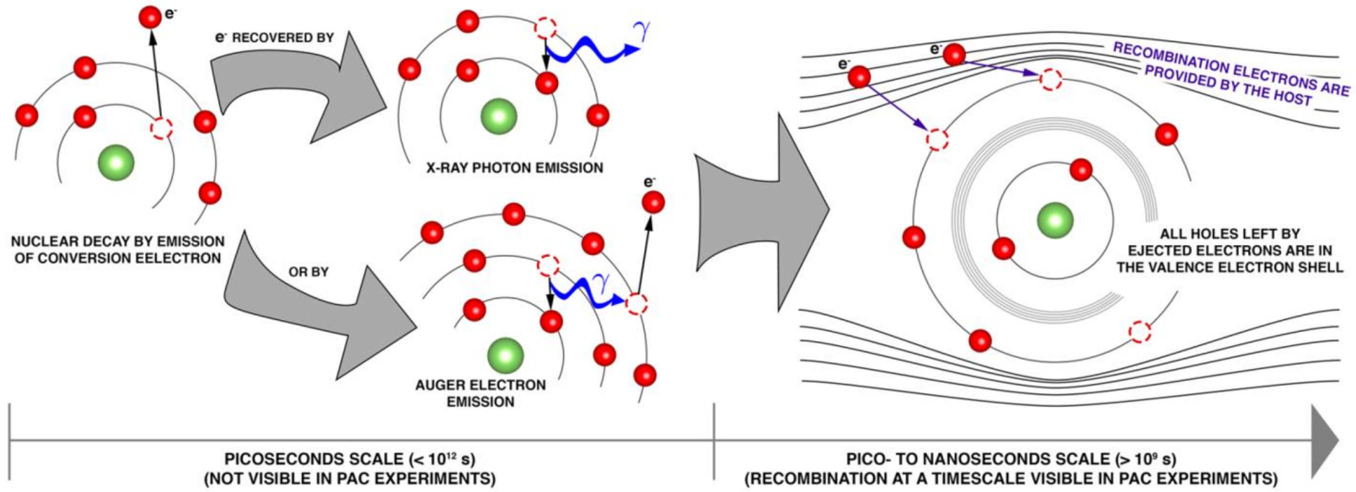


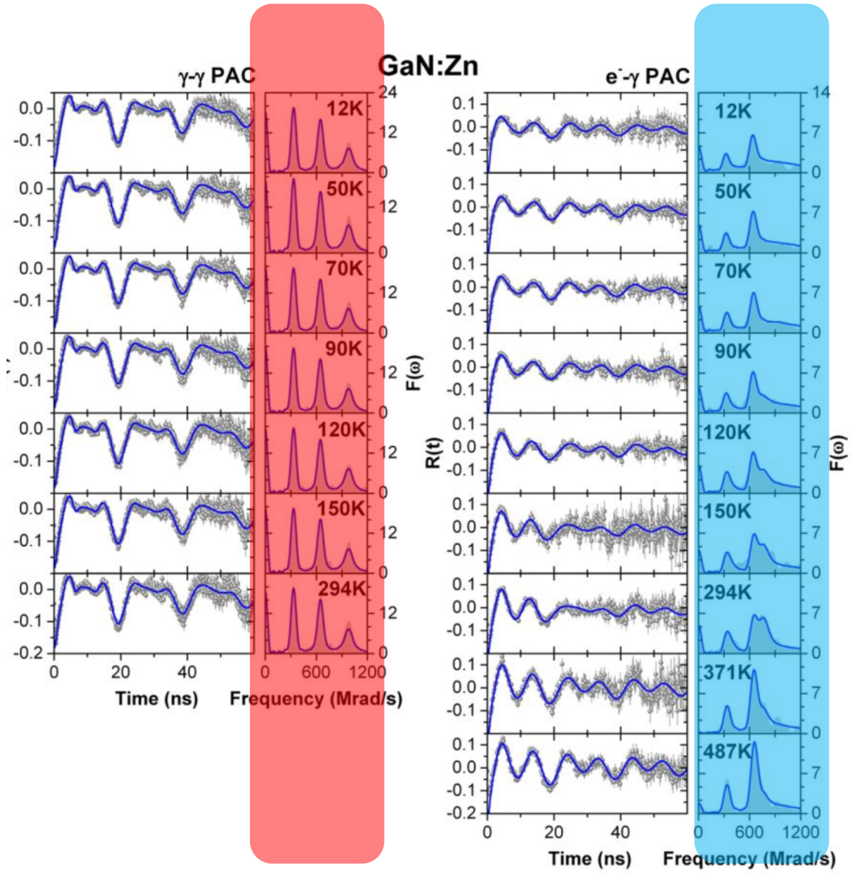
phase transition from rhombohedral α-BFO in *R3c* setting to orthorhombic β-BFO with its *Pbnm* space group at 820°C

γ-γ and e—γ PAC: hyperfine studies of semiconductors

Studying electronic properties in GaN without electrical contacts using γ-γ vs e^{-}-γ Perturbed Angular Correlations



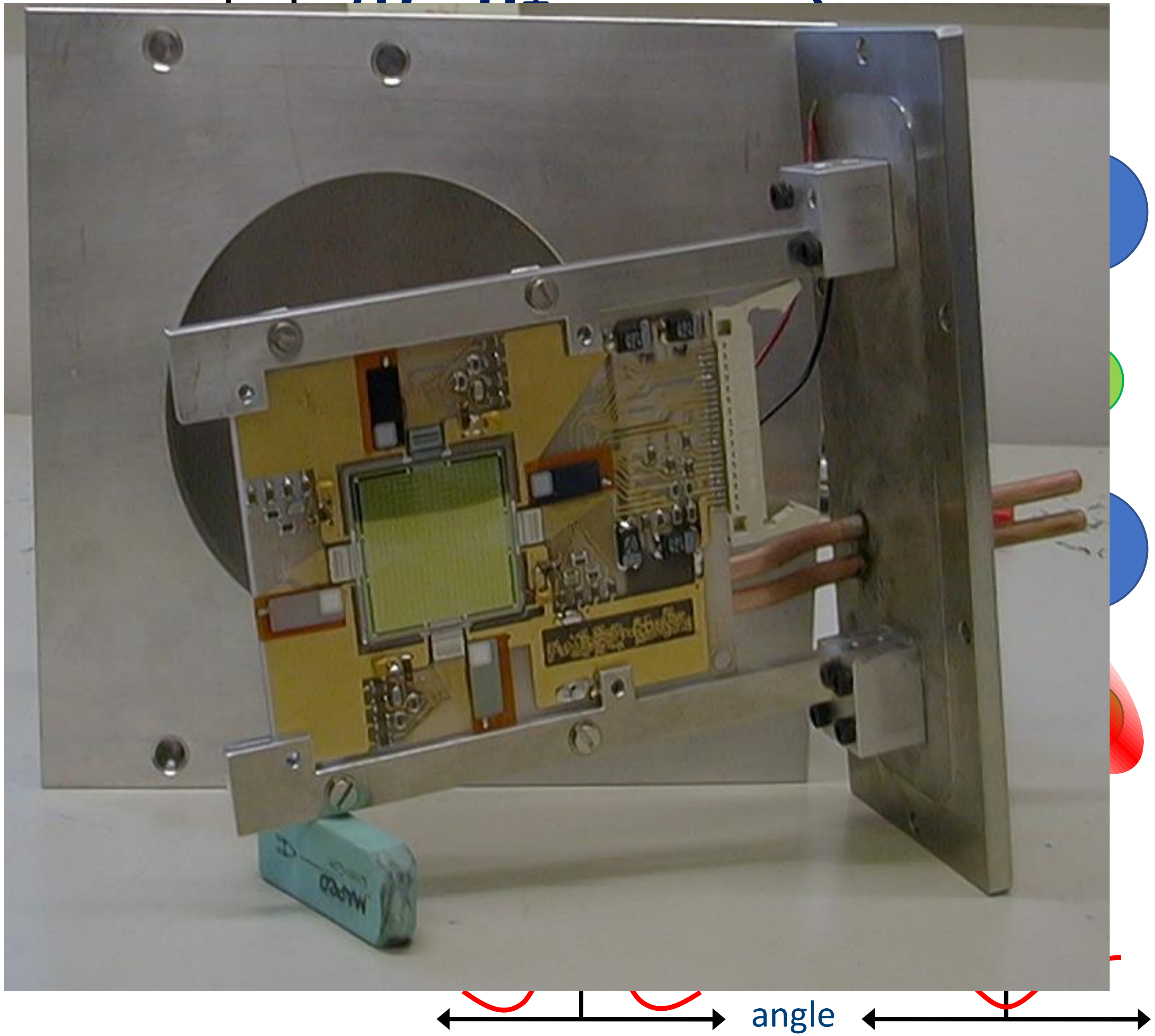




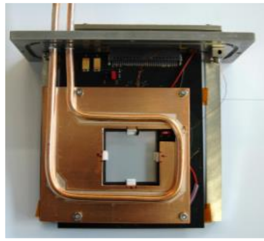
PAC revealing bulk properties of Si and Zn-doped Ga using γ-γ and e- - γ PAC identifiation of double donor

SCIENTIFIC REPORTS | (2019) 9:15734

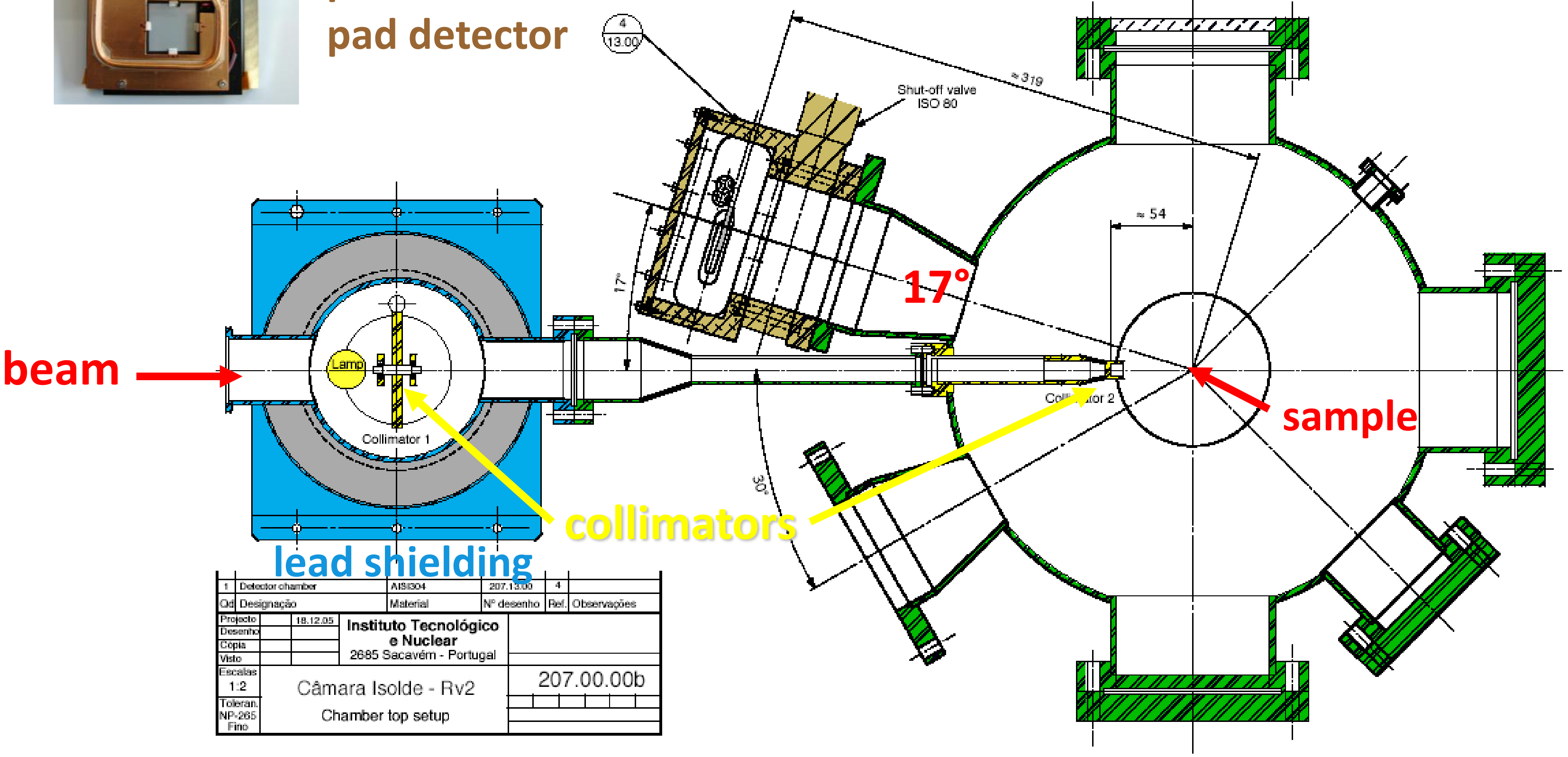
Emission channeling lattice location inside the



Emission channeling setup



3×3 cm² cooled position- sensitive Si pad detector

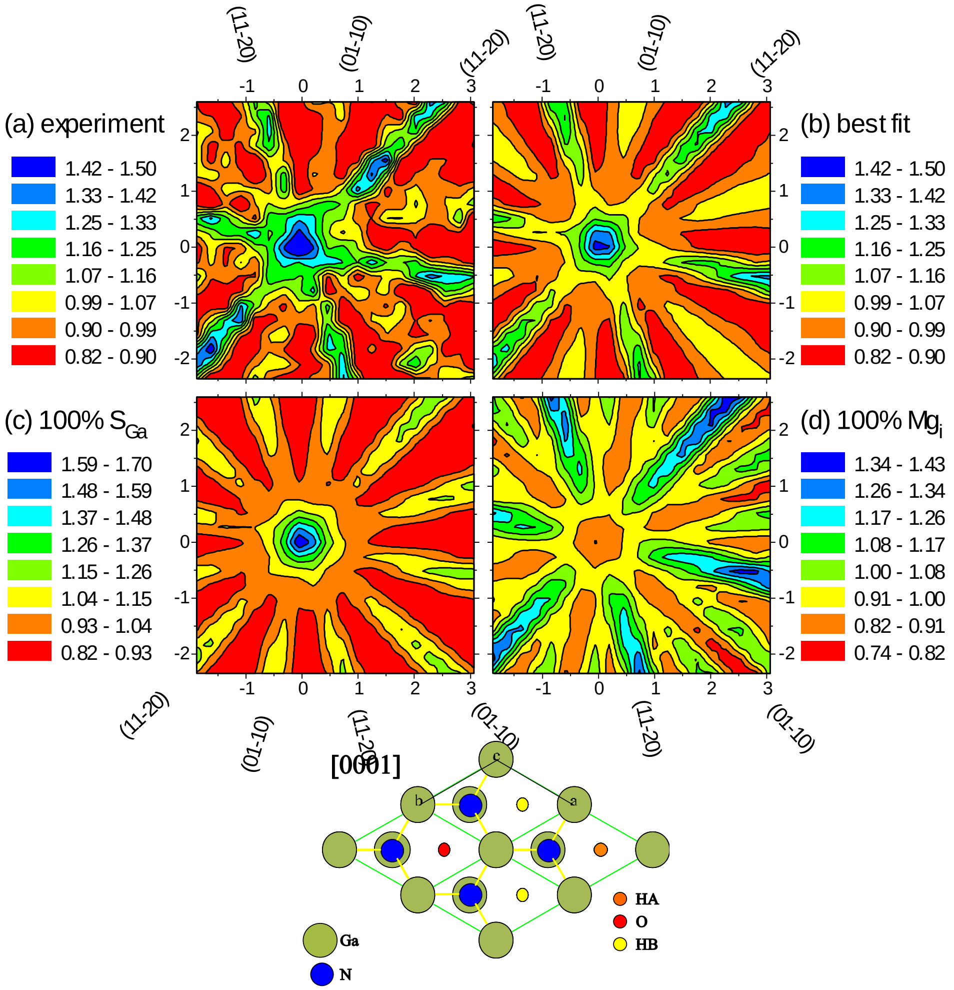


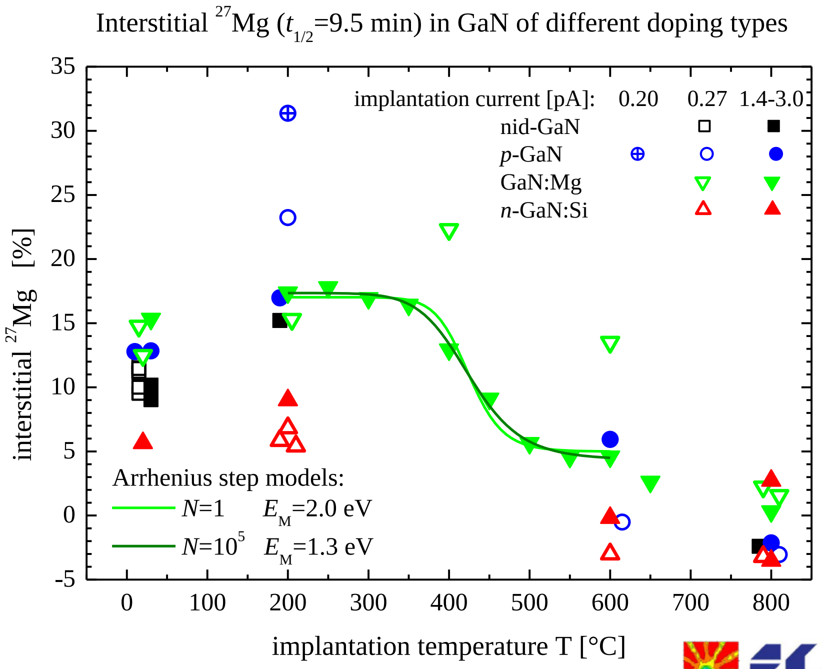
- beam collimated on sample by two apertures (last one ∅ 1mm)
- detector at 17° backward geometry for simultaneous implantation and measurement
- 22×22 pixels of 1.3 mm position-sensitive Si pad detector, water cooled

M.R. Da Silva et al , Rev. Sci. Instr. 84 (2013) 073506

Emission channelling in semiconductors

Lattice sites of ^{27}Mg in different pre-doped GaN





- 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}

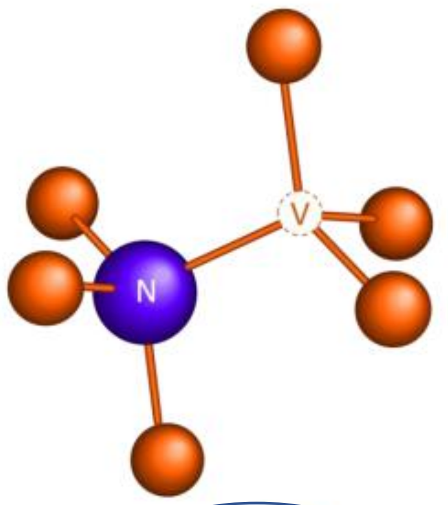
⇒ Activation energy for migration of **interstitial** Mg: E_M » 1.3 - 2.0 eV

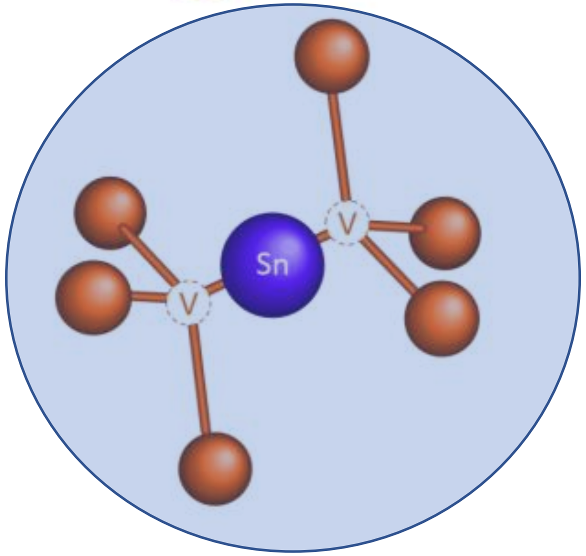
Phys. Rev. Lett. **118**, 095501(2017)

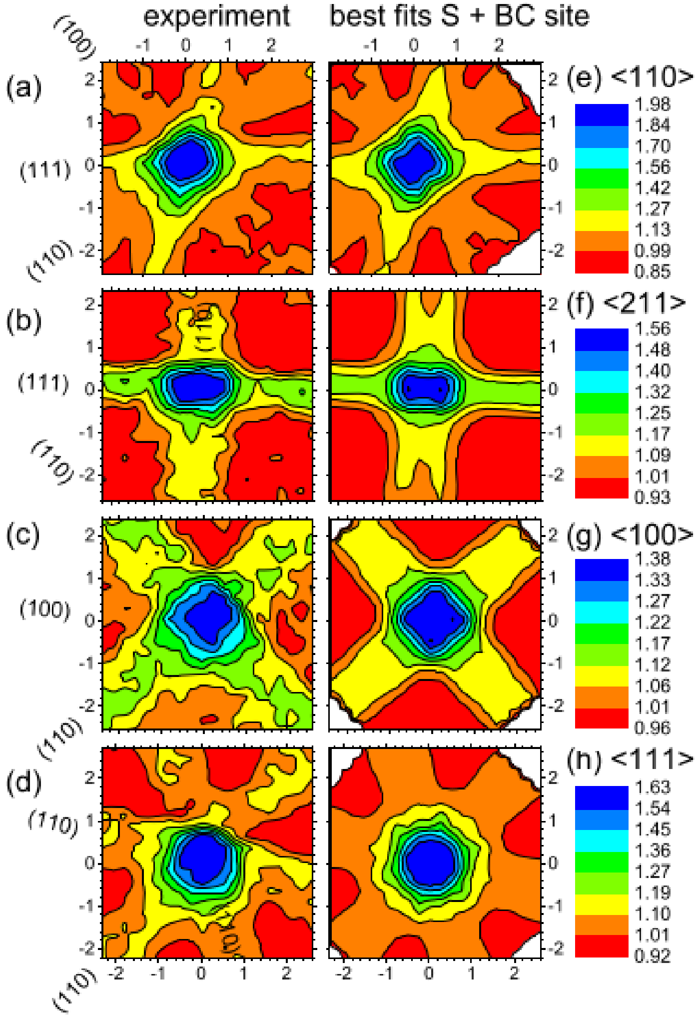
Emission channelling in semiconductors

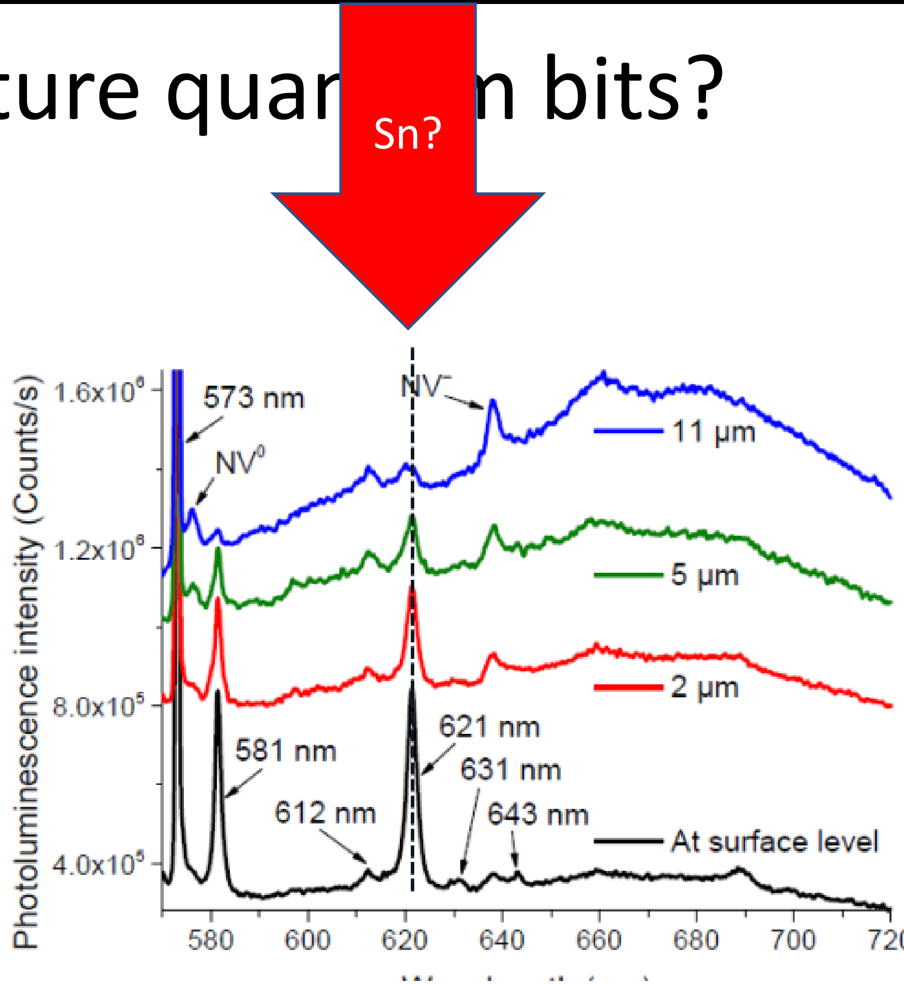
…but not radiotracer PL …(2021)

Colour Centres in diamond: future quantum bits?





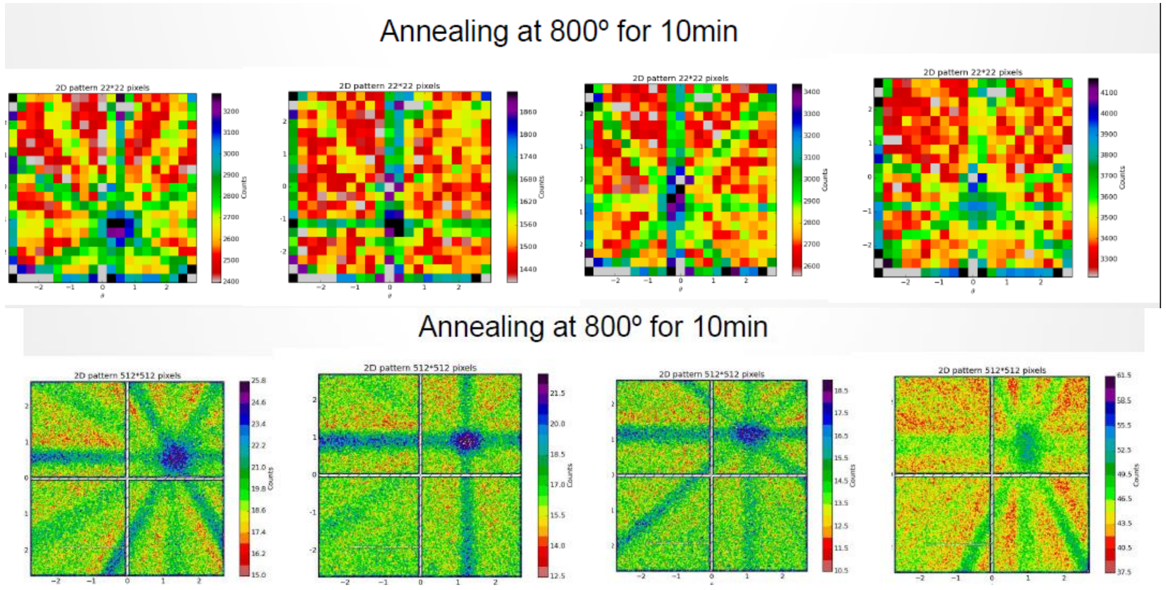


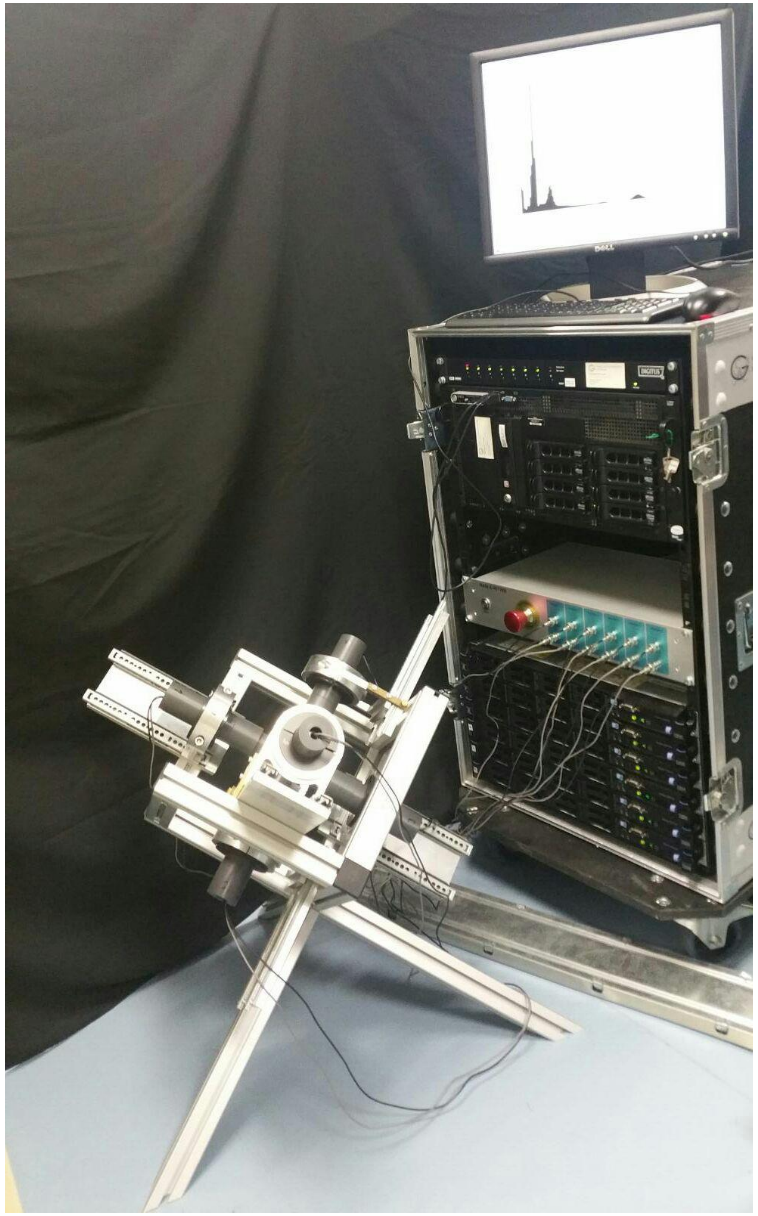


Direct Structural Identification and Quantification of the Split-Vacancy Configuration for Implanted Sn in Diamond

PHYSICAL REVIEW LETTERS **125,** 045301 (2020)

New developments

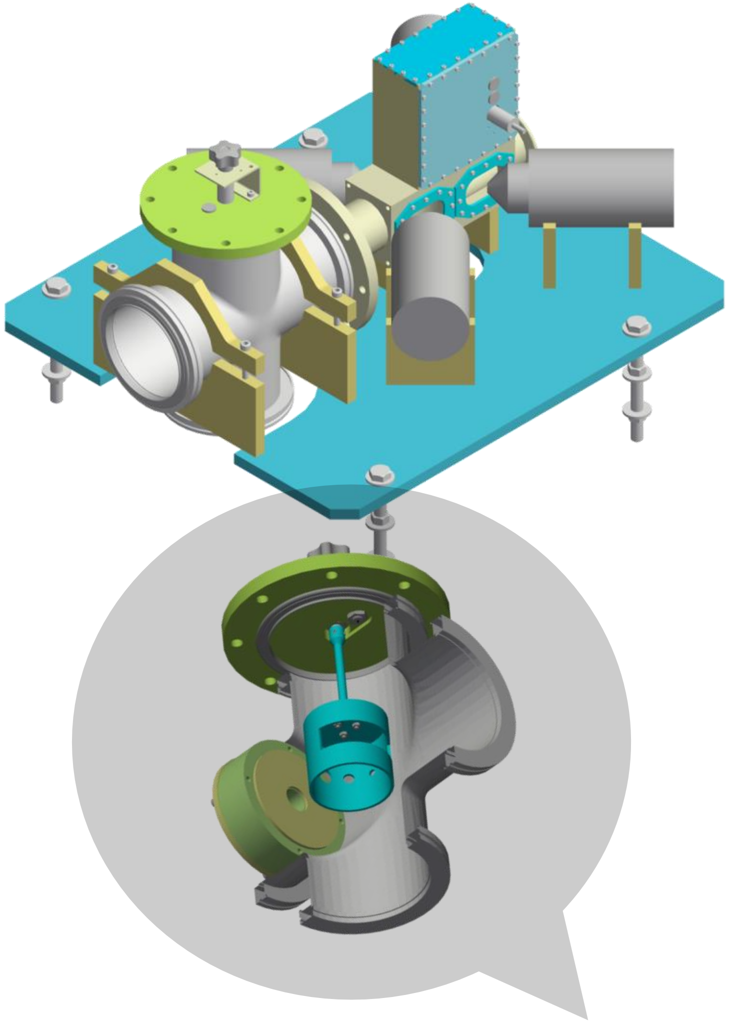




- Upgrading of detectors/spectrometers/upgrade DAQ.
- LaBr and CeBr detectors, allow for wider range of probes to be used.
- Spectrometer for biophysics for Mossbauer spectroscopy.

Controlling implantation

Online setup for 68Cu PAC



Surface implantation

Implantations on ice:
biology and surface science

Summary

- Ability to probe magnetic properties in dilute and sensitive way is essentially unique to hyperfine techniques such as PAC and Mossbauer and most radioactive methods… extremely attractive and becoming more so: devices are not getting any bigger…
- The interface of materials can be impossible to study reliably…radioactive probes are the ideal tool
- Flexibility of PAC techniques allows for temperature, surface, magnetic and other perturbative studies in materials
- Chemical information which can be addressed with radiotracer methods could reveal hidden aspects of quantum materials
- Especially powerful when various techniques are combined.
- With the range of isotopes available at ISOLDE can always attack a problem in a fresh and unique way…

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The solid state physics programme at ISOLDE: recent developments and perspectives

Karl Johnston *et al* 2017 *J. Phys. G: Nucl. Part. Phys.* **44** 104001

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