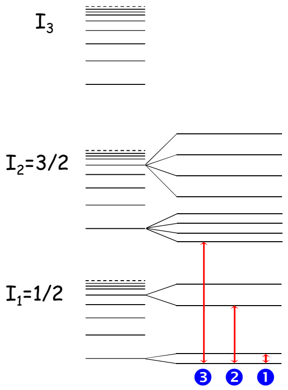
Perturbed Angular Correlation spectroscopy (PAC)

www. hyperfinecourse .org

Classification of nuclear methods

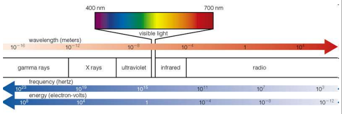


These 3 energy scales distinguish
3 different classes of experimental methods:

1
- Nuclear Magnetic Resonance (NMR)
- Nuclear Quadrupole Resonance (NQR)

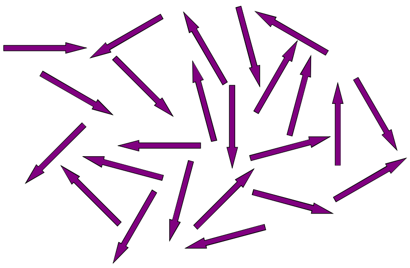
2
- laser spectroscopy
- Electron Paramagnetic Resonance (EPR)

3
- Low-Temperature Nuclear Orientation (LTNO)
- NMR on Oriented Nuclei (NMR/ON)
- forward scattering of synchrotron radiation
- Mössbauer Spectrocopy (MS)
- Conversion Electron Mössbauer Spectroscopy (CEMS)
- Perturbed Angular Correlation spectroscopy (PAC)



Perturbed Angular Correlation spectroscopy

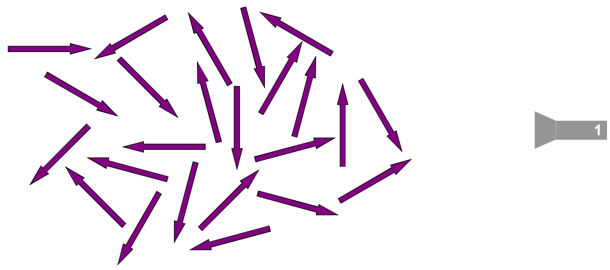
"mimicking strong nuclear orientation at room temperature"



A collection of nuclear spins randomly oriented at room temperature. They are all in an excited nuclear state.

stefaan.cottenier@ugent.be

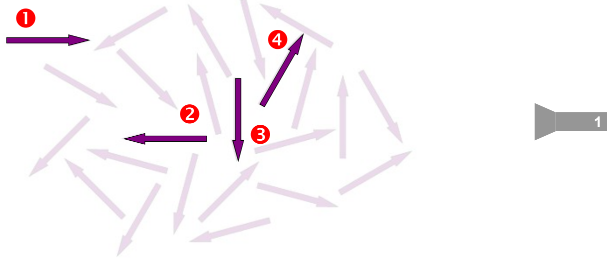
Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"



Measure the radiation emitted at each decay with a fixed detector "1". Which nuclei have the highest probability to deposit their radiation in this detector ?

4

Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"



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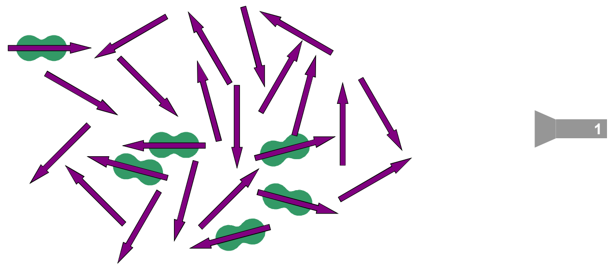
5

Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"



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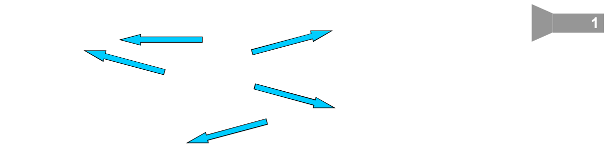
6

Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"



Imaginary 'label' the nuclei that were detected by detector 1. They form an oriented sub-ensemble. Can we do experiments on this sub-ensemble only ?

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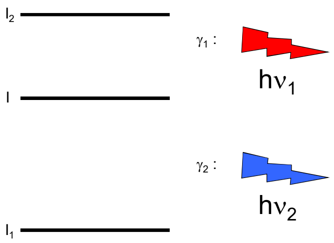
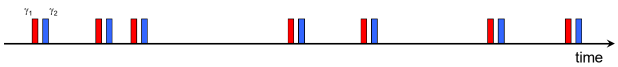
Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"

The trick: take a nucleus with a γ-γ-cascade in its decay scheme (two subsequent γ-rays).



The life-time of the intermediate level should be short compared to the typical time between two γ-γ-events in the sample:



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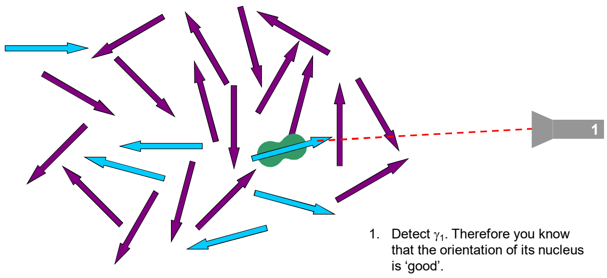
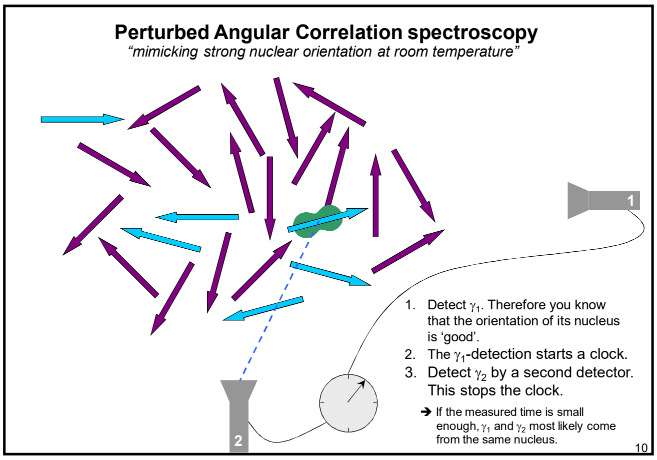
Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"



1. Detect γ_1. Therefore you know that the orientation of its nucleus is 'good'.

9


Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"
1
2
1. Detect γ_1. Therefore you know that the orientation of its nucleus is 'good'.
2. The γ_1-detection starts a clock.
3. Detect γ_2 by a second detector. This stops the clock.
→ If the measured time is small enough, γ_1 and γ_2 most likely come from the same nucleus.
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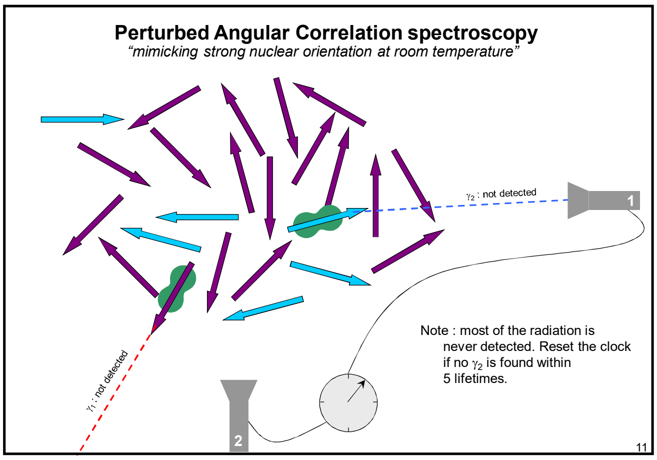
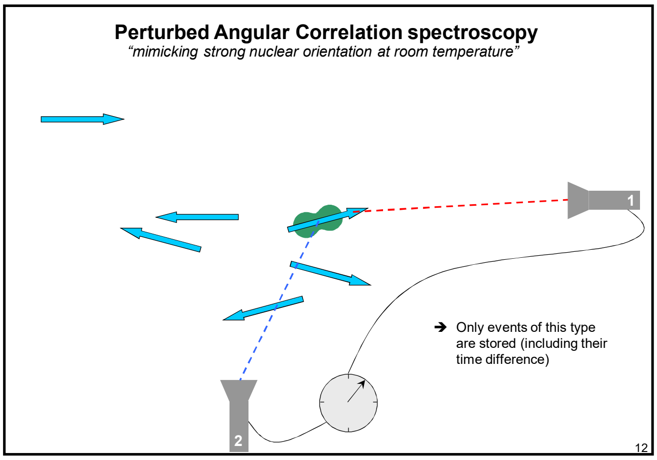
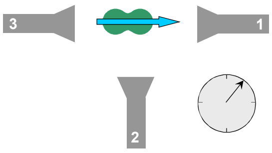

Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"
γ_2 : not detected
γ_1 : not detected
1
2
Note : most of the radiation is never detected. Reset the clock if no γ_2 is found within 5 lifetimes.
11

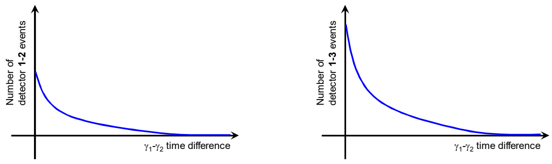

Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"
1
2
→ Only events of this type are stored (including their time difference)
12

Perturbed Angular Correlation spectroscopy
"mimicking strong nuclear orientation at room temperature"



In the absence of any hyperfine interaction.

Questions:
- why an exponential decay ?
- why a different count rate ?



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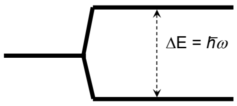
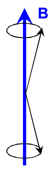
"mimicking strong nuclear orientation at room temperature"

Energy picture



A hyperfine field splits the nuclear levels by an energy $\Delta E = \hbar\omega$.

Vector picture



Nuclear spins precess with a frequency ω about the hyperfine field.

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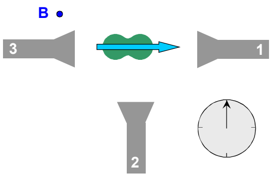
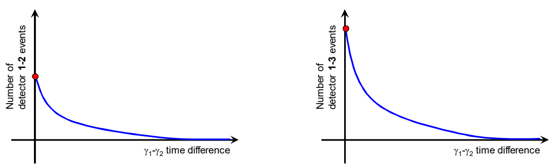
"mimicking strong nuclear orientation at room temperature"



At t=0



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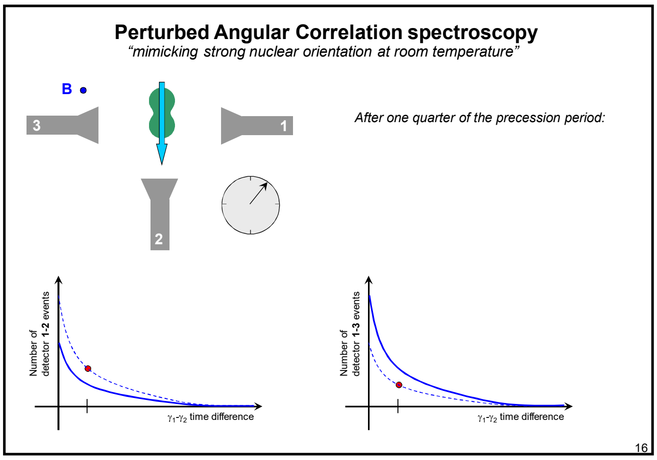
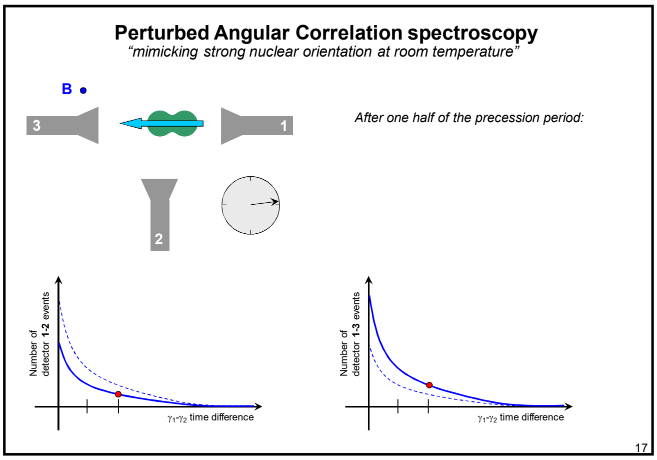
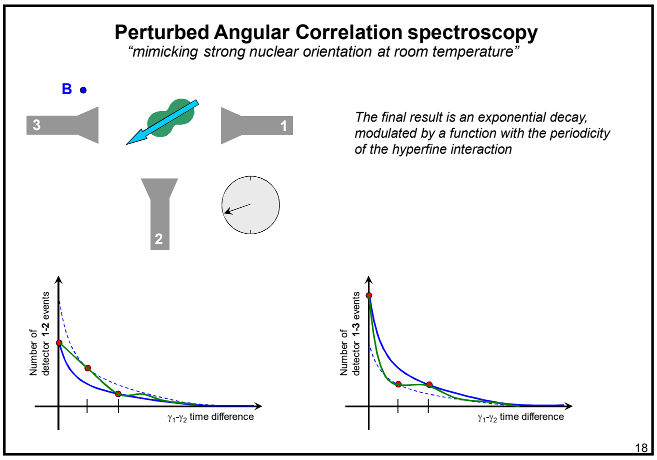
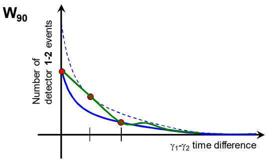

Perturbed Angular Correlation spectroscopy
“mimicking strong nuclear orientation at room temperature”
B
3
1
2
After one quarter of the precession period:
Number of detector 1-2 events
γ_1-γ_2 time difference
Number of detector 1-3 events
γ_1-γ_2 time difference
16

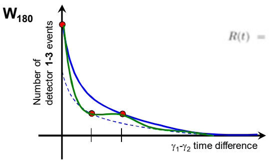

Perturbed Angular Correlation spectroscopy
“mimicking strong nuclear orientation at room temperature”
B
3
1
2
After one half of the precession period:
Number of detector 1-2 events
γ_1-γ_2 time difference
Number of detector 1-3 events
γ_1-γ_2 time difference
17


Perturbed Angular Correlation spectroscopy
“mimicking strong nuclear orientation at room temperature”
B
3
1
2
The final result is an exponential decay, modulated by a function with the periodicity of the hyperfine interaction
Number of detector 1-2 events
γ_1-γ_2 time difference
Number of detector 1-3 events
γ_1-γ_2 time difference
18

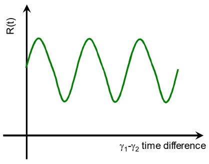
Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"





$$R(t) = 2\frac{W_{180}(t) - W_{90}(t)}{W_{180}(t) + 2W_{90}(t)}$$



➔ the frequency is a direct measure of the hyperfine interaction

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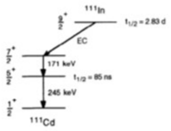
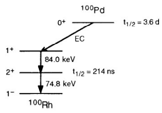
Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"

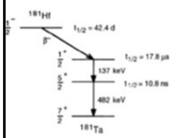
Some of the (few) convenient isotopes:



$\mu(5/2^+) = -0.7656(25)\mu_N$
$Q(5/2^+) = +0.83(13)$ b
$A_{22} = -0.18$
$A_{44} = -0.0015$
$A_{24} = -0.206$
$A_{42} = -0.0013$



$\mu(2^+) = +4.324(8)\ \mu_N$
$Q(2^+) = 0.076(20)$ b
$A_{22} = 0.175$



$\mu(5/2^+) = +3.24(5)\ \mu_N$
$Q(5/2^+) = +2.36(5)$ b
$A_{22} = -0.288$
$A_{44} = -0.076$
$A_{24} = -0.062$
$A_{42} = -0.318$

Requirements for a good PAC isotope :

- suitable life-time of parent activity
- life-time of intermediate level not too short
- life-time of intermediate level not too long
- nuclear moments of intermediate level not too small
- nuclear moments of intermediate level not too large
- anisotropy of radiation pattern sufficiently large

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Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"

Example of experimental curves:

^{111}Cd in single crystal hcp-Co

N.P. Barradas et al.,
Physical Review B 47 (1993) 8763
http://dx.doi.org/10.1103/PhysRevB.47.8763

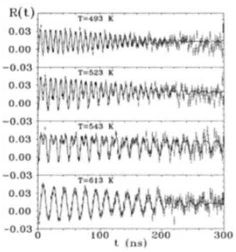

FIG. 2. Spectra taken between 493 and 613 K, with the *c* axis perpendicular to the detectors' plane. The transition from the "$2\omega_L$ to the ω_L frequencies" indicates the transition of the magnetization from the *c* axis to the basal plane. At 613 K only the "ω_L frequencies" are seen, which shows that the magnetization is in one single direction (see text).

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Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"

Example of experimental curves:

^{100}Rh impurities in fcc Ni :
In favourable cases, many oscillations can be followed.

M. Rots et al.,
Hyperfine Interactions 35 (1987) 967

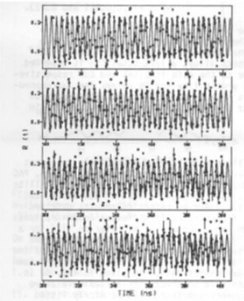

Fig.3. The time spectrum observed for ^{100}RhNi measured at room temperature.

1 measurement !
(the time axis is continuous)

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Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"

Recent development :

REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 073501 (2010)

A new all-digital time differential γ-γ angular correlation spectrometer

Matthias Nagl,[a] Ulrich Vetter, Michael Uhrmacher, and Hans Hofsäss[b]
II. Physikalisches Institut, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

(Received 16 January 2010; accepted 21 May 2010; published online 14 July 2010)

A new digital time differential perturbed angular correlation spectrometer, designed to measure the energy of and coincidence time between correlated detector signals, here correlated γ photons, is presented. The system overcomes limitations of earlier digital approaches and features improved performance and handling. By consequently separating the data recording and evaluation, it permits the simultaneous measurement of decays with several γ-ray cascades at once and avoids the necessity of premeasurement configuration. Tests showed that the spectrometer reaches a time resolution of 460 ps [using a ^{60}Co sample and $Lu_{1.8}Y_{0.2}SiO_5$:Ce (LYSO) scintillators, otherwise better than 100 ps], an energy resolution that is equivalent to the limit of the used scintillation material, and a processing capability of more than 200 000 γ quanta per detector and second. Other possible applications of the presented methods include nuclear spectroscopy, positron emission tomography, time of flight studies, lidar, and radar. *© 2010 American Institute of Physics.* [doi:10.1063/1.3455186]

FIG. 4. (Color online) A photo of the current setup. In the two mobile racks are the four recording computers and the server as well as network, high voltage, and control devices. On the left side the four detectors arranged around a sample are visible.

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Perturbed Angular Correlation spectroscopy

"mimicking strong nuclear orientation at room temperature"

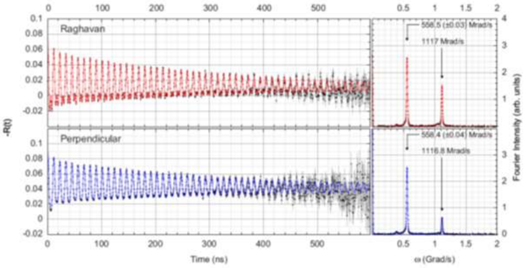

FIG. 8. (Color online) R(t) spectra (left) and the corresponding Fourier spectra (only cosine components, shown on the right) of a sample, where ^{111}In was implanted into a 100 μm thick Fe foil at an energy of 400 keV. Dots in the R(t) spectra correspond to the measured values at the centers of the channels chosen for this evaluation (channel width: 500 ps). The vertical gray bars indicate the absolute error of each channel (±σ). Continuous lines represent a fit that was made using WINFIT 3.0.4 (from the Division of Nuclear Solid State Physics at the University of Leipzig). The upper spectra correspond to a geometry where the surface normal of the foil is located within the detector plane with an angle of 45° toward the detectors' axes (Raghavan geometry), while in case of the lower spectra, the surface normal is perpendicular to the detector plane. No temper treatment was done to anneal radiation damage which might be the reason for the small damping of the R(t) functions as well as additional weak frequency components visible in the Fourier spectra (three components were fitted for each spectrum). The magnetic hyperfine interaction is observable by the Larmor frequencies ω_L and $2\omega_L$. Fully polycrystalline Fe should show both Fourier peaks with equal amplitude in the Raghavan geometry. The present sample therefore shows a clear texture in the plane of the Fe foil. The Larmor frequency can be used to calculate the magnetic field at the probe atoms' sites. This calculation results in a magnetic flux density of 38.1 T.

Very clean spectra !

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