

Joint Laboratory of Solid-State NMR
IMC AS CZ and JHIPC AS CZ

Institute of Macromolecular
Chemistry AS CR
Heyrovsky Sq. 2
162 06 Praha 6
Czech Republ.

(1)

NMR spectroscopy in characterization of organic solids - overview

Diagram illustrating the structure and dynamics of organic solids, showing a polymer chain and its corresponding NMR spectra.

Schedule

- Lecture 1. NMR spectroscopy in characterization of organic solids - overview
 - Basic principles
 - First NMR signals
 - Sample rotation
 - Cross-polarization
 - 2D spectroscopy
 - NMR crystallography and polymer systems
- Lecture 2. Dynamics of multicomponent polymer systems
 - Principles of 1H-1H wide-line separation experiments
 - Determination of size of domains: motional averaging and spin diffusion
 - Location of external water molecules
 - Measurements of 1H-13C dipolar spectra
 - Models of segmental motions - motional amplitudes
 - Domain-selective experiments for polymer nanocomposites
- Lecture 3. Structure of multicomponent polymer systems
 - 2D spectroscopy
 - Spin-diffusion and multiple-pulse decoupling
 - Morphology of polymer blends and networks
 - Measurements of interatomic distances
 - NMR crystallography - refinement of 3D structure
- Lecture 4. Structure of aluminosilicate materials
 - Amorphous aluminosilicate inorganic polymers (AIP) - synthesis
 - Primary structural data about Al/Si materials - 29Si a 27Al MAS NMR
 - Amorphous-crystalline phase transition of AIPs
 - How to get structural parameters
 - Multiple-quantum experiments
 - Location of water molecules

NMR spectroscopy in chemistry, biology and medicine

Structure and dynamics

Medicine

Biology

Chemistry

Physics

NMR spectroscopy

40-50h

60-70h

80-90h

present

Diagram illustrating the application of NMR spectroscopy across different fields: Physics (40-50h), Chemistry (60-70h), Biology (80-90h), and Medicine (present).

Dawn of the Universe and NMR

"Epoch of Nucleosynthesis" - 3 min - 400 000 years; 10⁹-3000 K - formation of heavier nuclei

"Lepton Epoch" - 1s - 3 min; 10¹⁰-10⁹K - formation of protons

"Hadron Epoch" - 10⁻⁶-1s; 10¹³-10¹⁶K - quarks combine to form protons and neutrons

"Electroweak Epoch" - 10⁻¹²-10⁻⁶s; 10¹⁵-10¹³K - formation of electrons and positrons

"Grand Unification Epoch" - 10⁻³⁵-10⁻¹²s; 10²⁷-10¹⁵K - formation of quarks

"Planck Epoch" - 10⁻⁴³-10⁻³⁴s; 10³²-10²⁷K

The Big Bang - time 0 s

Spin predicted by W. Pauli in 1924 as the 4-th quantum number
1945 - Nobel Prize

Diagram illustrating the epochs of the universe's expansion and the discovery of spin by W. Pauli in 1924.

Basic principles - spin precession

Rotating gyroscope in gravity field

Applied magnetic field

Precessional orbit

Spinning nucleus

Spin precession in magnetic field

$\Delta E = h\nu = \alpha\mu/2\pi$

Spin precession in magnetic field 11.9T

1H: 500 MHz
13C: 125 MHz
15N: 50 MHz

Diagram illustrating the basic principles of spin precession, comparing a rotating gyroscope in a gravity field to a spinning nucleus in a magnetic field.

Energy levels – sensitivity

Increasing difference at energy levels with increasing intensity of magnetic field

The difference for 1 000 000 spins is:

2,3 T

9,3 T

21 T

16 spins @ 100 MHz

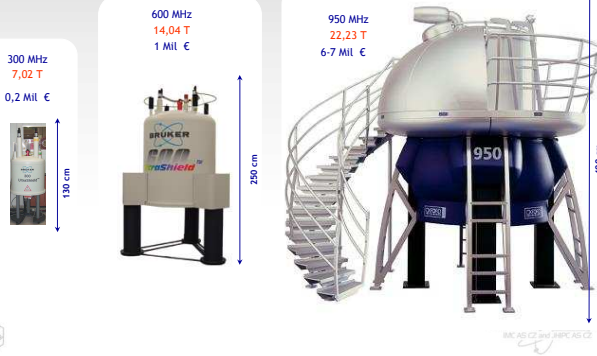
64 spins @ 400 MHz

135 spins @ 900 MHz

$N_{\alpha} / N_{\beta} = e^{\Delta E/kT} = 1.000064.....(400\text{MHz})$

Diagram illustrating the energy levels and the resulting difference in spin populations for 1,000,000 spins at different magnetic field strengths (2.3 T, 9.3 T, 21 T) and frequencies (100 MHz, 400 MHz, 900 MHz).

How to generate strong magnetic field



History - measurements of magnetic moment 1938

RADAR technology

Isidor Isaac Rabi
1898-1988
1944 - Nobel Prize

Rabi I., Zacharias J.R., Millman S., Kusch P.
A new method of measuring nuclear magnetic moment.
Phys Rev 1938; 53: 318.

SAZ AV ČR Inst. ANPAC AS CZ

History - first NMR signals 1946-51

Bloch's laboratory

Felix Bloch
1905-1983

Edward M. Purcell
1912-1997
1952 - Nobel Prize

Arnold J.T., S.S. Durrum, and M.E. Packard,
J. Chem. Phys., 1951, 19: p. 307.

Bloch, F.; Hansen, W. W.; Packard, M.
The nuclear induction experiment
Physical Review (1946), 70 474-85.

SAZ AV ČR Inst. ANPAC AS CZ

History - magic angle spinning 1958

Lowe, I.J.
Free Induction Decays in Rotating Solids, Phys.
Rev. Lett. (1959); 2: 285.

Andrew E.R., Bradbury A., Edgers R.G.
NMR spectra from a Crystal Rotated at High Speed,
Nature (1958); 182: 1459.

Magic angle spinning

Static sample

Rotating sample, 12 kHz

Powder averaging

SAZ AV ČR Inst. ANPAC AS CZ

History - MAS and proton NMR signals (1970)

NARROWING OF PROTON NMR LINES BY MAGIC ANGLE ROTATION

D. DOSKOČILOVÁ and B. SCHNEIDER
Institute of Macromolecular Chemistry,
Czechoslovak Academy of Sciences, Prague, Czechoslovakia

Received 16 June 1970

Narrowing of NMR signals of protons by "magic angle" rotation has been achieved in some solid polymers, and in liquids sorbed on, or dispersed in solid lattices in these, resolution equal to that of pure liquids is obtained.

Bohdan Schneider

Danica Doskočilová

SAZ AV ČR Inst. ANPAC AS CZ

Line narrowing under MAS: ¹³C vs. ¹H

¹³C CP/MAS NMR

0 kHz

0.5 kHz

2.0 kHz

3.0 kHz

12 kHz

Increasing frequency of MAS

¹H MAS NMR

0 kHz

5 kHz

10 kHz

15 kHz

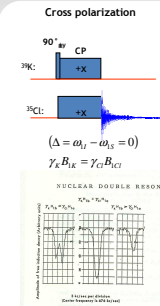
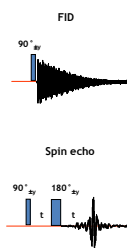
27 kHz

SAZ AV ČR Inst. ANPAC AS CZ

History - Hahn's experiments (1950-1962)



Erwin L. Hahn
*1921



Hahn, E. L., Spin echoes, *Phys. Rev.*, **80**, 580-594 (1950).

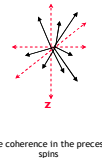
Hahn, E. L., Free nuclear Induction, *Physics Today*, Nov. (1953), pp. 4-9.

Hartmann S.R., Hahn E.L., Nuclear Double Resonance in Rotating Frame, *Phys. Rev.* (1962); **128**: 2042.

What happens in magnetic field

Spins out of magnetic field

No macroscopic magnetization

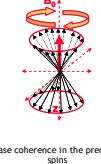


No phase coherence in the precession of spins



Spins in magnetic field

Longitudinal magnetization

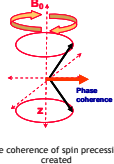


No phase coherence in the precession of spins



Spins after a pulse

Transverse magnetization



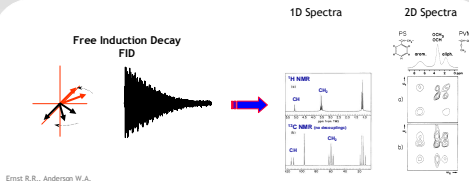
Phase coherence of spin precession is created



History - Pulsed NMR (1966, 1985 1822)



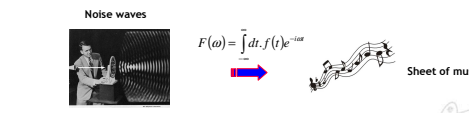
Richard R. Ernst
*1933
1991 - Nobel Prize



Ernst R.R., Anderson W.J., Application of FT Spectroscopy to Magnetic resonance, *Rev. Sci. Instr.*, (1966); **37**: 93.
Caravatti P., Neuenschwander P., Ernst R.R., Characterization of Heterogeneous Polymer Blends by 2D ¹H Spin Diffusion Spectroscopy, *Macromolecules* (1985); **18**: 119.



Jean Baptiste Joseph Fourier
1768-1830



Fourier J.B.J., *Theorie analytique de la chaleur*, Firmin Didot, pere et fils, Paris. (1822).

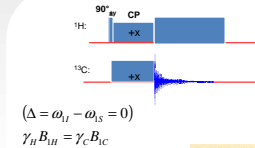
History - cross-polarization (1972)

Sensitivity enhancement

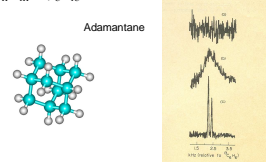


Alex Pines
*1945

Pines A., Gibby M.G., Waugh J.S., Proton-Enhanced Nuclear Induction Spectroscopy, A Method for High Resolution NMR of Dilute Spins in Solids, *J. Chem. Phys.*, (1972); **56**: 1776.



- 1) Transverse magnetization is created in ¹H spin system.
- 2) Then ¹H magnetization is spin-locked.
- 3) Hartmann-Hahn matching condition is established.
- 4) ¹³C transverse magnetization is created.
- 5) Repetition period depends on the relaxation of ¹H spins (short).



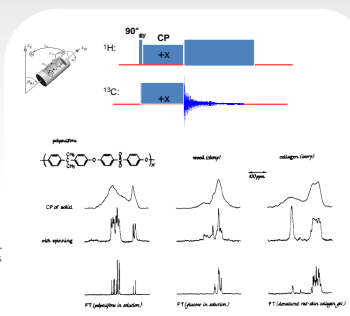
History - cross-polarization & MAS (1976)

Sensitivity enhancement combined with MAS

Schoeller J., Stojkai E.O.J., ¹³C NMR of Polymers Spinning at Magic Angle, *J. Am. Chem. Soc.* (1976); **98**: 1031.



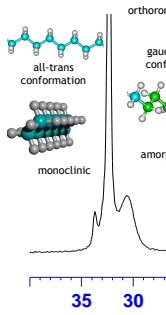
J. Schaefer



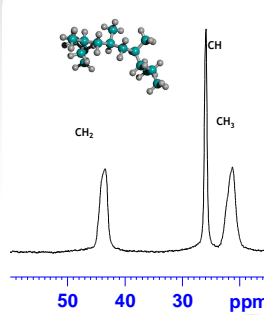
- 1) Sample rotates at magic angle to remove chemical shift anisotropy broadening
- 2) Transverse magnetization is created in ¹H spin system.
- 3) Then ¹H magnetization is spin-locked.
- 4) Hartmann-Hahn matching condition is established.
- 5) ¹³C transverse magnetization is created.
- 6) Repetition period depends on the relaxation of ¹H spins (short).

Typical solid-state NMR spectra of polymers

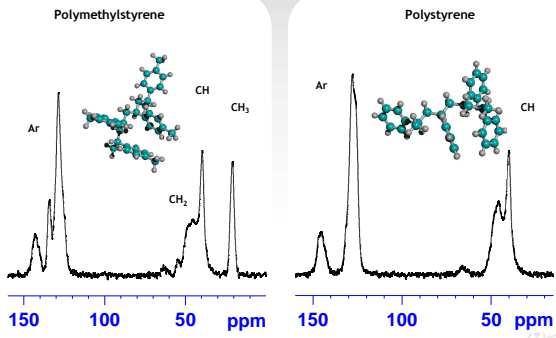
Polyethylene



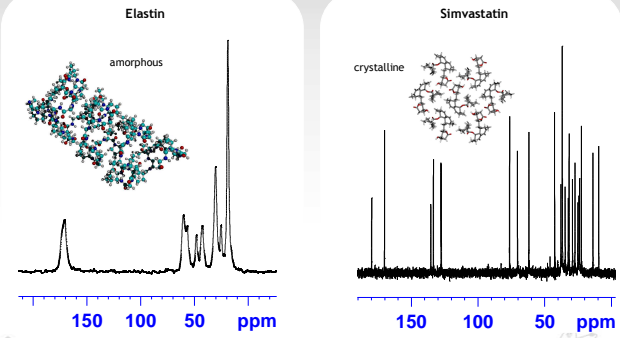
Polypropylene



Typical solid-state NMR spectra of polymers



Typical ss NMR spectra amorphs and crystals



Two-dimensional NMR spectroscopy(1971)

Transfer of magnetization through bonding electrons

Lecture at Summer School, Basko Polje, Yugoslavia, 1971
 Two-dimensional NMR, COSY
 Aue W.P., Bartholdi E., Ernst R.R.
 2D Spectroscopy, Application to NMR, J. Chem. Phys. (1976); 64: 229.

Jean Luis Charles Jeener
 *1931

3D structure of proteins (1986)

Allen G. Khan, Werner Braun and Kurt Wüthrich.
 Studies by ¹H nuclear magnetic resonance and distance geometry of the solution conformation of the α -amylase inhibitor Tendamistat. J.MOL.BIOL. 189 (2): 377-382 MAY 20 1985

Kurt Wüthrich
 *1938
 2002 - Nobel Prize

2D correlation experiments in solid state - 1985

Morphology of polymer blends

Carrazzini P., Neuschwander P., Ernst R.R.
 Characterization of Heterogeneous Polymer Blends by 2D ¹H Spin Diffusion Spectroscopy, Macromolecules. (1985); 18: 119.

2D ¹H MAS NMR pulse sequence
 BR24 Mixing 100-300 μ s BR24
 54° 90° 90° 54°
 t1 2t1 t2

Relayed coherence transfer
¹H-¹H correlation of chemical shifts

Separation experiments (1987 1995)

2D ¹H-¹³C WISE

Hans W. Spiess
 *1933

Schmidt-Rohr K., Claus J., Spiess H.W.
 Correlation of Structure and Mobility and Morphology by 2D Wideline-Separation NMR, Macromolecules. (1992); 25: 3273.

2D ¹H-¹⁵N SLF NMR

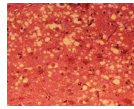
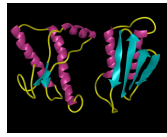
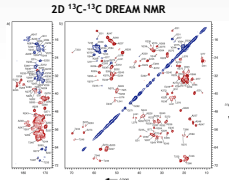
RG Griffin

Griffin R.G.
 Measurement of Heteronuclear Bond Distances in Polycrystalline Solids by Solid-State NMR, J.Am.Chem.Soc. (1987); 109: 4163.

3D structure of prion proteins (2005)



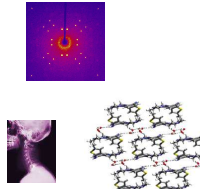
Meier B.H., et al., Correlation of Structural Elements and Infectivity of the HET-s prion, *Nature* (2005); 435(9): 844.



JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

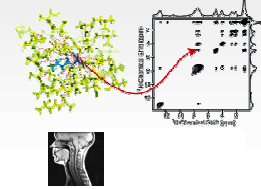
NMR crystallography

XRD



Frutczel-Edens S. et al. *Crystal Growth & Design* 3, 897 (2003)

ss-NMR



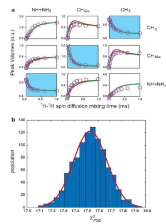
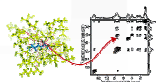
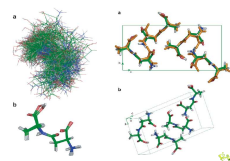
Elmsa B. et al. *J. Am. Chem. Soc.* (2006); 128, 9055.

JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

Crystal structure refinement - ¹H spin diffusion

Elmsa B. et al. Solid-state ¹H NMR crystallography, *J. Am. Chem. Soc.* (2005); 127(25), 9140.
Elmsa B. et al. Molecular Structure Determination in Powders by NMR Crystallography from Proton Spin Diffusion, *J. Am. Chem. Soc.* (2004); 126, 9555.



$$\frac{dM}{dt} = -K(M - M_0) \quad k_{ij} = \sum_k \left(\frac{\mu_0^2 \gamma^2 \hbar^2}{4\pi} \right) \frac{A}{(r_{ik})^3} \quad k_{ij} = -\sum_k k_{ik}$$

$$M(t, \tau_{SD}) = \exp(-K \tau_{SD}) M(t, 0) \quad P(\tau_{SD}) = \exp(-K \tau_{SD}) M(t)$$

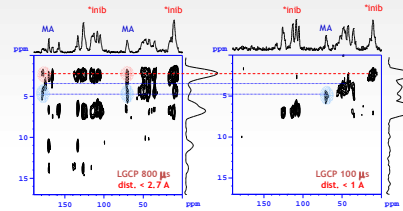
n ... Functional dependence on internuclear distance

$$\chi^2 = \sum_i \frac{(calc_i - t_i)^2}{\sigma_i^2}$$

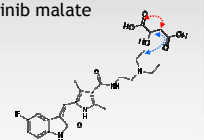
JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

Crystal structure ... - intermolecular contacts

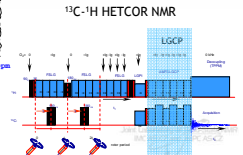
¹³C-¹H HETCOR NMR



*inib malate



¹³C-¹H HETCOR NMR

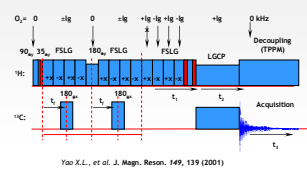
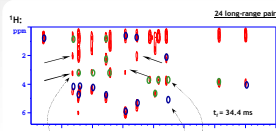


JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

Crystal structure ... - interatomic distances

Dipolar couplings and interatomic distances
Basic experimental approach

Extended 3D experiment
REDOR dephased ¹H-¹³C FSLG-LGCP-HETCOR



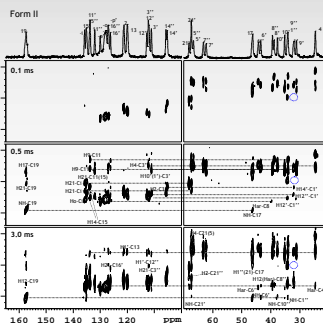
Yao X.L., et al. *J. Magn. Reson.* 149, 139 (2001)

JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

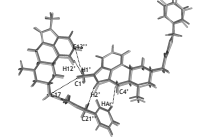
JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

Brus J. et al., Through-bonds and through-space solid-state NMR correlations at natural isotopic abundance: Signal assignment and structural study of stromvastatin, *JOURNAL OF PHYSICAL CHEMISTRY A* (2004); 108: 3955.

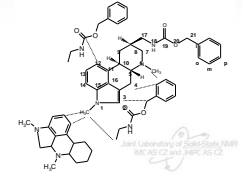
Structural fragments of Metergoline II



Refined structure



ss-NMR fragments



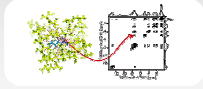
Husak M., Jegerov A., Brus J. et al., Metergoline II: structure solution from powder diffraction data with preferred orientation and from microcrystal, *STRUCTURAL CHEMISTRY* (2008); 19: 517.

JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

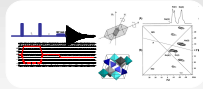
JKM Laboratory of Solid State NMR
MSE, MS, CS and NMR, AG-03

Summary

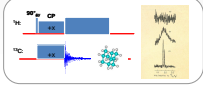
NMR crystallography



MQ/MAS NMR - inorganic systems

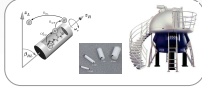


Cross-polarization

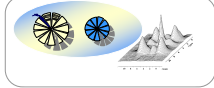


Solid-state NMR
and

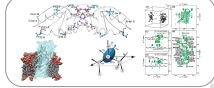
MAS - magic angle spinning



Structure and dynamics of polymers



Structure of proteins



of Solid-State NMR
for Biopolymers