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2nd Edition of the International Summer School
Physical and Chemical Principles in Materials Science
SMiLES group @ Laboratoire de Chimie de la Matière Condensée de Paris

Spectroscopy, Modelling, interfaces for natural Environment and health topics.

Spectroscopic and numerical approaches for synthetic and natural materials.
Solid state NMR in materials science

Bio-solids

Nanomaterials

Polymorphism

Hybrid materials

Biological materials
In this method, developed independently by two research groups headed respectively by F. Bloch and E. M. Purcell, the detection of the passage through the resonance is based on a modification occurring at resonance in the electromagnetic device itself that «drives» the resonant transition of interest...

in: *Principles of Nuclear Magnetism*, A. Abragam, 1961 (CEA, Collège de France)
Purcell’s vision

IN the well-known magnetic resonance method for the determination of nuclear magnetic moments by molecular beams,\(^1\) transitions are induced between energy levels which correspond to different orientations of the nuclear spin in a strong, constant, applied magnetic field. We have observed the absorption of radiofrequency energy, due to such transitions, in a solid material (paraffin) containing protons. In this case there are two levels, the separation of which corresponds to a frequency, \(\nu\), near 30 megacycles/sec., at the magnetic field strength, \(H\), used in our experiment, according to the relation \(h\nu = 2\mu H\). Although the difference in population of the two levels is very slight at room temperature \((h\nu/kT \sim 10^{-5})\), the number of nuclei taking part is so large that a measurable effect is to be expected providing thermal equilibrium can be established. If one assumes that the only local fields of importance are caused by the moments of neighboring nuclei, one can show that the imaginary part of the magnetic permeability, at resonance, should be of the order \(h\nu/kT\). The absence from this expression of the nuclear moment and the internuclear distance is explained by the fact that the influence of these factors upon absorption cross section per nucleus and density of nuclei is just cancelled by their influence on the width of the observed resonance.

A crucial question concerns the time required for the establishment of thermal equilibrium between spins and

in: *Spin Dynamics*, M. H. Levitt., 2002

« ... There the snow lay around my doorstep – great heaps of protons quietly precessing in the Earth’s magnetic field. To see the world for a moment as something rich and strange is the private reward of many discovery ... »
J. Jeener and R. Ernst: 2 dimensional (2D) Fourier Transform NMR

The unpublished Baško Polje (1971) lecture notes about two-dimensional NMR spectroscopy

J. Jeener

Faculté des Sciences (CPI-232), Campus Plaine, Université Libre de Bruxelles, B-1050 Brussels, Belgium

Abstract. — The main part of this paper is a reproduction of (previously unpublished) lecture notes, which were circulated in 1971, and which are often cited as the initiation of two-dimensional NMR spectroscopy. A brief discussion follows about the way of handling data and durations in time-dependent quantum mechanics, and about the use of diagrams in NMR pulse spectroscopy in the usual or the superoperator formalism.

The Nobel Prize in Chemistry 1991
Richard R. Ernst

The Nobel Prize in Chemistry 1991
Nobel Prize Award Ceremony
Richard R. Ernst

Richard R. Ernst

The Nobel Prize in Chemistry 1991 was awarded to Richard R. Ernst "for his contributions to the development of the methodology of high resolution nuclear magnetic resonance (NMR) spectroscopy".

Discrete Fourier transform
Uniform sampling
δ and J: selection, transfer, edition, correlation ... (COSY, INEPT, HETCOR...)

D: relaxation ... (NOESY...)

99% $^{15}$N-human ubiquitin
extension to solid state NMR of proteins
Magnetic Resonance Imaging (MRI)

adding field gradients

http://irfu.cea.fr/en/Phocea/
The Nobel Prize in Physiology or Medicine 2003
Paul C. Lauterbur, Sir Peter Mansfield

The Nobel Prize in Physiology or Medicine 2003
Nobel Prize Award Ceremony
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Sir Peter Mansfield

Paul C. Lauterbur  Sir Peter Mansfield

The Nobel Prize in Physiology or Medicine 2003 was awarded jointly to Paul C. Lauterbur and Sir Peter Mansfield "for their discoveries concerning magnetic resonance imaging"
NMR interactions: structural spies

Key questions:

* Solution vs Solid State NMR?

* Intrinsic resolution when studying powdered samples?
Magic Angle Spinning (MAS) – “reorientation” of sample → DYNAMICS!

rotor axis  \[ \theta_m = 54.7^\circ \]

\[ B_0 \]

\[ ^{13}C: 1,2,3\text{-trimethoxybenzene} \]

isotropic region: \[ \delta_{iso} = 1/3 (\delta_{11} + \delta_{22} + \delta_{33}) \]


\[ \phi: 7\text{mm} \rightarrow \text{up to 6 kHz} \]

\[ \phi: 4\text{mm} \rightarrow \text{up to 15 kHz} \]

\[ \phi: 2.5\text{mm} \rightarrow \text{up to 35 kHz} \]

\[ \phi: 1\text{mm} \rightarrow \text{up to 100 kHz} \]

question: is it really possible?...
Outline

• Hybrid materials: *bio-inspired* materials as a first example

• *Ab initio* calculations of NMR parameters

• Liposils as nano-cargos for drug delivery

• **Sensitivity** issues:
  * applications of DNP MAS to synthetic and natural biological materials
  * applications of Magic Angle Coil Spinning (MACS)
Hybrid interfaces: a first example

Coll.: B. Alonso & colleagues from CEMHTI, Orléans, France

- 1H-1H dipolar interaction
- ureidopyrimidinone models
- bio-inspired materials
Ureidopyrimidinone based systems

**Diagram:**
- Inorganic pillars
- Biomolecular assembly
- Hydrolysis
- H-bonding
- XRD of precursors
- Ureidopyrimidinone derivatives

**Chemical Structure:**
- Ureidopyrimidinone derivatives
- Inorganic pillars
- Biomolecular assembly
- Hydrolysis
- H-bonding

**Table:**
- **XRD of precursors**
  - MONOCLINIC
  - \( P 21/n \)
  - \( a = 9.0372 \, \text{Å} \)
  - \( b = 15.5020 \, \text{Å} \)
  - \( c = 23.3873 \, \text{Å} \)
  - \( \beta = 92.837^\circ \)
Fast MAS $^1$H-$^1$H BABA: ureidopyrimidinone based systems

\[
\begin{align*}
\text{excitation} & \quad \text{reconversion} \\
\begin{array}{c}
\text{excitation} \\
\tau_R/2 \quad \tau_R/2 \\
\tau_R/2 \quad \tau_R/2
\end{array} & \quad \\
\begin{array}{c}
\text{reconversion} \\
\tau_R/2 \quad \tau_R/2 \\
\tau_R/2 \quad \tau_R/2
\end{array}
\end{align*}
\]

synchronization with MAS

BAck to BAck

2Q Hamiltonian
Application to hybrid silica

Organosilicas based on purine-pyrimidine base pair assemblies: a solid state NMR point of view.
Towards bio-inspired materials: Adenine (A) and Thymine (T) derivatives

Nanostructuring of hybrid silicas through self-recognition process.
Extension to ultra-fast MAS (1mm JEOL probe – 850 MHz Warwick)

- very high field (850 MHz)
- $^1$H-$^1$H DQ MAS at 80 kHz
- more adapted pulse sequences

**Coll.:** D. Iuga, J. V. Hanna & M. E. Smith, Warwick & Lancaster, UK
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- Ab initio calculations of NMR parameters
- Liposils as nano-cargos for drug delivery
- Sensitivity issues:
  * applications of DNP MAS to synthetic and natural biological materials
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**First principles calculations: the GIPAW approach**


**GIPAW**

- DFT
- periodic systems
- all-electron hamiltonians
- evaluation of \( j(1)(r') \) using pseudopotentials

\[
B_{in}^{(1)}(r) = \frac{1}{c} \int d^3 r' \ j^{(1)}(r') \times \frac{r-r'}{|r-r'|^3}
\]

- CSA
- EFG

♦ assignment
♦ dynamics
♦ amorphous samples

**Coll.: C. Gervais, LCMCP, Paris.**

Validation of GIPAW: the example of $^{31}$P

$\rightarrow$ Si$_5$O(PO$_4$)$_6$

\[ \delta_{\text{iso}} \]

\[ \Delta_{\text{CSA}} \]

\[ \eta_{\text{CSA}} \]

Exp.

Calc.

$31p$ -44.0 ppm

New perspectives in the PAW/GIPAW approach: $J_{P-O-Si}$ coupling constants, antisymmetric parts of shift tensors and NQR predictions (pages S86–S102)


Article first published online: 29 JUN 2010 | DOI: 10.1002/mrc.2635
First principles calculations of $J$ coupling constants: $\text{Si}_5\text{O(PO}_4\text{)}_6$

$\rightarrow \text{Si}_5\text{O(PO}_4\text{)}_6$

INEPT MAS data: $J \sim [4 \text{ Hz} - 15 \text{ Hz}]$

<table>
<thead>
<tr>
<th>Phase</th>
<th>Sites</th>
<th>$^2J_{P-O-Si}$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Si}_5\text{O(PO}_4\text{)}_6$</td>
<td>Si(1)-O(3)-P</td>
<td>15 ± 2</td>
</tr>
<tr>
<td></td>
<td>Si(2)-O(2)-P</td>
<td>$14 \pm 4 \pm 2$</td>
</tr>
<tr>
<td></td>
<td>Si(2)-O(5)-P</td>
<td>$-14,18 \pm 2$</td>
</tr>
<tr>
<td></td>
<td>Si(3)-O(4)-P</td>
<td>$12 \pm 2$</td>
</tr>
</tbody>
</table>

New perspectives in the PAW/GPAW approach: $J_{P-O-Si}$ coupling constants, antisymmetric parts of shift tensors and NQR predictions (pages S86–S102)


Article first published online: 29 JUN 2010 | DOI: 10.1002/mrc.2635
More references: applications of GIPAW to glasses

- A pioneering work by T. Charpentier (CEA, Saclay, France): MD, DFT, GIPAW

- MD–GIPAW methodology for NMR glass studies

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A combined approach: silica based nano-cargos

**Coll.: T. Azaïs, LCMCP, Paris.**

L-\(\alpha\)-dipalmitoylphosphatidylycholine

- Liposomes (DPPC) and silica
- Drug delivery systems

See also: J. Brinker et al. *(proto-cell concept, JACS, 2009)*
Liposils (Liposomes and silica)

- a realistic model for hydroxylated amorphous silica
- a realistic model for silica/DPPC interactions
- full NMR ab initio calculations
- selection of adequate configurations!

Investigation of the interface in silica-encapsulated liposomes by combining solid state NMR and first principles calculations.
A model for hydroxylated amorphous silica


~ 6 OH/nm²


\[ C_Q = a (0.5 + \cos \alpha/(\cos \alpha - 1)) b + m(d-d_0) \]

\[ \delta(29\text{Si}) \text{ (ppm)} \]

\[ \delta(17\text{O}) \text{ (MHz)} \]

\[ \delta(1\text{H}) \text{ SiOH (ppm)} \]

\[ \text{OH...O (Å)} \]
The DPPC/silica interface: the role of water

decreasing number of H- bonds

GIPAW $\delta_{iso.}(^{31}P)$
config. 1: $\delta \sim 7.0$ ppm
config. 4: $\delta \sim -0.3$ ppm
exp.: $\delta = -0.7$ ppm
Local dynamics: $^{31}\text{P}$ slow MAS and static NMR

for « liposils »:

$\Delta_{\text{CS}} (\text{exp}) = -99.5 \text{ ppm} \quad \Delta_{\text{CS}} (\text{averaged}) = -98.22 \text{ ppm}$

$\eta_{\text{CS}} (\text{exp}) = 0.6 \quad \eta_{\text{CS}} (\text{averaged}) = 0.63$

$\varphi \sim 90^\circ$
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New trends in DNP

- transfer of electronic polarization to nearby nuclei under fast MAS, low T
- microwave (µW) irradiation of the spin system
- using radicals...

Overhauser, Schlichter, Abragam ....

R. G. Griffin: 1993 → today !
Substitutions in apatitic (HAp) structures

$\text{Ca}_{10} (\text{PO}_4)_6 (\text{OH})_2$

$\text{Mg}^{2+}$, $\text{Zn}^{2+}$, $\text{Na}^+$, $\text{K}^+ \ldots$

$\text{SO}_4^{2-}$, $\text{CO}_3^{2-} \ldots$

$\text{CO}_3^{2-}$, $\text{F}^-$, $\text{Cl}^-$ \ldots
Carbonated nanosized HAp

- synthetic HAp, ~ 5 wt %

\[ ^1H \rightarrow ^{13}C \]

\[ ^1H \rightarrow ^{31}P \rightarrow ^{13}C \]

\( \varepsilon \sim 23 \text{ to } 42 \)

Coll.: M. Caporini, G. Bodenhausen, EPFL, Lausanne & F. Aussenac, Bruker Biospin
NMR of hybrid mesoporous thin films

Magic Angle Coil Spinning

rotor at $\theta_m$

$\mu$-coil

Static coil


Applications potentielles:

- films
  - $S \sim 2 \text{ cm}^2$
  - $h \sim 300 \text{ nm}$
  - $m \sim 100 \mu\text{g}$

$^1\text{H} \ldots ^{29}\text{Si}, ^{13}\text{C}, ^{47/49}\text{Ti} (!) \ldots$
MACS experiments

(Coll.: D. Sakellariou)

1H: biopsies

1H HSQC

43Ca-1H HETCOR

17O

1H: films

23Na in bone

"hand made" micro-coils

100 µg

70 µg

MEMS techniques applied to micro-coils

Coll.: V. Badilita, U. Wallrabe, J. G. Korvink – IMTEK, Freiburg, Germany

Microfabricated inserts for magic angle coil spinning (MACS) wireless NMR spectroscopy.
PloS one, Vol., 7(8), 2012, pp. e42848-e42848.
Microcoil based solid state NMR: more references in the literature

**Solid State Nuclear Magnetic Resonance**

**Review Article**

Microcoils and microsamples in solid-state NMR
Kazuyuki Takeda

**Journal of Magnetic Resonance**

**Communication**

Nondestructive high-resolution solid-state NMR of rotating thin films at the magic-angle
Munehiro Inukai, Yasuto Noda, Kazuyuki Takeda

**Microcoil High-Resolution Magic Angle Spinning NMR Spectroscopy**

Hans Janssen, Andreas Brinkmann, Ernst R. H. van Eck, P. Jan M. van Bentum, and Arno P. M. Kentgens

Department of Physical Chemistry/Solid-State NMR, Institute for Molecules and Materials, Radboud University Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands

DOI: 10.1021/ja061350+$

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**Disk MAS NMR**

**Piggy back set up**