Introduction to solid state physics at ISOLDE

Th. Wichert (Universität des Saarlandes)

Radioactive ion beams
for getting information on

- the chemical identity of a specific defect or impurity atom in a solid
- the lattice site of an impurity atom
- the interaction between impurity atoms and other defects
- thermal properties of defects (diffusion, binding between defects)
- optical and electrical properties
- magnetic properties

1. Advantage of radioactive isotopes

- Background free (10^{23} atoms) detection due to nuclear radiation.
- Very high sensitivity to very low concentrations of impurity atoms in materials, on surfaces, at interfaces.
- Several problems can only be solved by the use of radioactive isotopes.

2. Required are

Facilities like ISOLDE providing a large variety of isotopically clean radioactive ion beams.

Existing Radioactive Nuclear Beam Facilities:

ANL -- ATLAS Exotic Beam Facility (Argonne, IL, USA)
CERN -- ISOLDE (Genéve, Switzerland)

CERN – ISOLDE (Géneve, Switzerland)

unique facility

for the next 5 – 7 years

JYFL -- IGISOL (Jyväskylä, Finland)
Radioactive Ion Beams in CYCLONE (Louvain-la-Neuve, Belgium)
LBL Berkeley BEARS ISOL facility (Berkeley, CA, USA)
LBL Berkeley IRIS facility (Berkeley, CA, USA)
Nuclear Science Centre, (New Delhi, India)
NSCL - K1200 Cyclotron/A1900 Fragment Separator (East Lansing, MI, USA)
ORNL -- Holifield Radioactive Ion Beam Facility (Oak Ridge, TN, USA)
OSIRIS (Studsvik, Sweden)
RIKEN RI Beam Factory - RRC and RIPS (Saitama, Japan)
TRIUMF - ISAC (Vancouver, Canada)
TWINSOL at the University of Notre Dame (Notre Dame, IN, USA)

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2. Required are

Facilities like ISOLDE providing a large variety of isotopically clean radioactive ion beams.

3. Introduction of these isotopes into solids

- by ion implantation ➔ well defined, clean conditions
- by diffusion
- during crystal growth
- soft landing on surfaces

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SSP topics at ISOLDE

- Semiconductors
- Magnetic semiconductors
- High-T_C superconductors
- Oxides
- Ceramics
- Metals
- Surfaces and interfaces

Experimental methods used

REQUIREMENTS

Take advantage of the emitted radiation:

- **Radiotracer diffusion** — **some decay radiation**
- **Emission channeling (EC)** — **charged particles**

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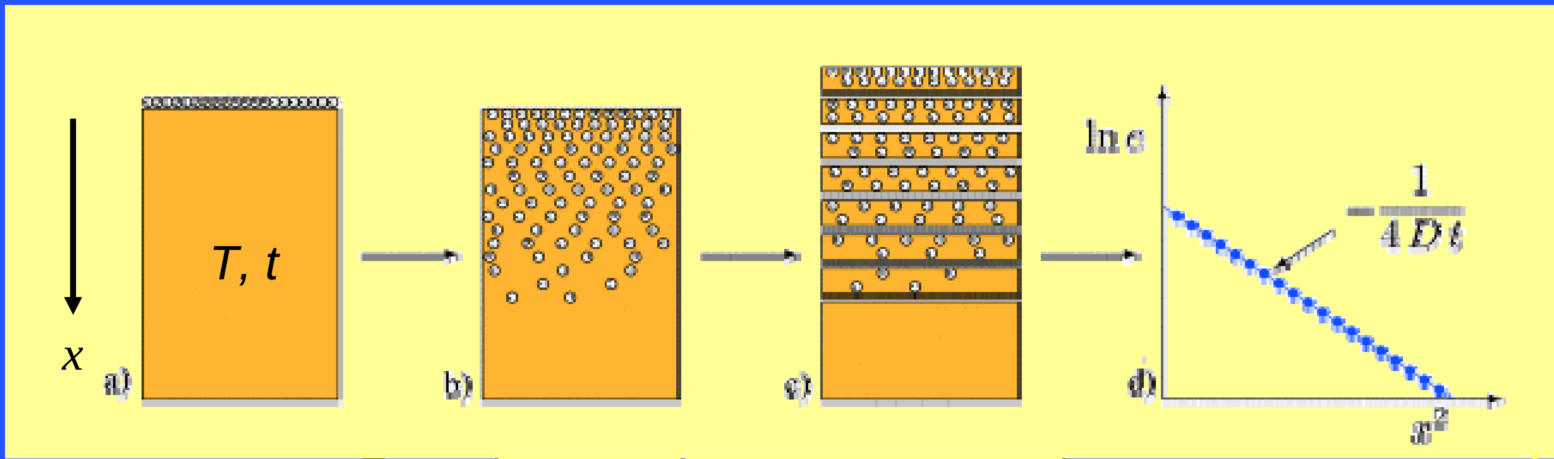
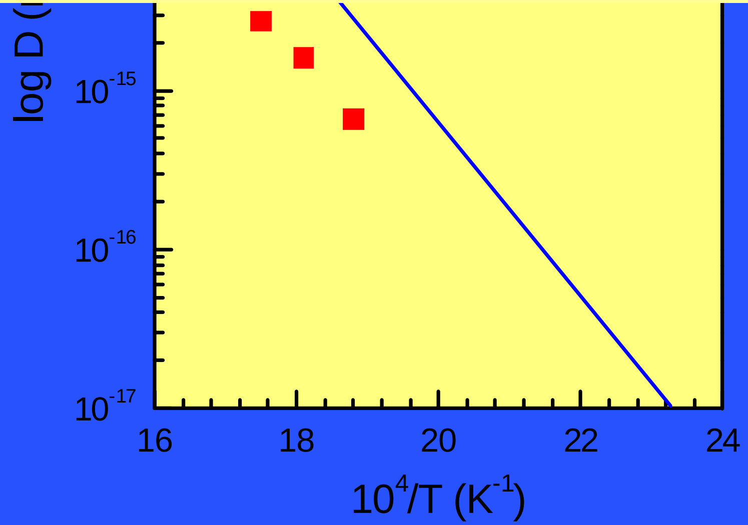
History (**1920**): Tracer diffusion

Using "natural" radioactive isotopes from U or Th decay series to study diffusion in solids (v. Hevesy, 1920):

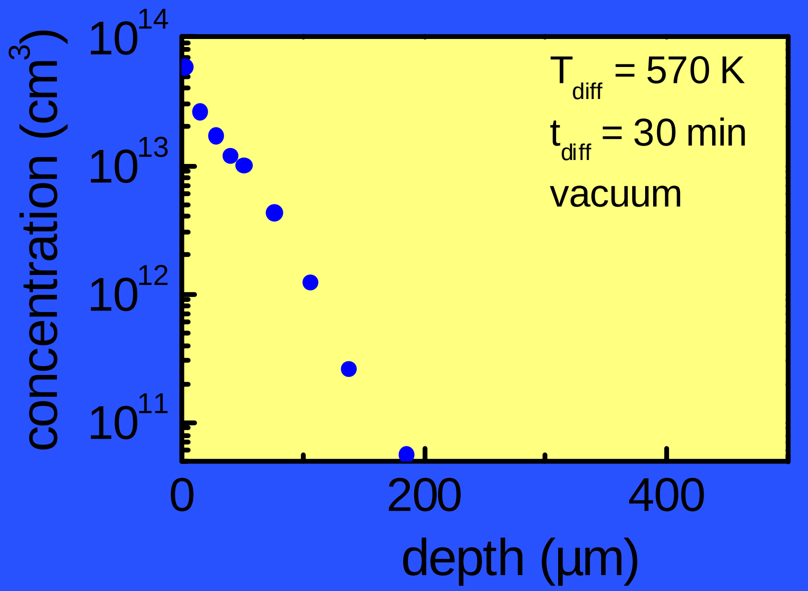
$$x^2 = D(T) \cdot t$$





$$D = D_0 e^{-\frac{E_A}{k_B T}}$$

Today (**2005**): Tracer diffusion of ^{111}Ag in CdTe



“Normal” diffusion profile

(i.e. monotonous decrease of concentration)

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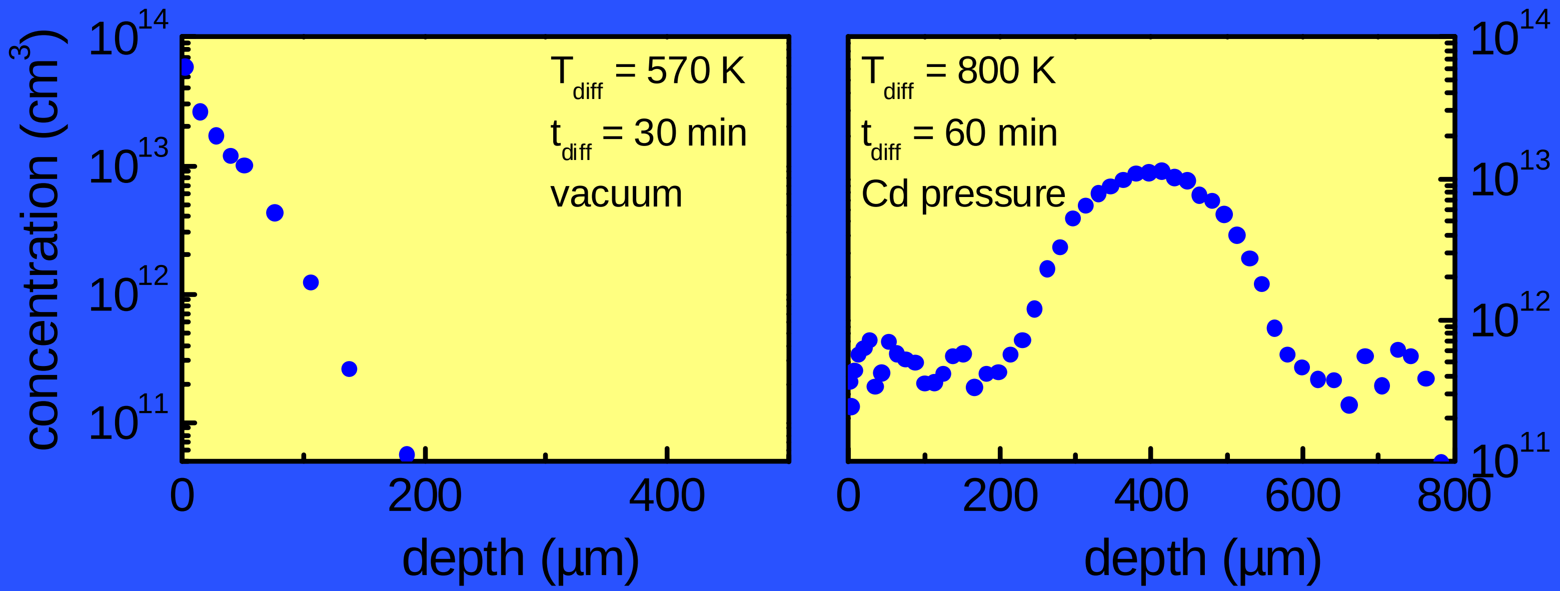

“Normal” diffusion profile

(i.e. monotonous decrease of concentration)

Symmetrical diffusion profile

(here: depletion of surface regions)

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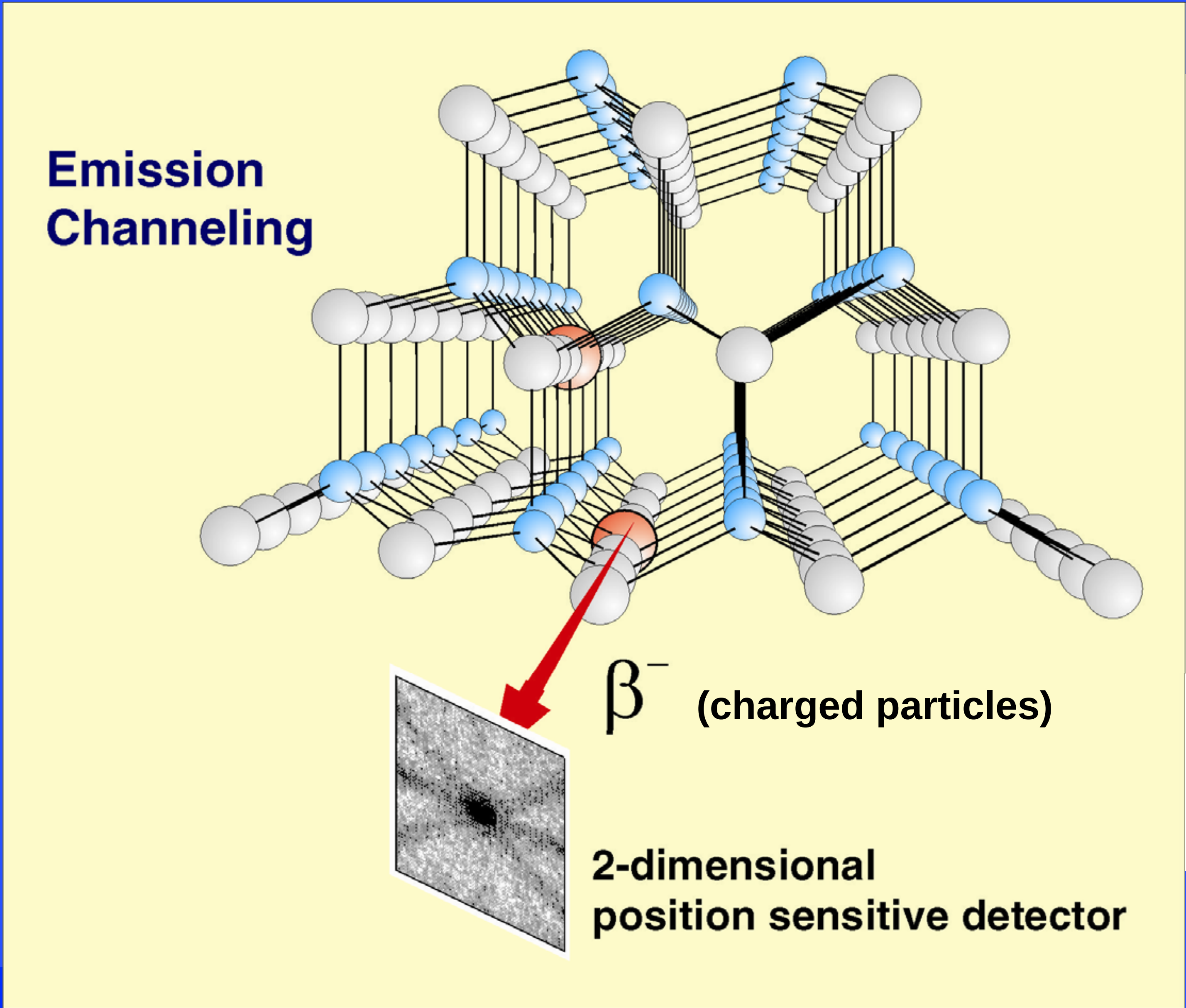
Emission channeling (EC)



Experimental methods used

REQUIREMENTS

Take advantage of the emitted radiation:

- Radiotracer diffusion
- Emission channeling (EC)

Interaction of nuclear moments with fields in solids:

- Perturbed γ-γ (e-γ) angular correlation (PAC)
- Mössbauer effect (ME)
- β-NMR
- NMR on oriented nuclei (NMR-ON)

} particular nuclear properties

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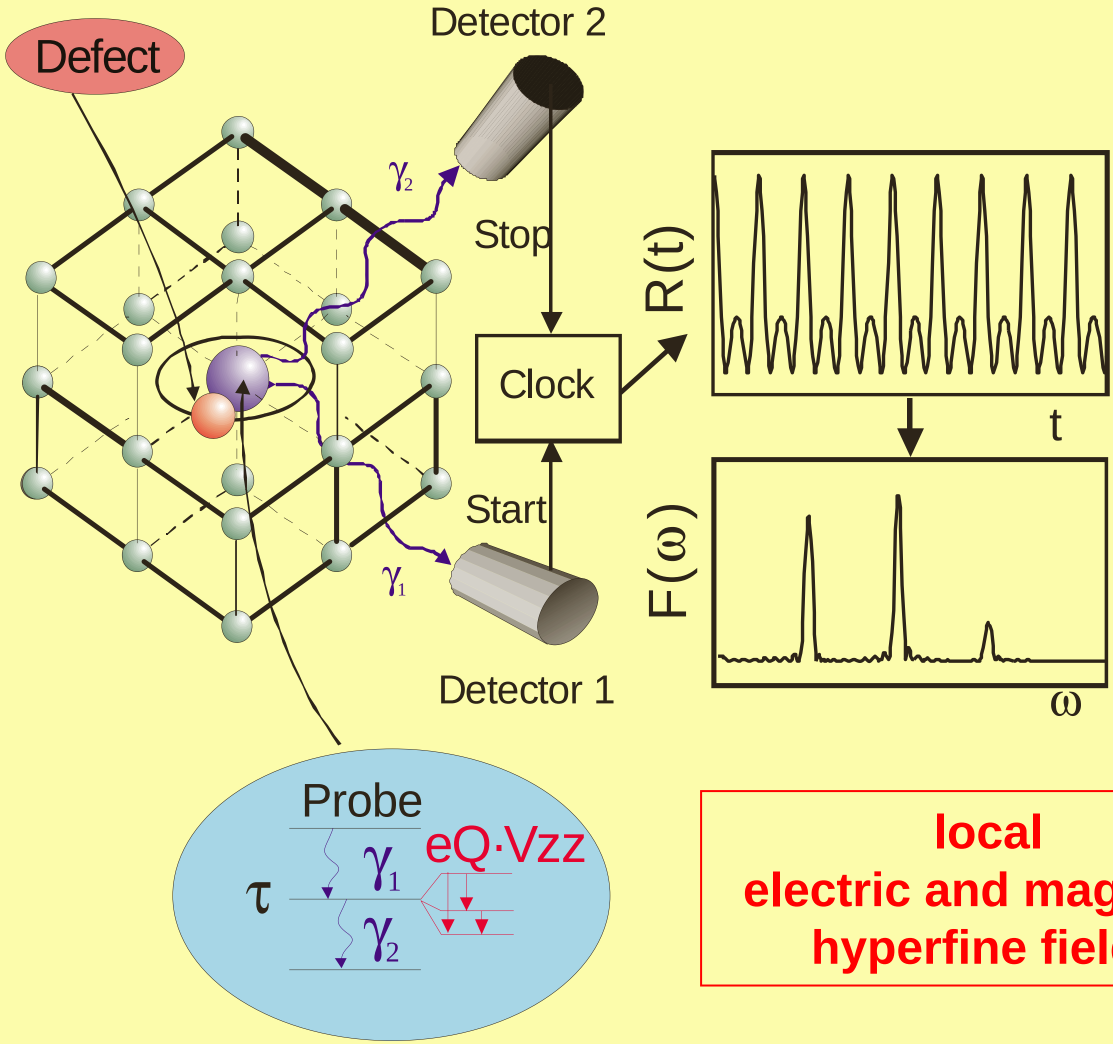
Perturbed γγ Angular Correlation (PAC)



$$\nu_Q = \frac{eQ \cdot V_{zz}}{h}$$ Fingerprint

$$\eta = \frac{V_{xx} + V_{yy}}{V_{zz}}$$ Symmetry

Fraction of probe-defect complexes

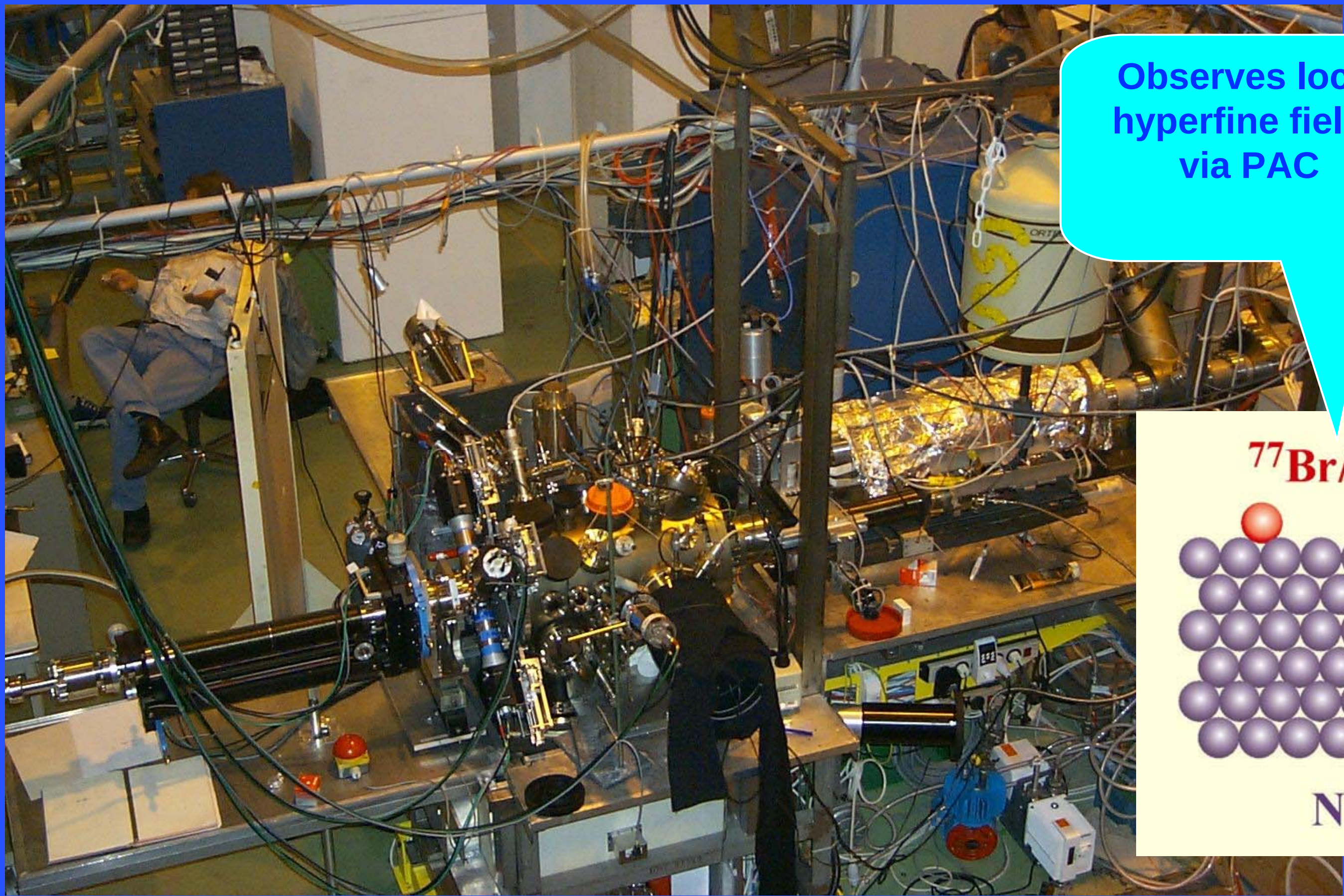
Orientation of probe-defect complexes

local electric and magnetic hyperfine fields

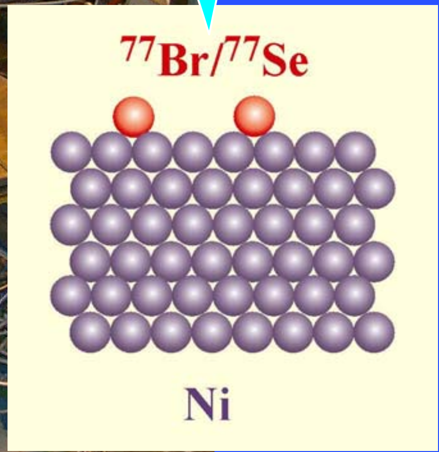
Surfaces, interfaces, ultra-thin layers

ASPIC

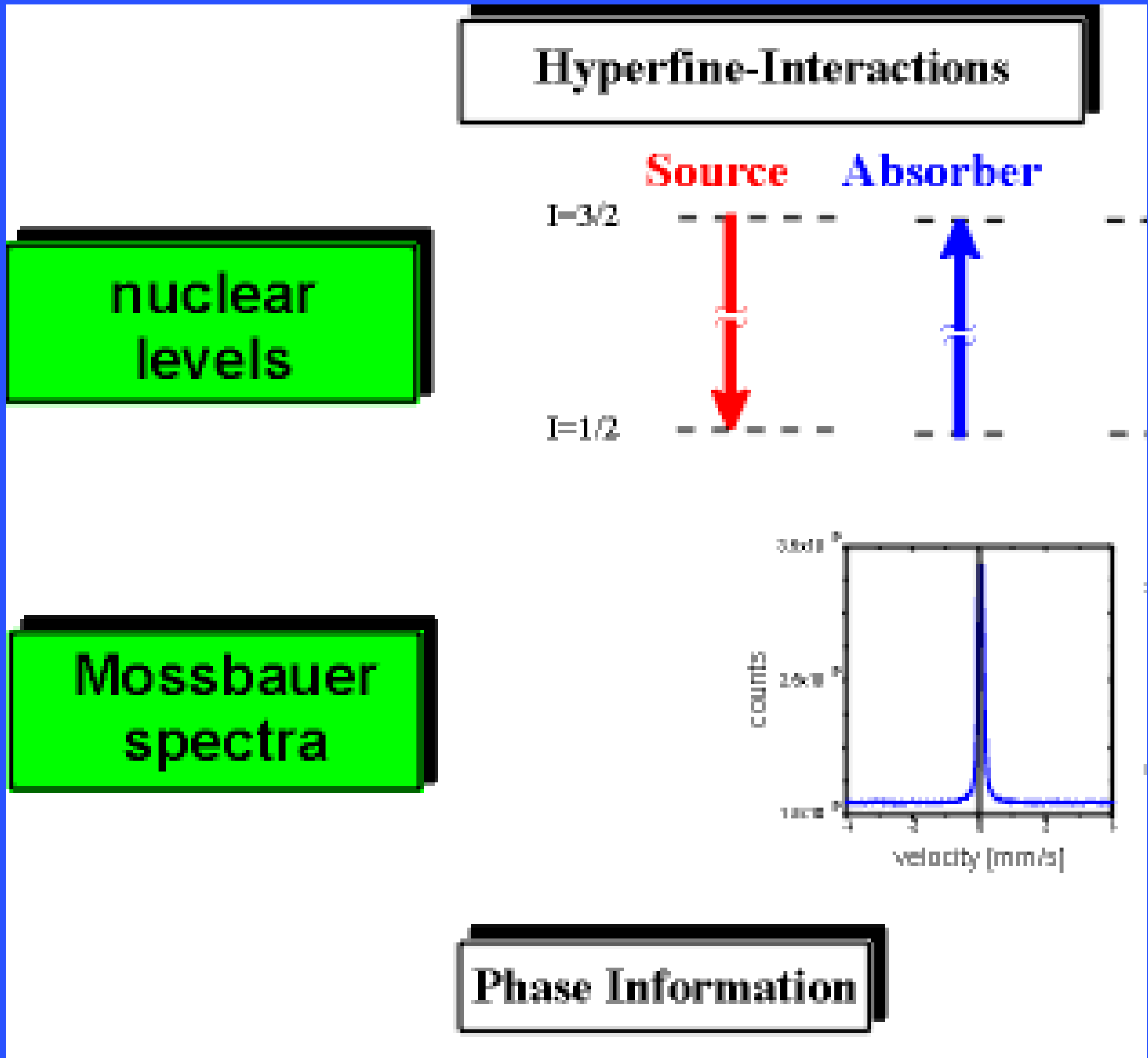
(Apparatus for Surface Physics and Interfaces at CERN)



Observes local hyperfine fields via PAC

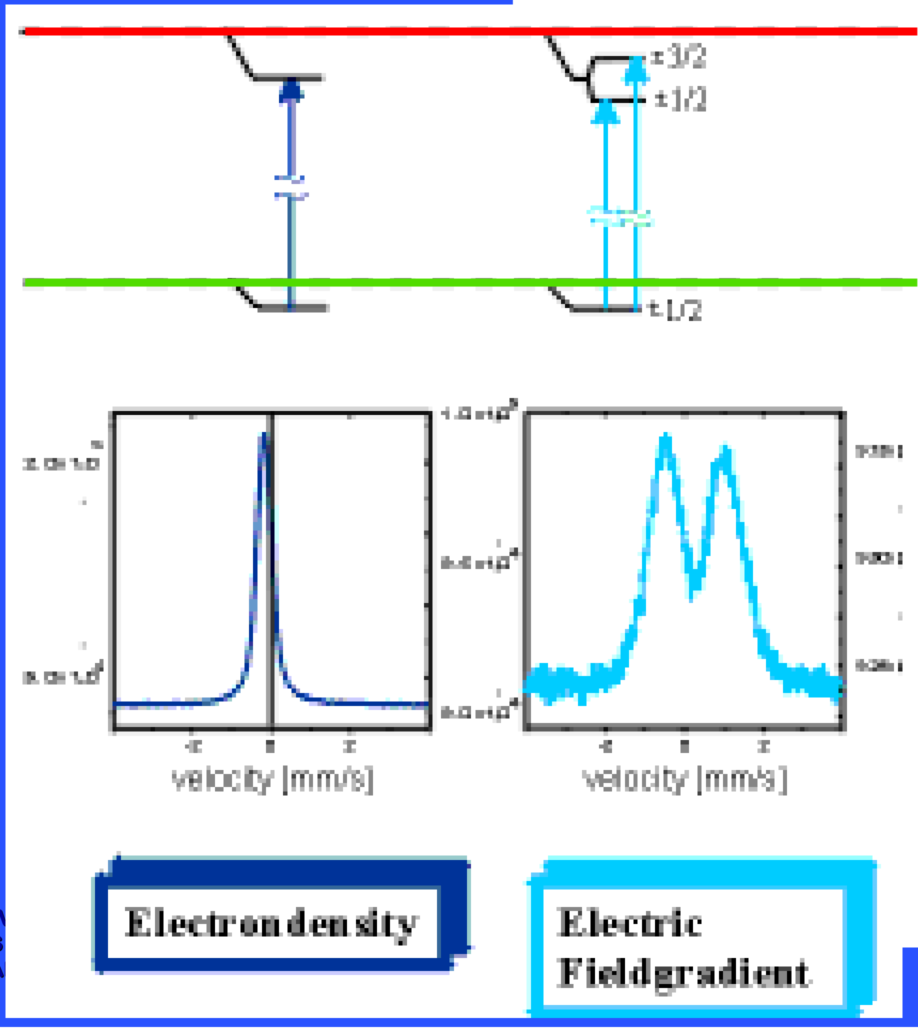


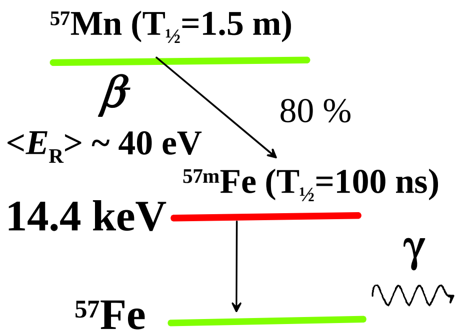
Mössbauer effect



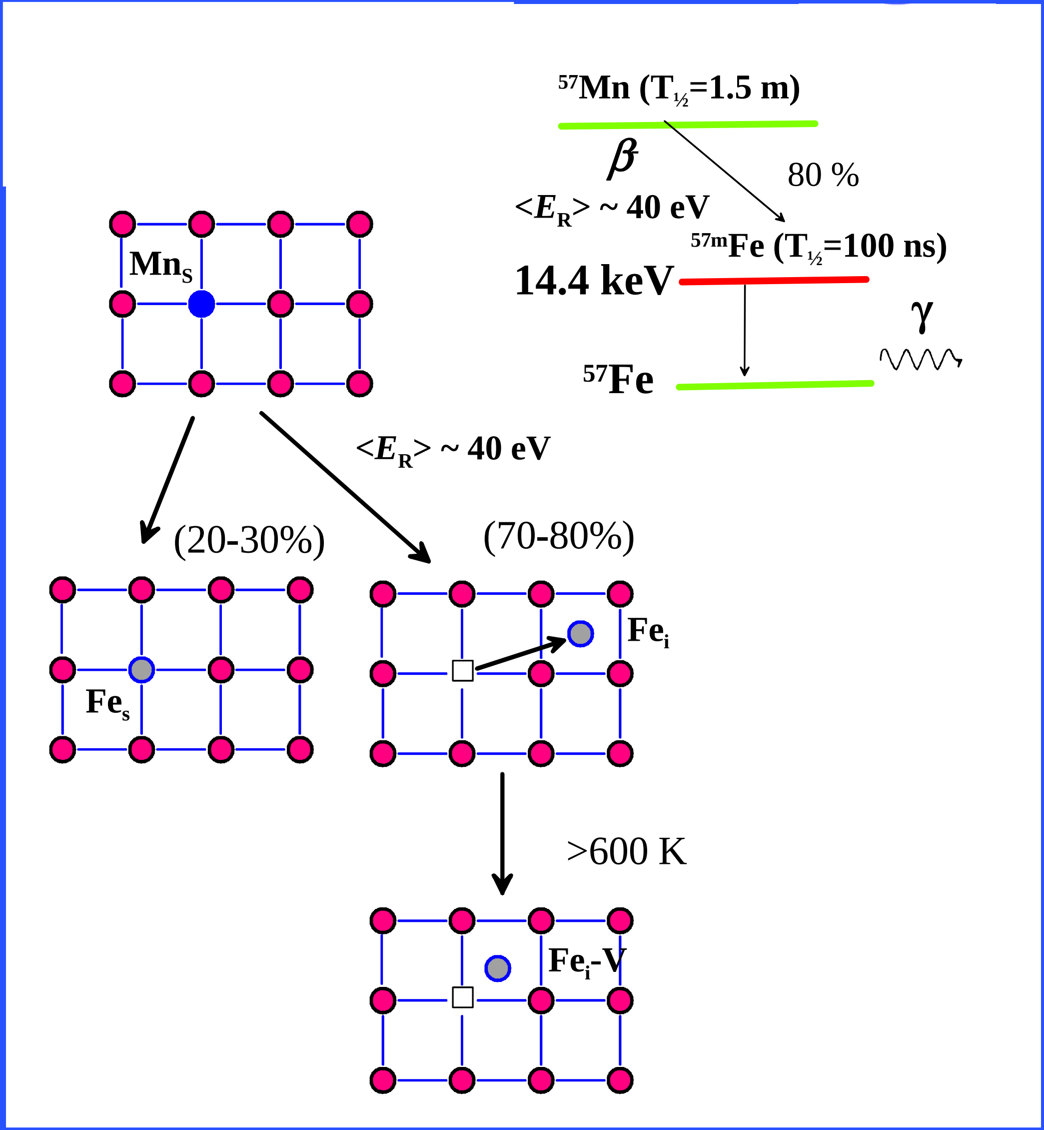
Implantation of $^{57}Mn \rightarrow {}^{57}Fe$ into Si

Implantation of





Implantation of ^{57}Mn → ^{57}Fe into Si



^{57}Fe atoms in different local environments

Experimental methods used REQUIREMENTS

Take advantage of the emitted radiation:

- Radiotracer diffusion
- Emission channeling (EC)

Interaction of nuclear moments with fields in solids:

- Perturbed γ-γ (e-γ) angular correlation (PAC)
- Mössbauer effect (ME)
- β-NMR
- NMR on oriented nuclei (NMR-ON)

Label chemically blind techniques with radioactive isotopes:

- Photoluminescence spectroscopy (PL)
- Deep level transient spectroscopy (DLTS)
- Hall effect measurements

} nuclear lifetime

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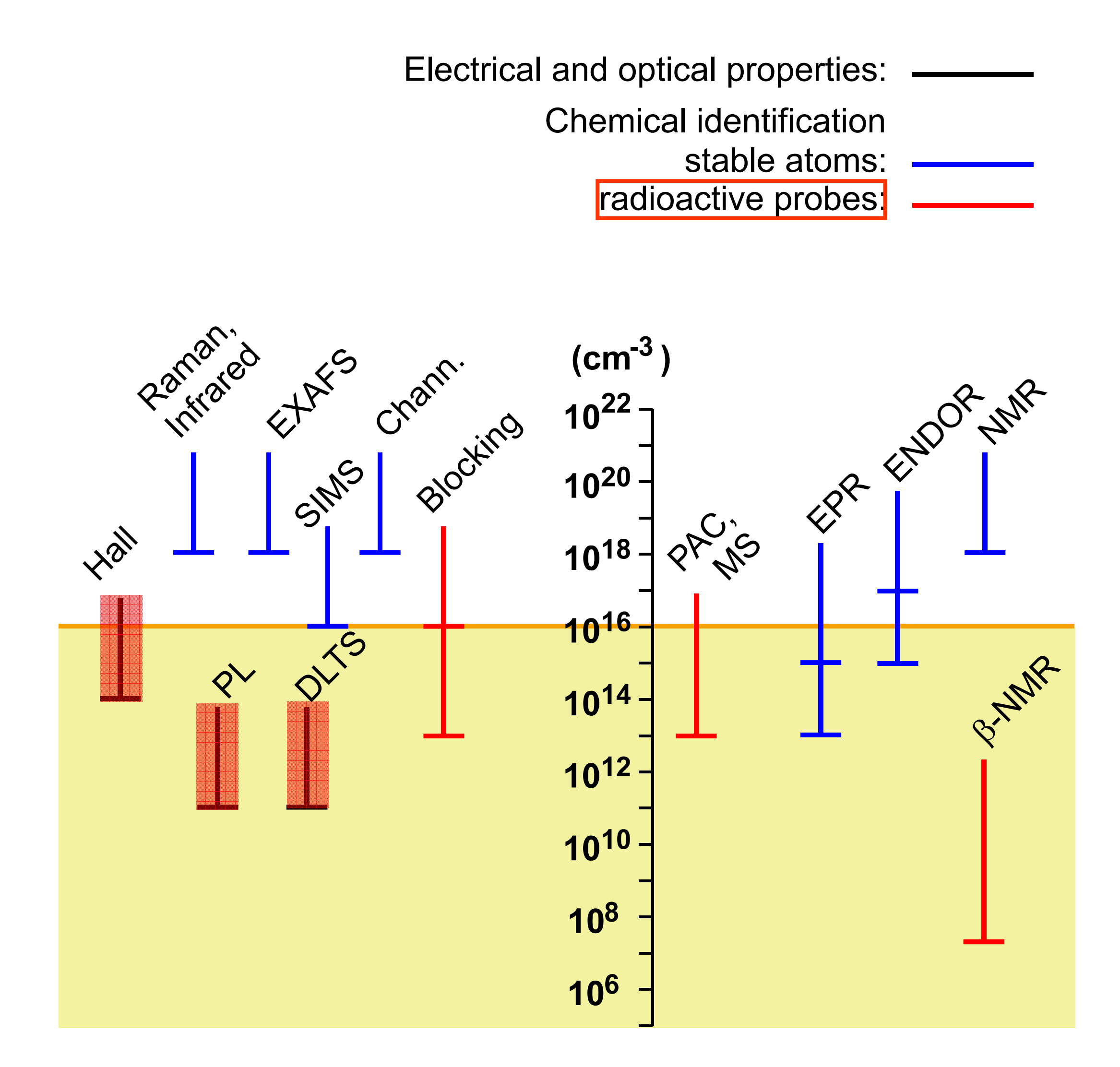
ISOLDE isotopes as analytical tool

10^{16} e / cm^3 <=> 1 ohm · cm



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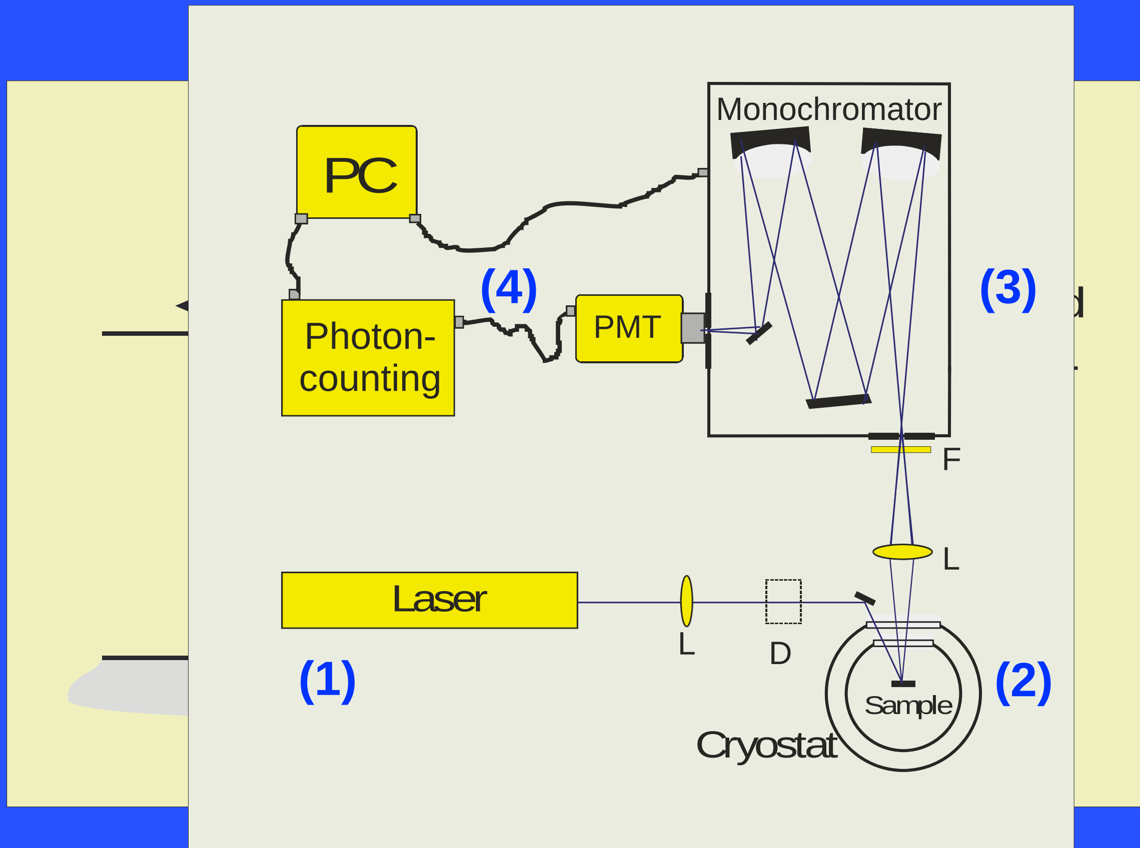
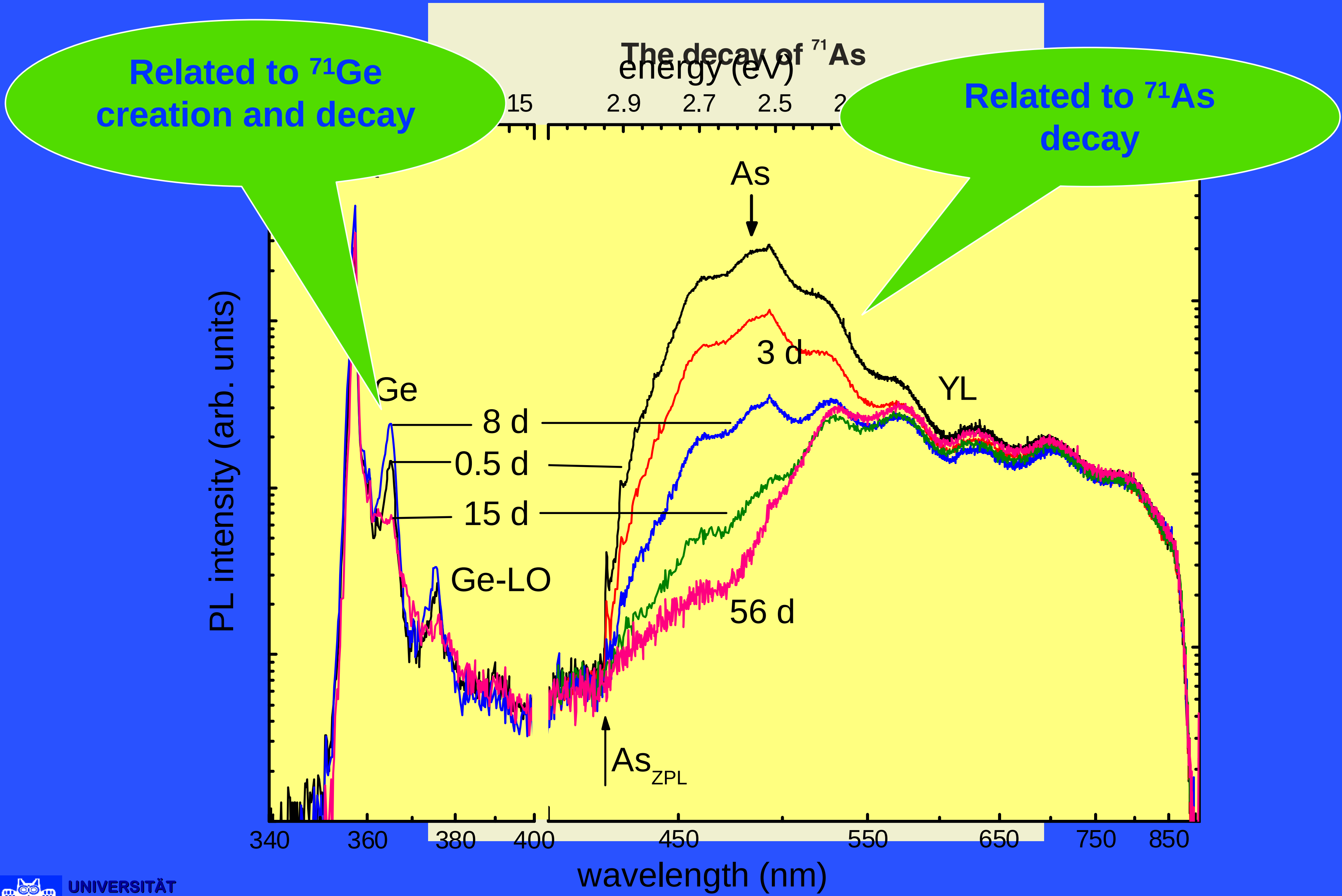
Optical properties of impurity atoms

<u>'Classical' spectroscopical techniques</u> used in semiconductor physics are <u>very sensitive</u> to optical/electrical properties of dopants (i.e. their band gap states),

but: they do not directly reveal information about their <u>microscopic origin</u>.



PL spectrum of GaN after ^{71}As implantation



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AUDIT of 'Solid State Physics at ISOLDE'

CERN, February 27, 2002

21 acccepted experiments
4 accepted proposals
2 letters of intent

Participating institutes	
Participating countri...	

Conclusion of AUDIT REPORT (2002)

"It is the general opinion of the Audit Commission that the ISOLDE-SSP community is <…> reaching a scientific level and scientific output that is far above average."

Inves...		
Maintena... Operation...		150 k€/year
	...es	650 k€/year
Positions (10...	...CERN	1
	at home institutes	53

Publications	181
PhD thesis	27
Invited talks and schools	94
Conference contributions	113

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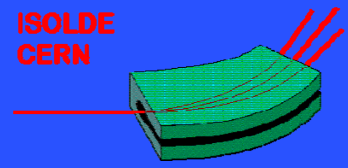
Running SSP experiments at ISOLDE

IS325	Combined electrical, optical and nuclear investigations of impurities and defects in II-VI semiconductors	CERN, Berlin, Erlangen, Lisbon
IS360	Studies of High Tc Superconductors Doped with Radioactive Isotopes	Aveiro, Berlin, Grenoble, Jerusalem, Leipzig, Leuven,
IS368	Lattice location of transition metals in semiconductors	Leuven, Lisbon, CERN
IS390	Studies of Colossal Magnetoresistive Oxides with Radioactive Isotopes	Aveiro, Grenoble, Leipzig, Leuven, Lisboa, Orsay, Porto, Sacavem, Stuttgart, Tokyo, Tsukuba, CERN
IS391	Radiotracer spectroscopy on group II acceptors in GaN	Jena, Konstanz, Troizk, CERN
IS395	^{31}Si Self-Diffusion in Si-Ge Alloys and Si-(B-)C-N Ceramics and Diffusion Studies for Al and Si Beam Developments	Stuttgart, Jyväskylä, Århus, CERN
IS396	Doping Properties of Ferromagnetic Semiconductors investigated by the Hyperfine Interaction of Implanted Radioisotopes	Freiberg, Konstanz, Kishinev, CERN
IS401	Semiconductor Spectroscopy with Short Lived Isotopes	Konstanz, Jena, Dublin, Dresden, Saarbrücken, CERN
IS416	Production of rare earth isotope beams for radiotracer-DLTS on SiC	Jena, Saarbrücken, Konstanz, CERN
IS425	Radioactive Probes on Ferromagnetic Surfaces	HMI-Berlin, FU-Berlin, Århus, Krakow, CERN
IS426	Mn and Fe impurities in $Si_{(1-x)}Ge_{(x)}$ alloys	Århus, Berlin, Durban, CERN, Milano
IS432	Diffusion of ^{52}Mn in GaAs	Helsinki, Lund, CERN



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