# 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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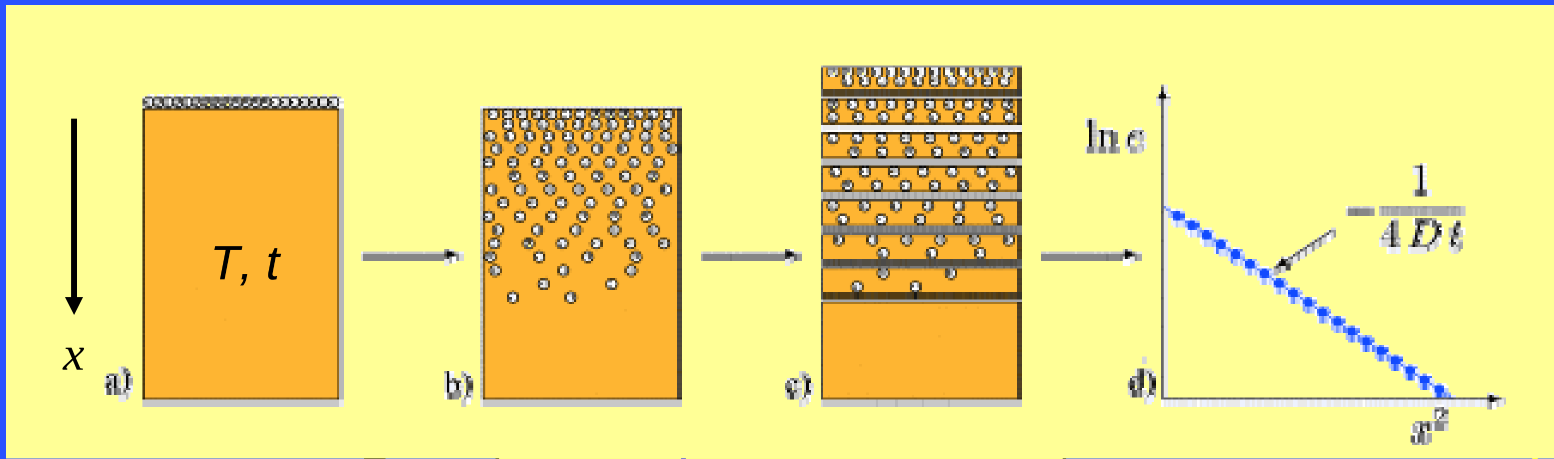
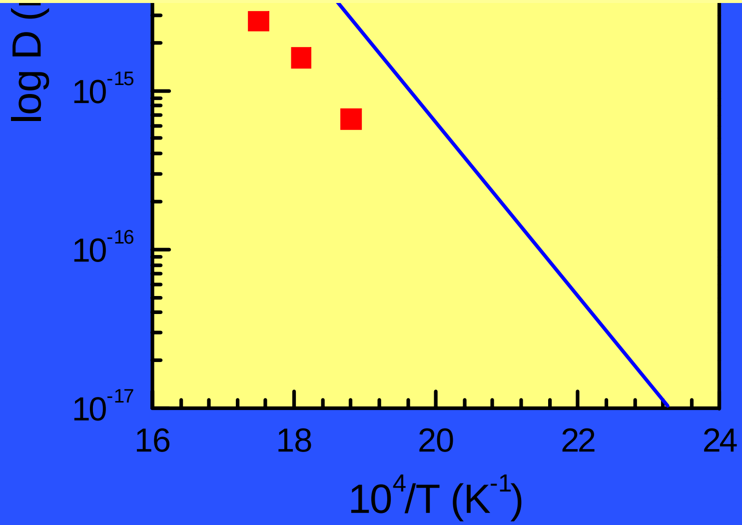
# History (**1920**): Tracer diffusion

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

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




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

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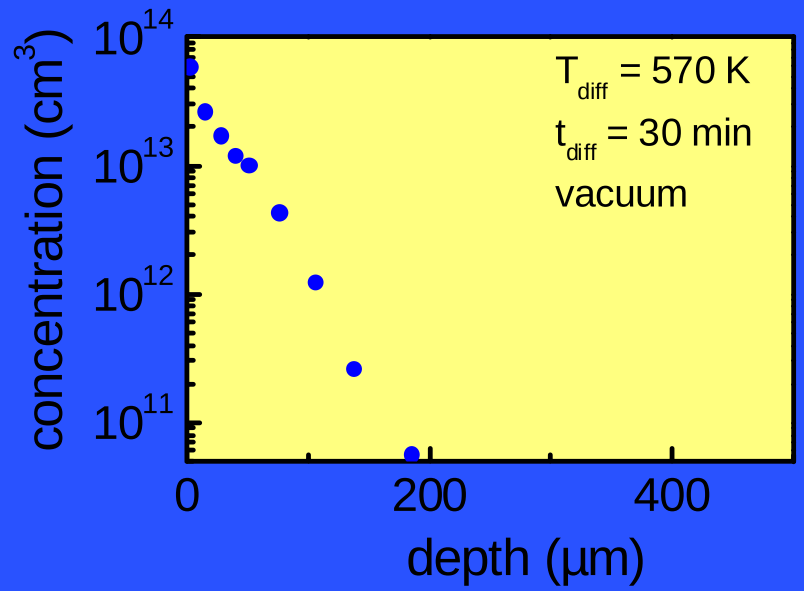
# Today (**2005**): Tracer diffusion of $^{111}$Ag in CdTe




**“Normal” diffusion profile**

**(i.e. monotonous decrease of concentration)**

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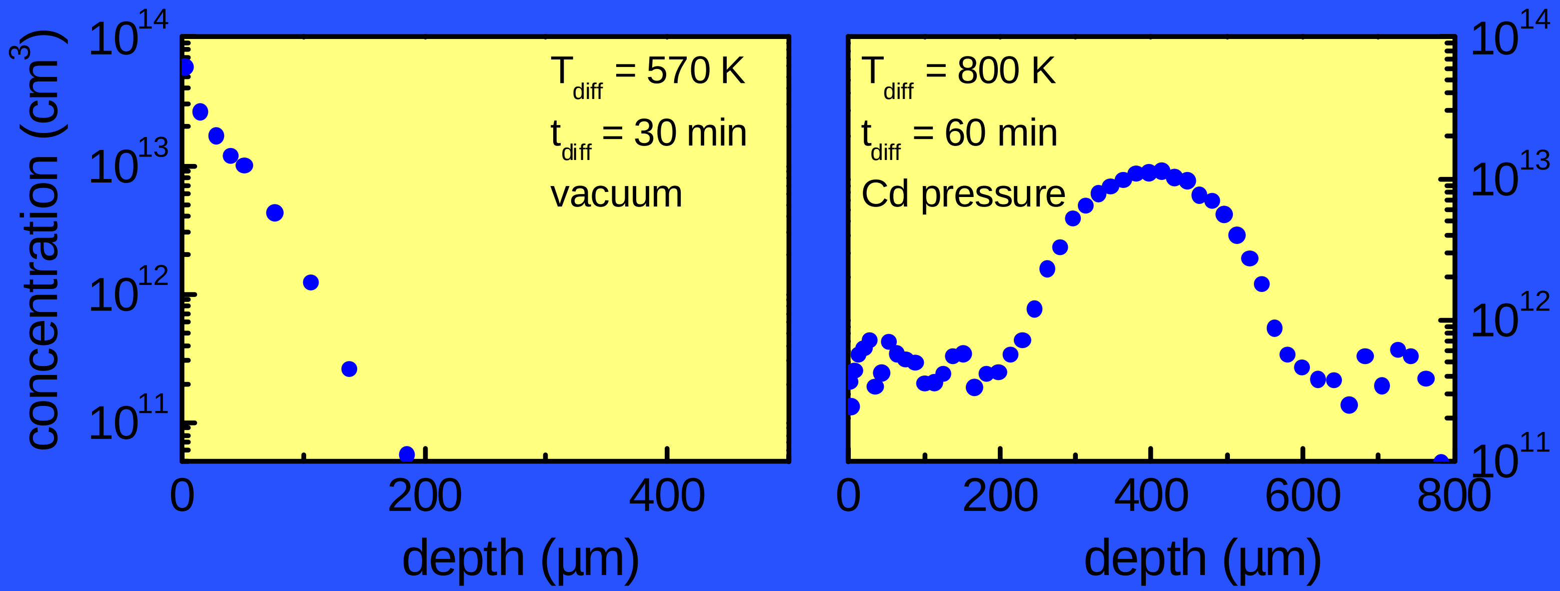


**"Normal" diffusion profile**

**(i.e. monotonous decrease of concentration)**

**Symmetrical diffusion profile**

**(here: depletion of surface regions)**

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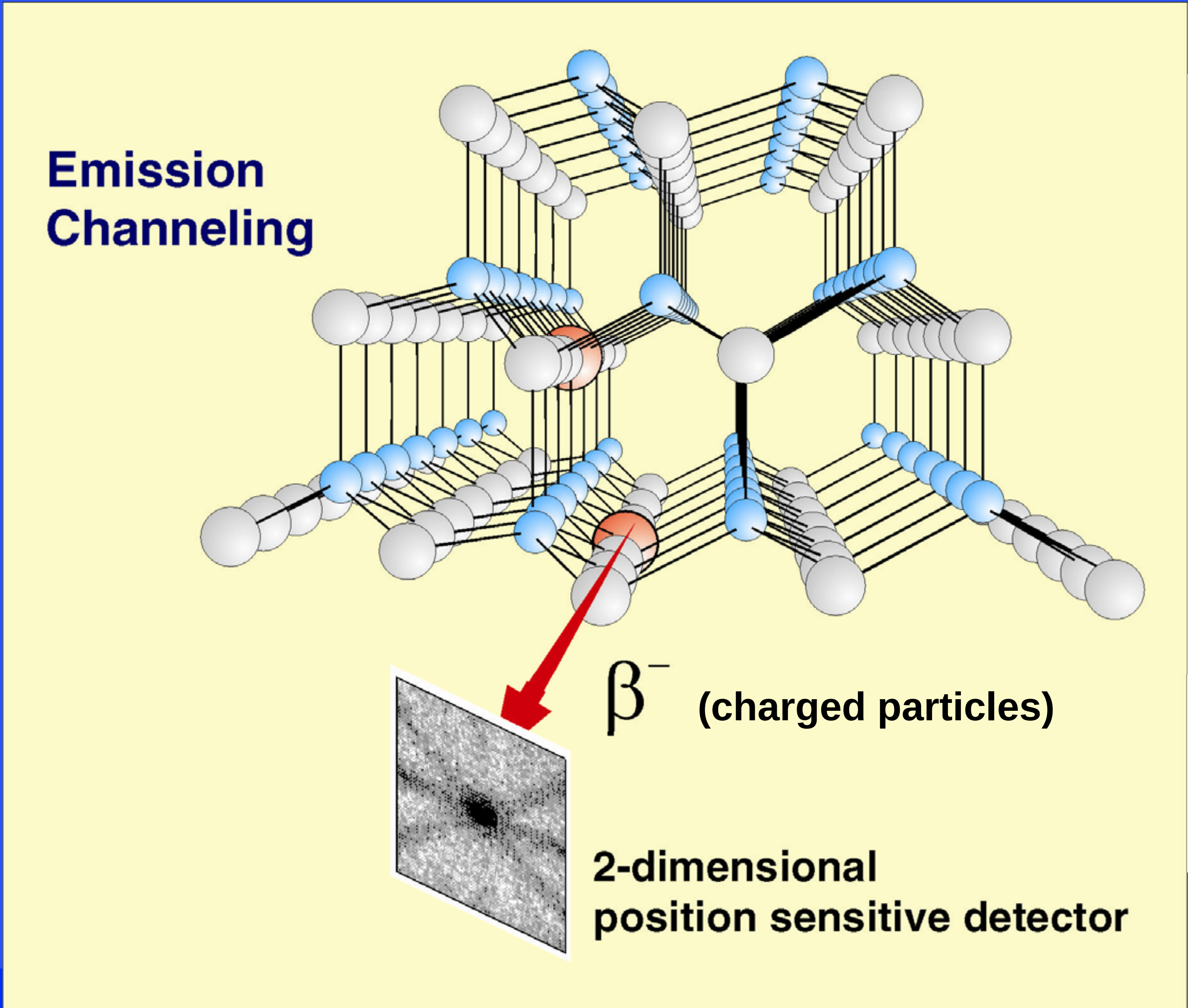
# Emission channeling (EC)



# Experimental methods used

REQUIREMENTS

*Take advantage of the emitted radiation:*

- Radiotracer diffusion
- Emission channeling (EC)

*Interaction of nuclear moments with fields in solids:*

- Perturbed $\gamma$-$\gamma$ (e-$\gamma$) angular correlation (PAC)
- Mössbauer effect (ME)
- $\beta$-NMR
- NMR on oriented nuclei (NMR-ON)

} particular nuclear properties

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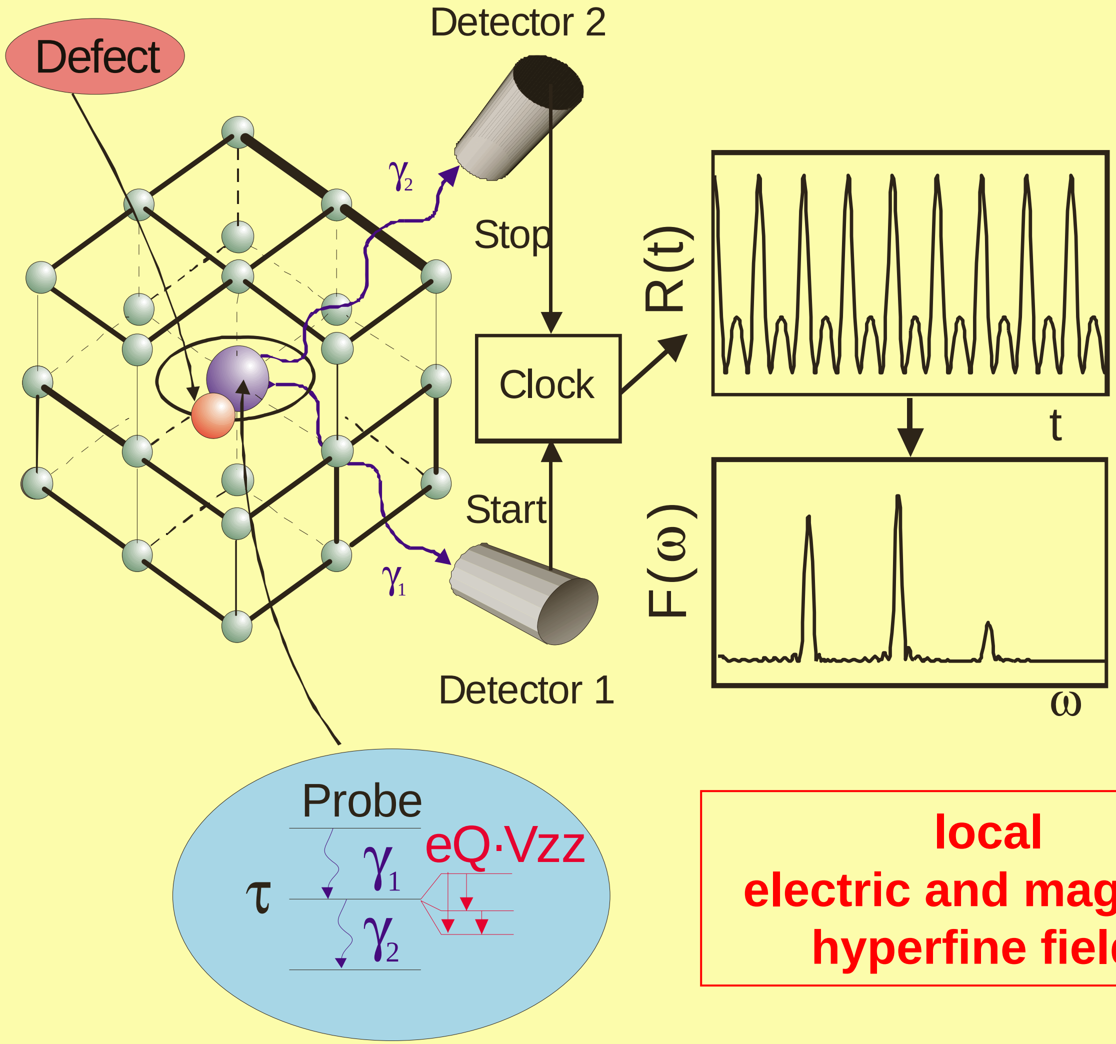
# Perturbed γγ Angular Correlation (PAC)




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

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

Fraction of probe-defect complexes

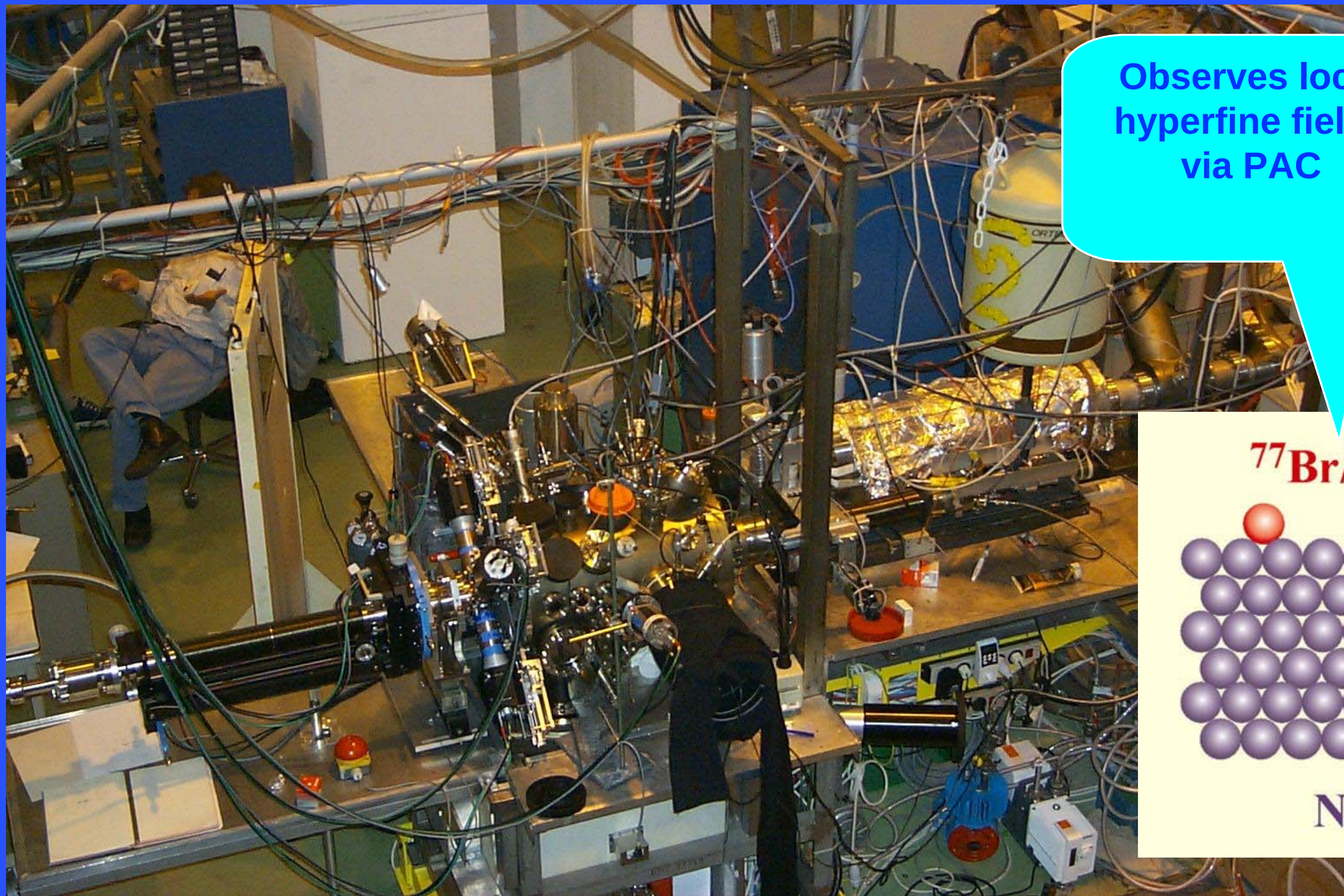
Orientation of probe-defect complexes

**local electric and magnetic hyperfine fields**

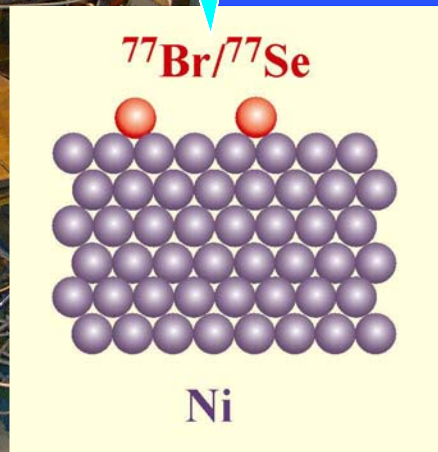
# Surfaces, interfaces, ultra-thin layers

## ASPIC

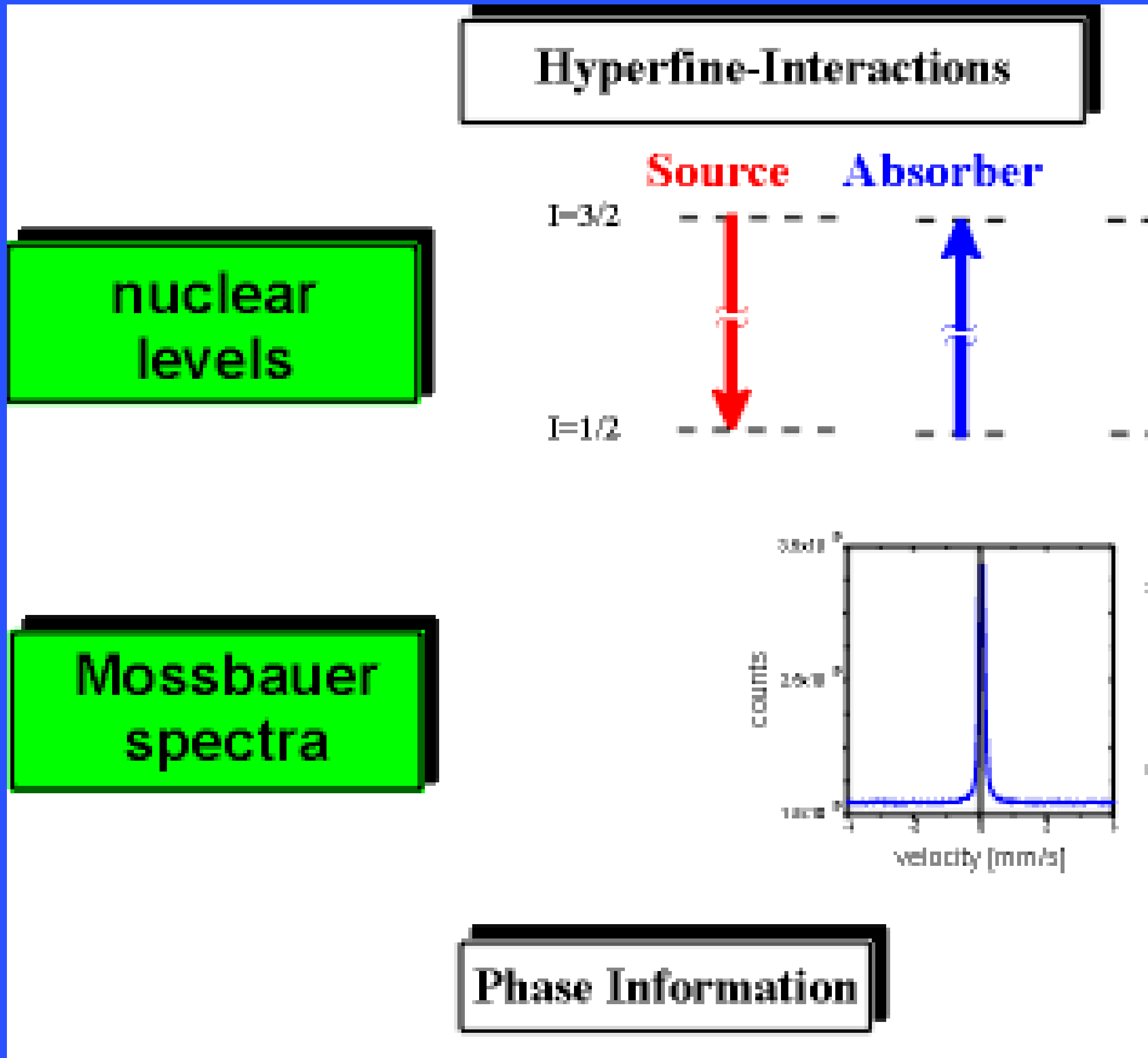
**(Apparatus for Surface Physics and Interfaces at CERN)**



**Observes local hyperfine fields via PAC**

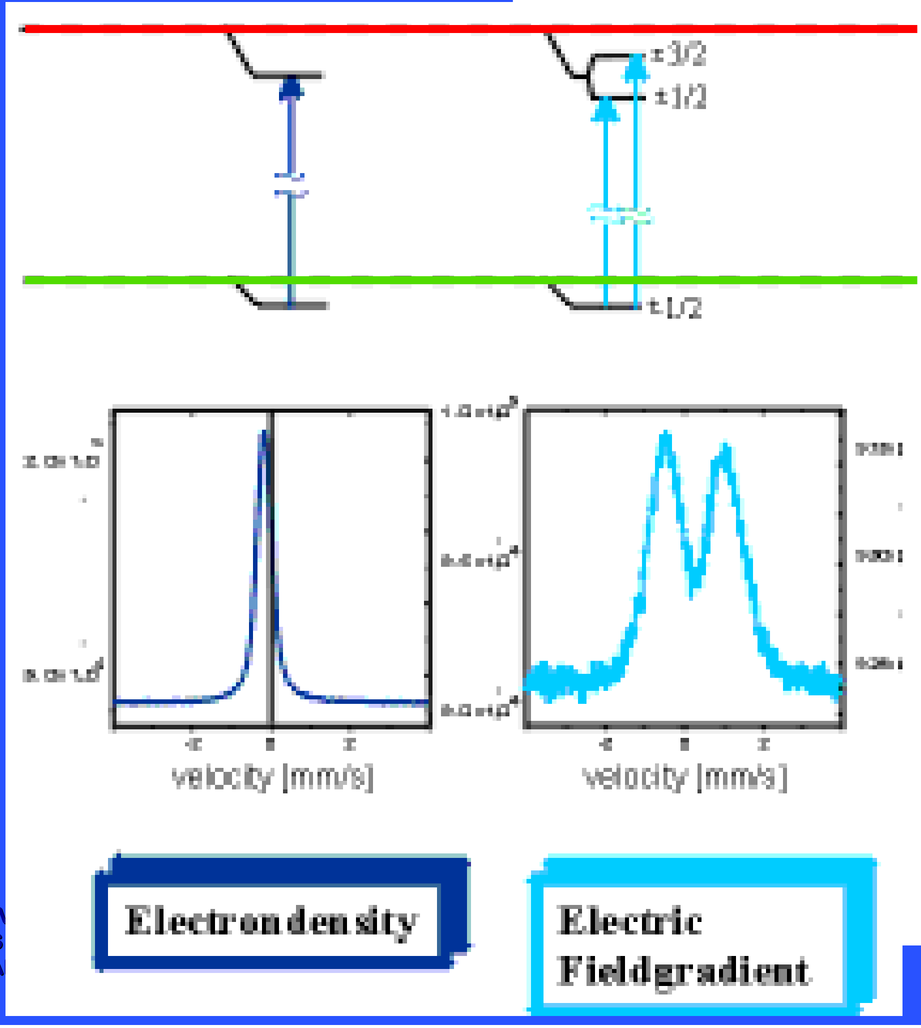


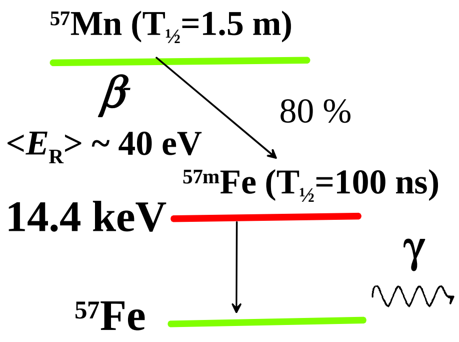
# Mössbauer effect



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

Implantation of



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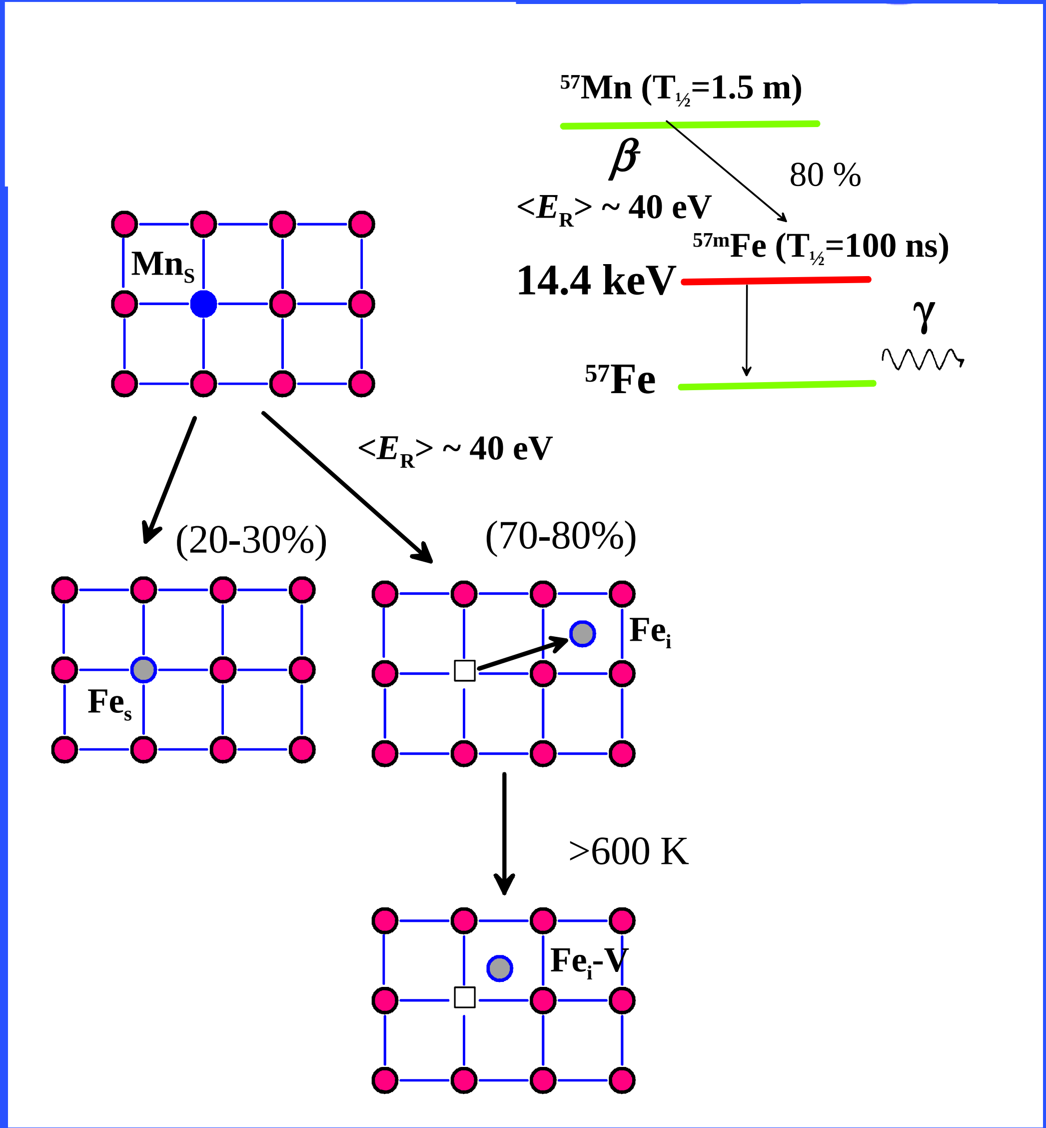


$^{57}$Fe atoms in different local environments

# Experimental methods used

REQUIREMENTS

***Take advantage of the emitted radiation:***

- **Radiotracer diffusion**
- **Emission channeling (EC)**

***Interaction of nuclear moments with fields in solids:***

- **Perturbed $\gamma$-$\gamma$ (e-$\gamma$) angular correlation (PAC)**
- **Mössbauer effect (ME)**
- **$\beta$-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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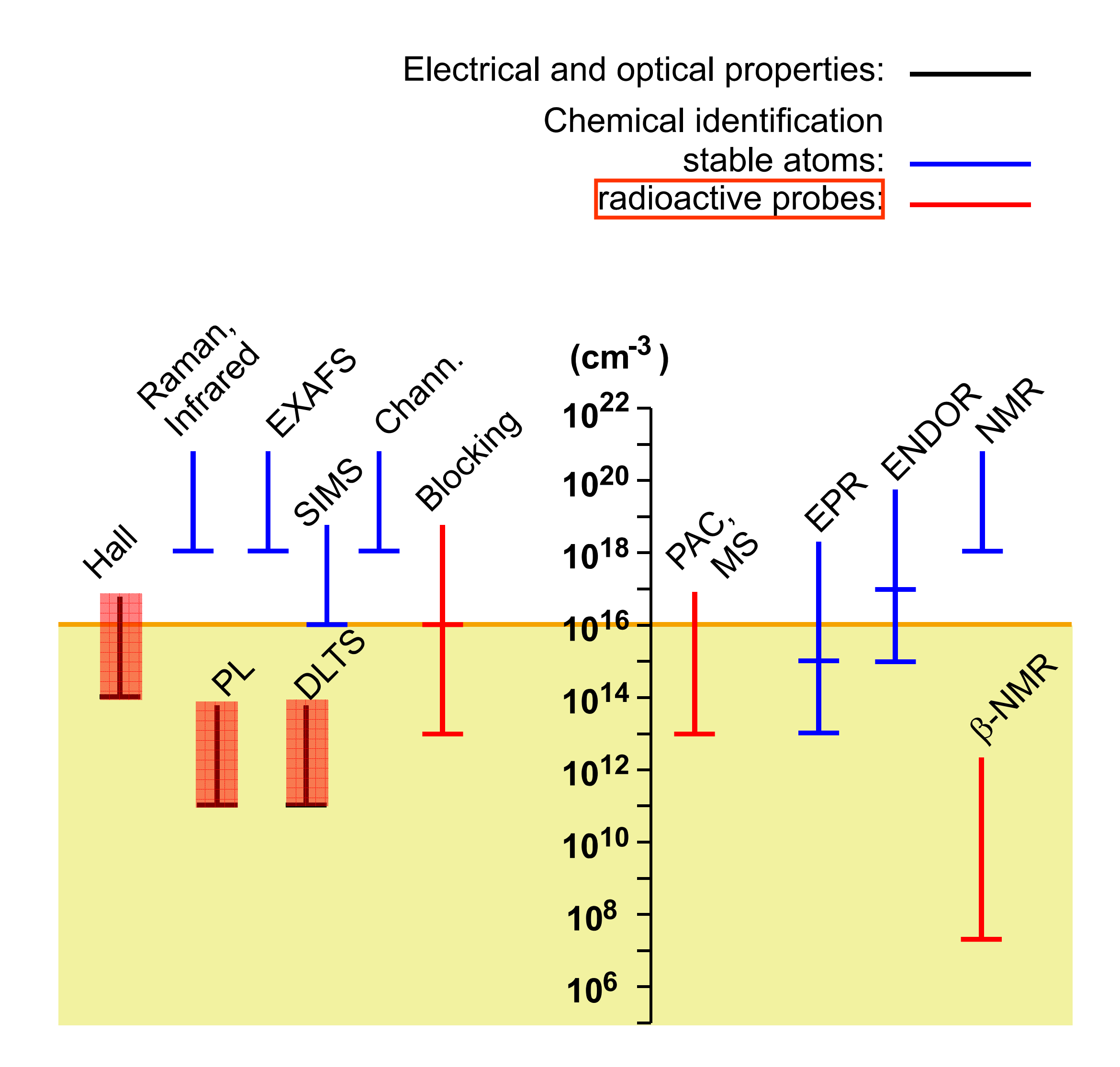
# ISOLDE isotopes as analytical tool

**$10^{16}$ e / cm$^3$ <=> 1 ohm · cm**

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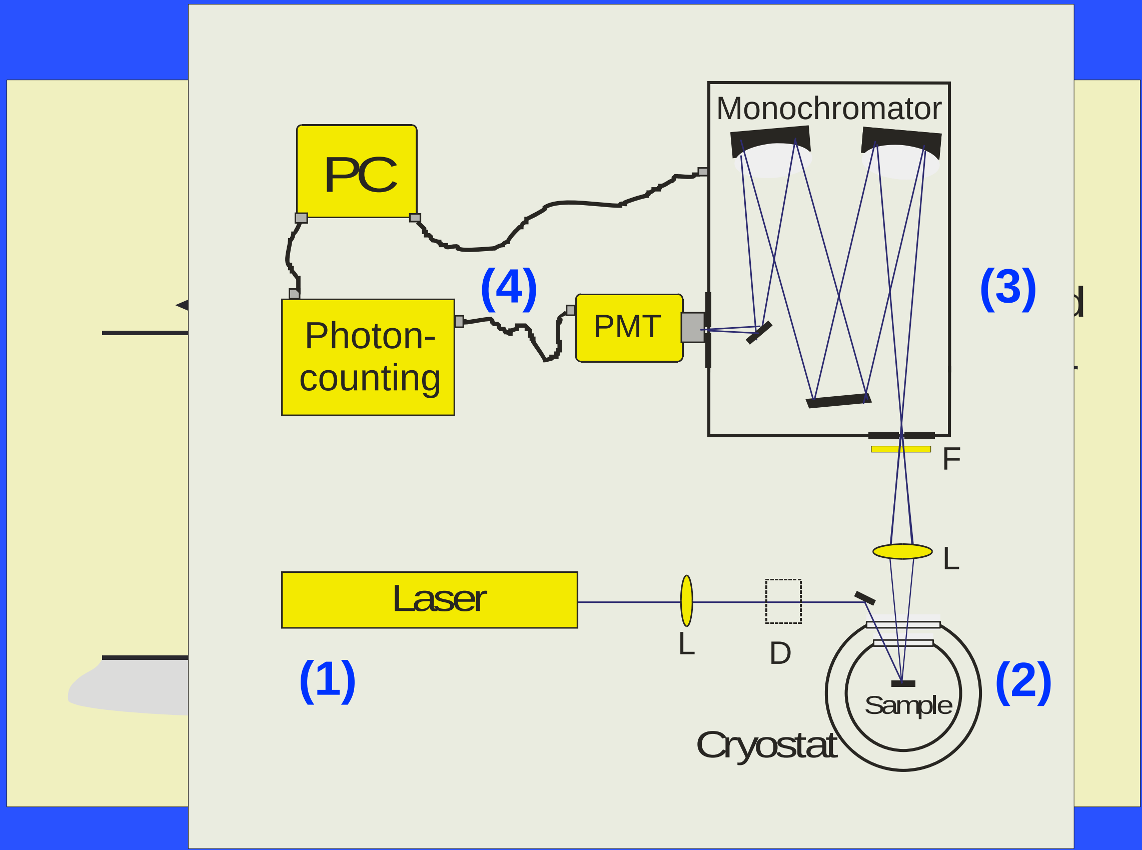
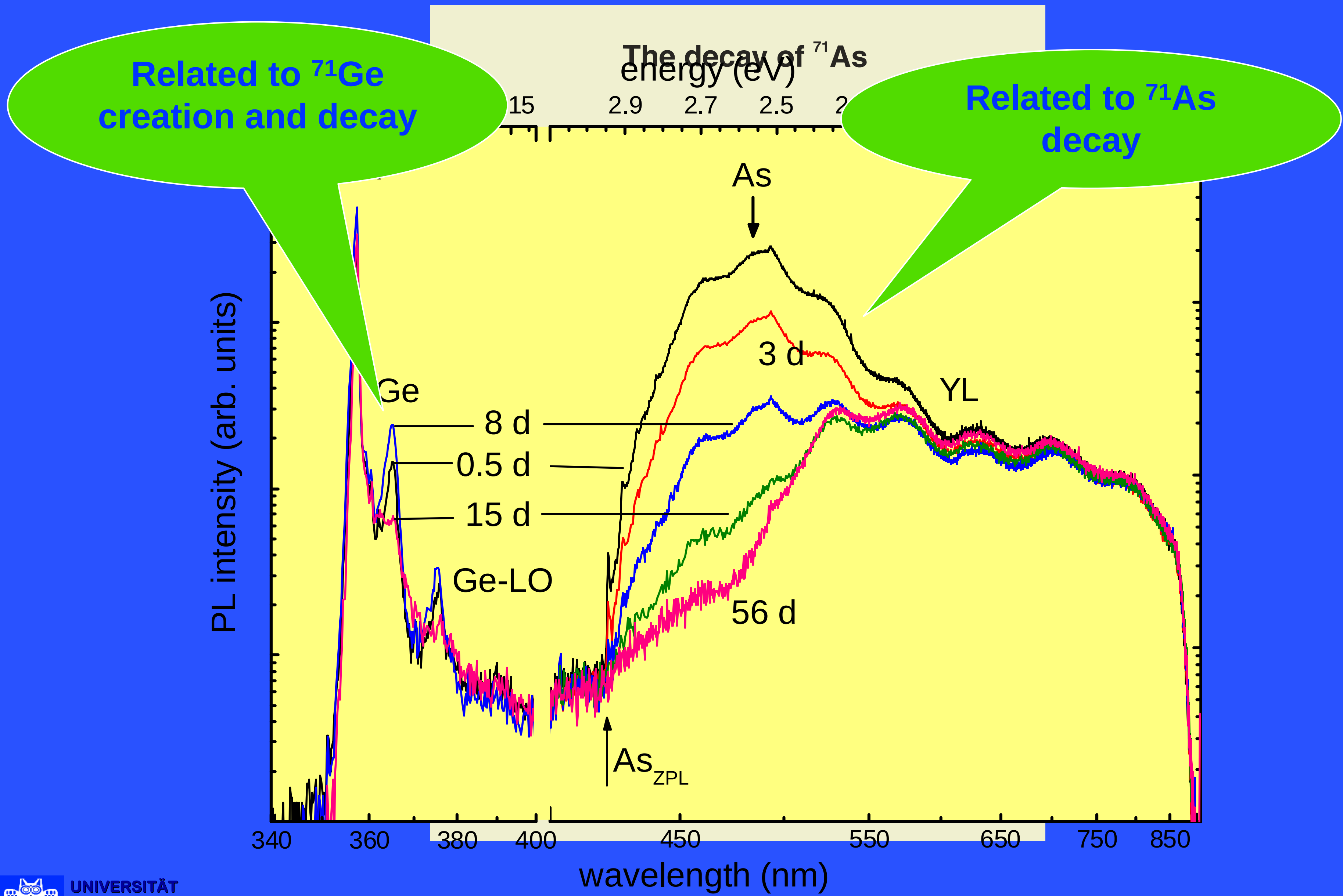
# Optical properties of impurity atoms

<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



# 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)

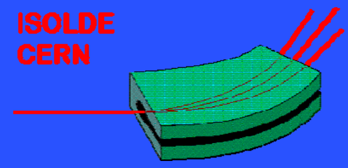
"It is the general opinion of the Audit Commission that the ISOLDE-SSP community is <…> reaching a scientific level and scientific output that is far above average."

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

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

# 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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