2221-2

Hands-on Tutorial on Electronic Structure Computations

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NMR and EPR Spectroscopy

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NMR and EPR spectroscopy

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Based on material by
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Outline

- **PART I:**
  - Basic principles of magnetic resonance spectroscopy
  - Introduction to experimental NMR
  - Interpretation of NMR spectra
  - Solid state NMR

- **PART II:**
  - Effective NMR spin hamiltonian
  - The GIPAW method
  - Examples
  - Brief introduction to EPR spectroscopy and EPR parameters

- **PART III: (Emine Kuçukbenli)**
  - GIPAW pseudopotentials
  - The gipaw.x code: input file and description of the output

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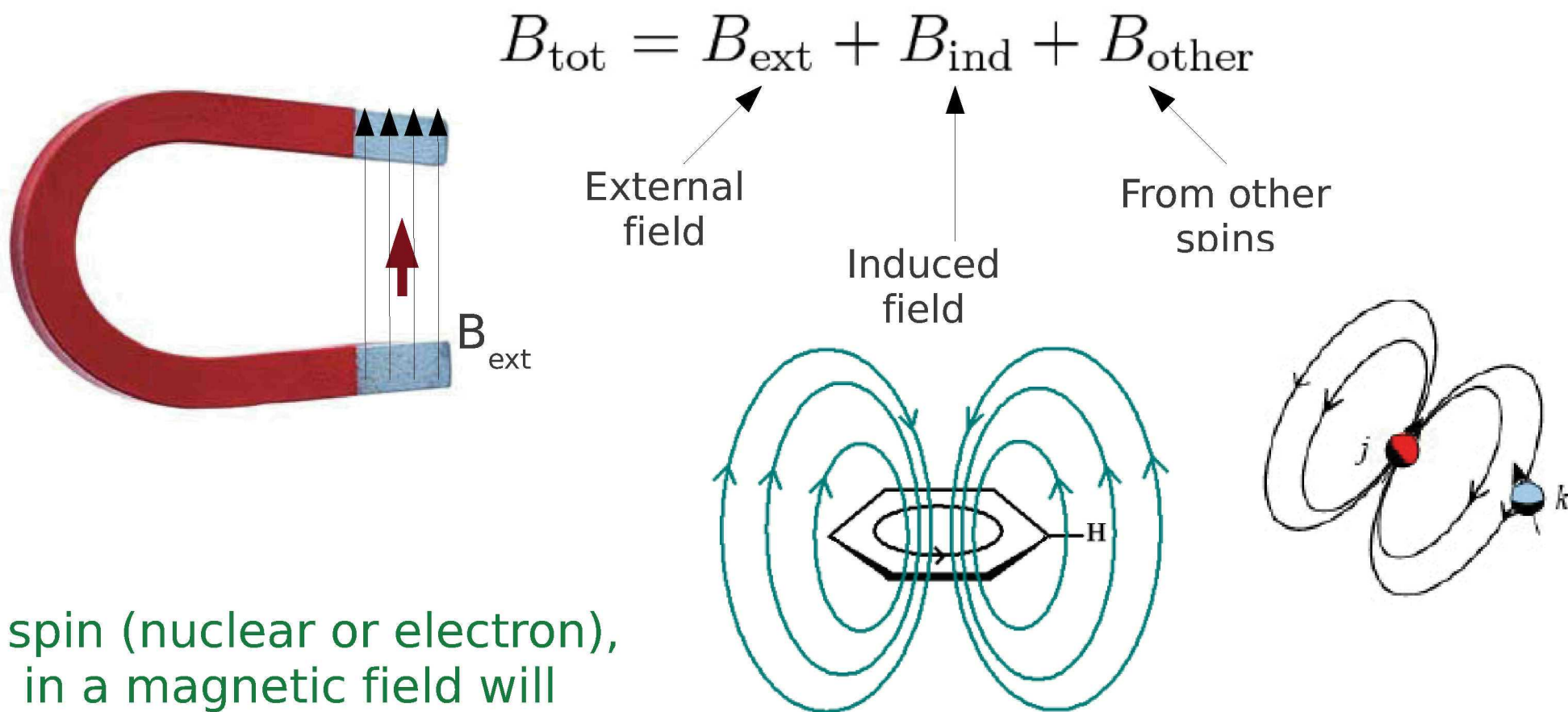 - Brief introduction to EPR spectroscopy and EPR parameters

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Principles of magnetic resonance

NMR = Nuclear Magnetic Resonance
EPR = Electron Paramagnetic Resonance (also ESR)

$$B_{tot} = B_{ext} + B_{ind} + B_{other}$$

External field

Induced field

From other spins

B_{ext}

A spin (nuclear or electron), in a magnetic field will tend to align

Principles of magnetic resonance

A spin in a magnetic field will align parallel or antiparallel to the field.
The Zeeman splitting is proportional to the <u>total</u> magnetic field.
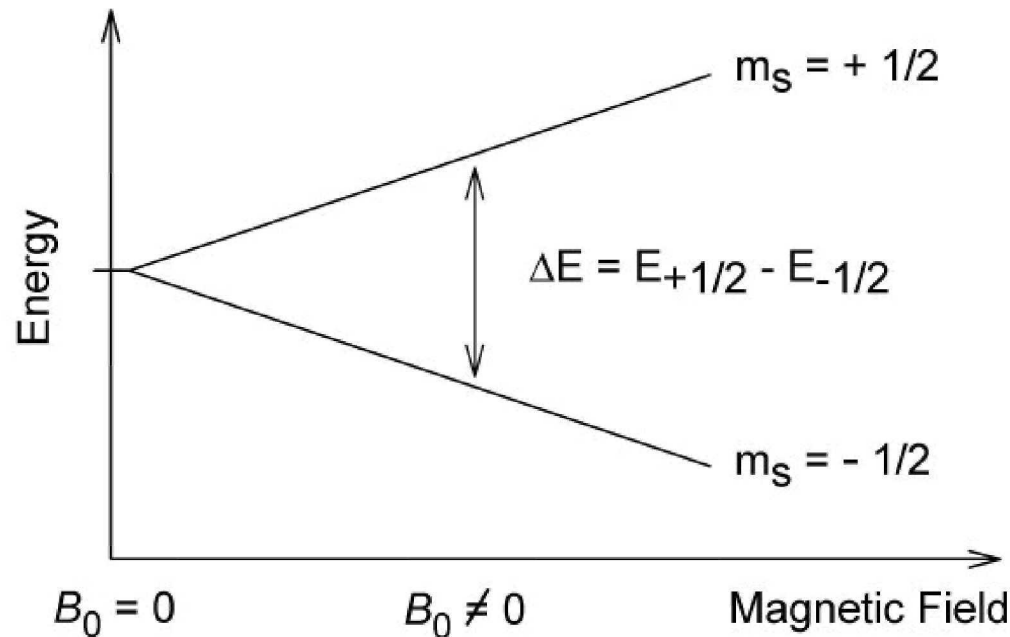
$$\Delta E = \hbar \, \gamma \, B_{\text{tot}} \, \Delta m_s$$

Zeeman splitting

Gyromagnetic ratio

The energy splitting can be probed by an electromagnetic wave of frequency ω:

$$\Delta E = \hbar \omega$$

Some useful relations

For a nucleus

$$\gamma = \frac{Q}{2M}g = \frac{g\mu_N}{\hbar}$$

γ = gyromagnetic ratio
Q = charge
m = mass
g = g-factor
μ_N = nuclear magneton

For the electron

$$\gamma_e = \frac{e}{2m_e}g_e = \frac{g_e\mu_B}{\hbar}$$

μ_B = bohr magneton (>> nuclear magneton)

For example:
g(^{1}H) = 5.585694 → γ(^{1}H) = 2.67·10^8 Hz/T
g(elec.) = −2.002319 → γ(elec.) = 1760·10^8 Hz/T

Resonance frequency is proportional to γ: **^{1}H @ 9.306 T → 400 MHz**

NMR active nuclei

Atom	Isotope	Spin	Larmor frequency (MHZ at 9.306 T)	Abundance (%)	Absolute sensitivity	Quadrupole (barn)
Hydrogen	1H	1/2	-400.00	99.98	1.00E+000	0
Deuterium	2D	1	-61.40	0.02	1.45E-006	0.00273
Lithium	6Li	1	-58.86	7.42	6.31E-004	-0.0008
Lithium	7Li	3/2	-155.45	92.58	2.70E-001	-0.045
Boron	10B	3	-42.98	19.58	3.90E-003	0.074
Boron	11B	3/2	-128.34	80.42	1.30E-001	0.0355
Carbon	13C	1/2	-100.58	1.11	1.76E-004	0
Nitrogen	14N	1	-28.90	99.63	1.01E-003	0.016
Nitrogen	15N	1/2	40.53	0.37	3.85E-006	0
Oxygen	17O	5/2	54.23	0.04	1.08E-005	-0.026
Fluorine	19F	1/2	-376.31	100.00	8.30E-001	0
Sodium	23Na	3/2	-105.80	100.00	9.25E-002	0.12
Magnesium	25Mg	5/2	24.48	10.13	2.71E-004	0.22
Aluminum	27Al	5/2	-104.23	100.00	2.10E-001	0.149
Silicon	29Si	1/2	79.46	4.70	3.69E-004	0
Phosphorus	31P	1/2	-161.92	100.00	6.63E-002	0
Sulfur	33S	3/2	-30.68	0.76	1.72E-005	-0.055
Chlorine	35Cl	3/2	-39.19	75.53	3.55E-003	-0.08
Chlorine	37Cl	3/2	-32.62	24.47	6.63E-004	-0.0632
Potassium	39K	3/2	-18.67	93.10	4.73E-004	0.055
Potassium	41K	3/2	-10.24	6.88	5.78E-006	0.067
Calcium	43Ca	7/2	26.91	0.15	9.28E-006	-0.05

NMR history

1937   **Rabi** predicts and observes nuclear magnetic resonance
1946   **Bloch, Purcell** first nuclear magnetic resonance of bulk sample
1953   **Overhauser** NOE (nuclear Overhauser effect)
1966   **Ernst, Anderson** Fourier transform NMR
1975   **Jeener, Ernst** 2D NMR
1985   **Wüthrich** first solution structure of a small protein (BPTI)
         from NOE derived distance restraints
1987   3D NMR + 13C, 15N isotope labeling of recombinant proteins
1990   pulsed field gradients (artifact suppression)
1996   new *long range* structural parameters: residual dipolar couplings
and cross-correlated relaxation

Nobel prizes
1944   *Physics*   Rabi
1952   *Physics*   Bloch, Purcell
1991   *Chemistry*   Ernst
2002   *Chemistry*   Wüthrich
2003   *Medicine*   Lauterbur, Mansfield

First ¹H NMR spectra of water
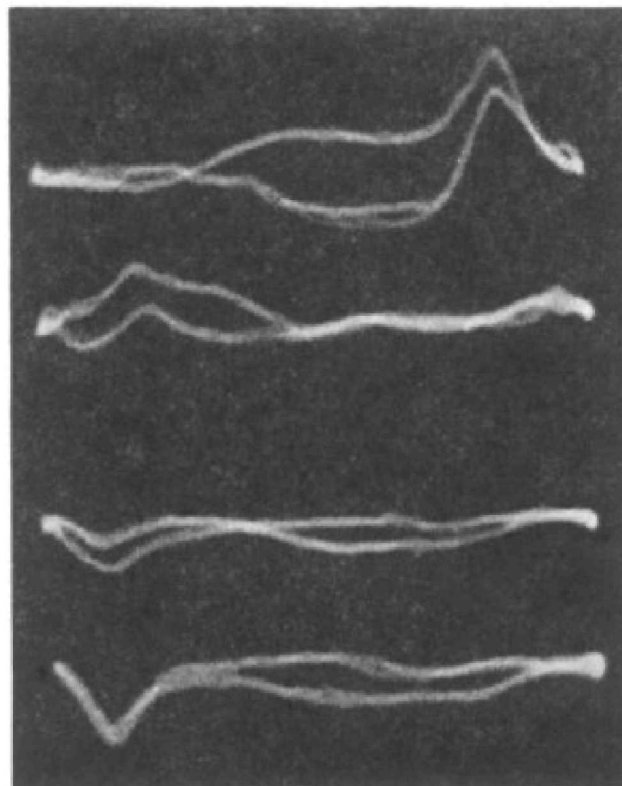
Fig. 10. Photographic record of the proton signal in water. The four traces from top to bottom correspond to the times t_1, t_2, t_3, t_4 of Fig. 9. In the text they are referred to as a, b, c, d, respectively.
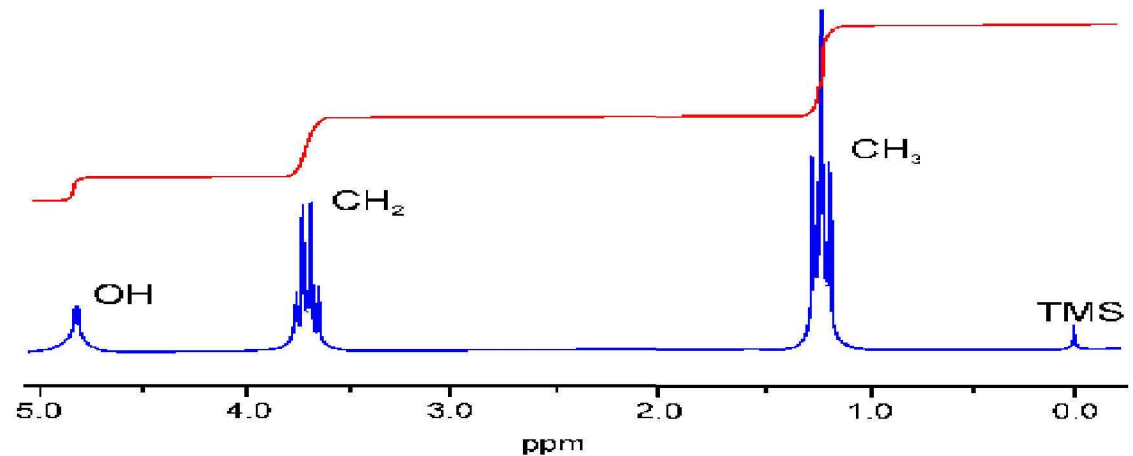
Bloch, Hansen and Packard, **The nuclear induction experiment**
Physical Review **70**, 474 (1946),

First observation of the chemical shift
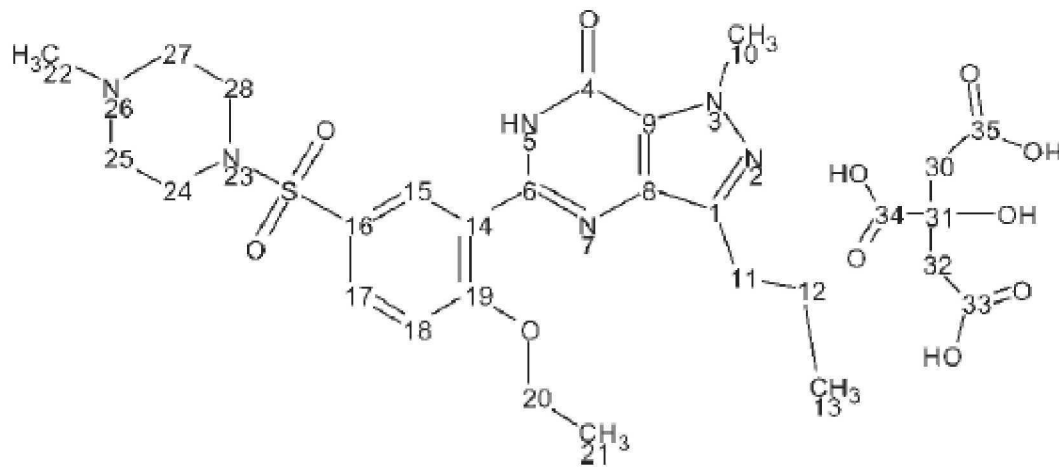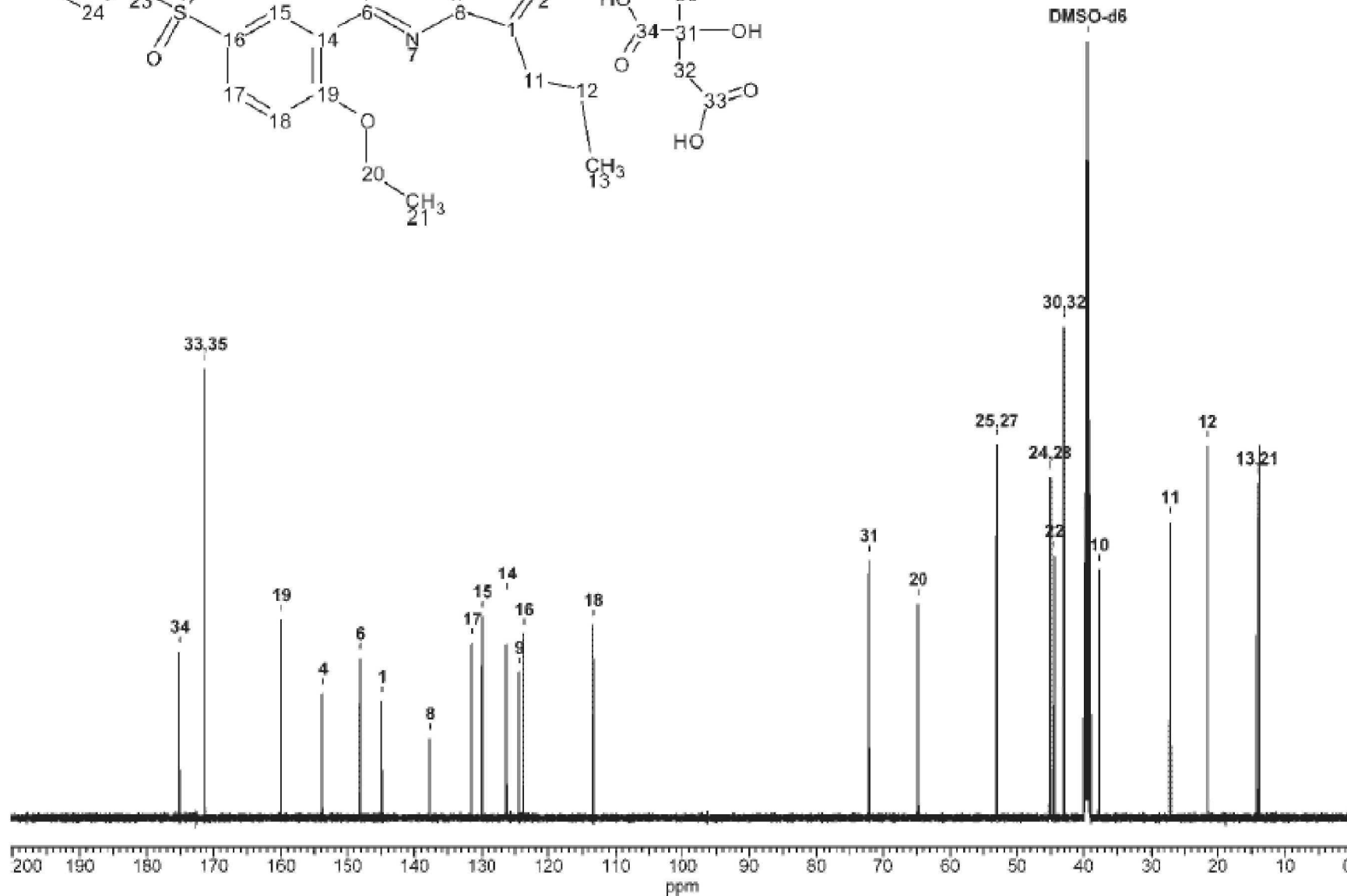
¹H NMR spectra ethanol
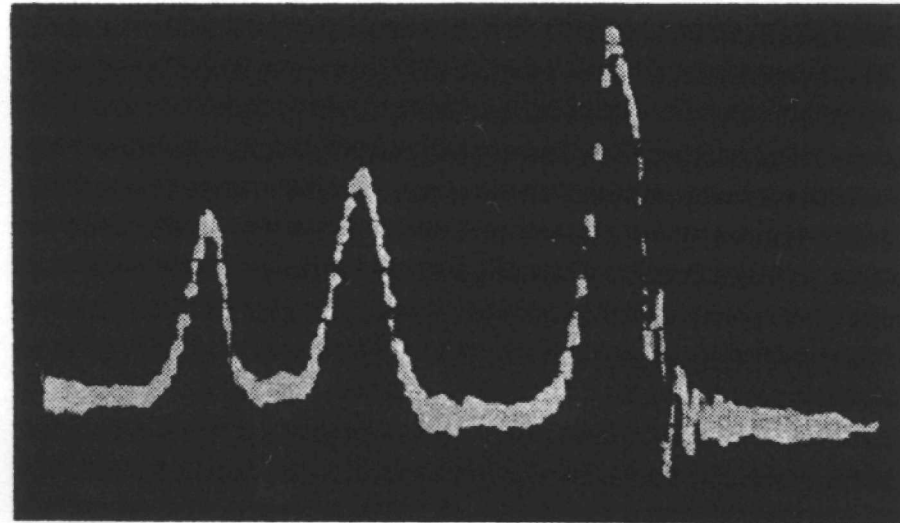
Modern ethanol spectra

Arnold, Dhamatti and Packard, J. Chem. Phys. **19,** 507 (1951)

Chemical shift as molecular fingerprint

Sildenafil-citrate (Viagra)

Typical applications of NMR

1) Structural (chemical) elucidation
    Natural product chemistry
    Synthetic organic chemistry
        - analytical tool of choice of synthetic chemists
        - used in conjunction with mass spectroscopy and IR

2) Study of dynamic processes
        reaction kinetics
        study of equilibrium (chemical or structural)

3) Structural (three-dimensional) studies
        Proteins, Protein-ligand complexes
        DNA, RNA, Protein/DNA complexes
        Polysaccharides

4) Drug Design   *MRI images of the Human Brain*

5) Medicine: MRI

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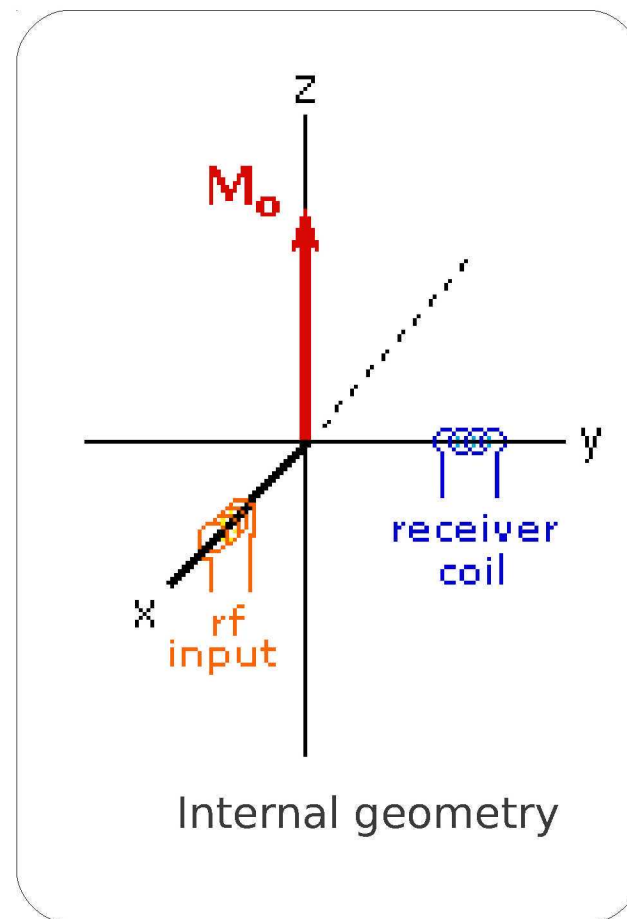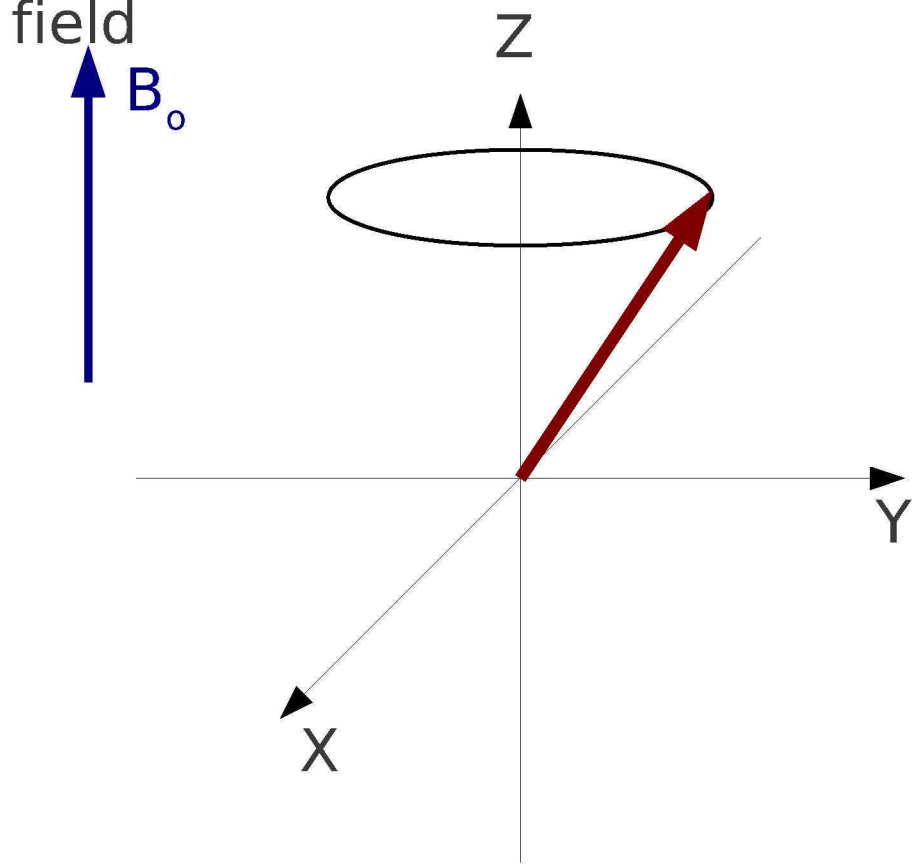 - The gipaw.x code: input file and description of the output

NMR spectrometer
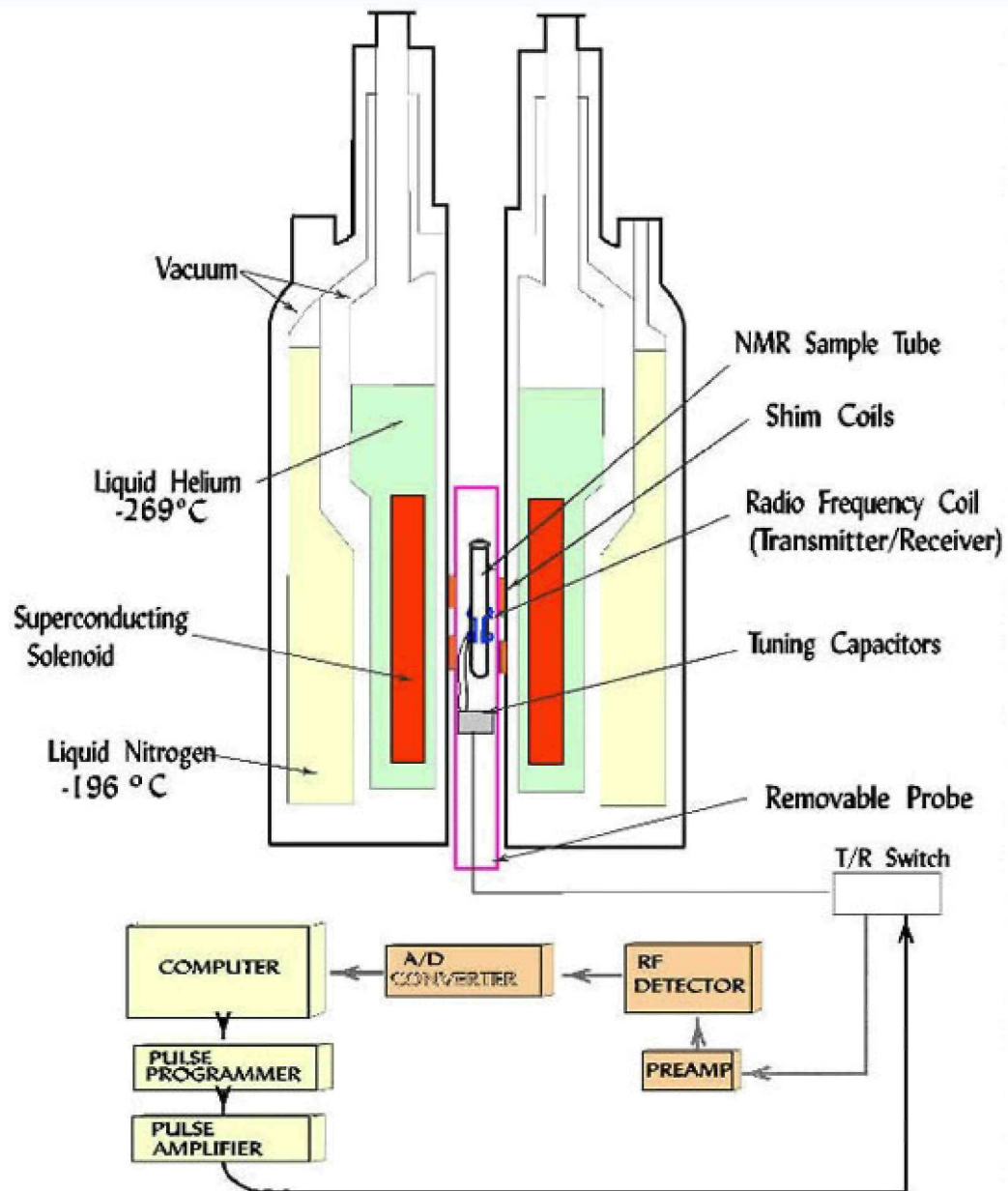
Typical fields   ~14 T
Resonance   ~600 MHz
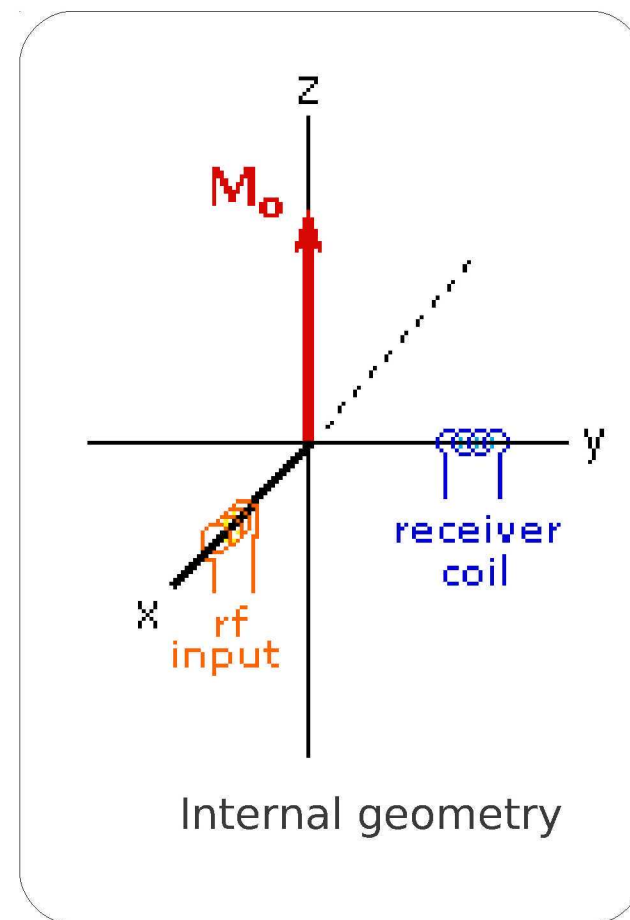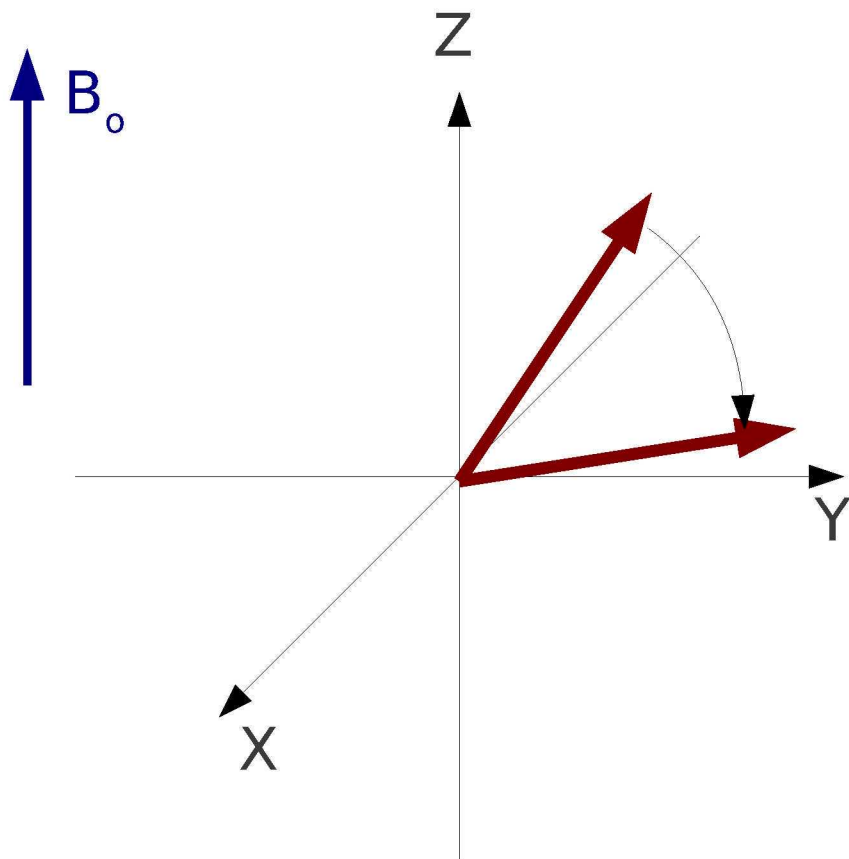Cost   ~800 k$

Classical description of NMR

Spin in a magnetic field B_0 precesses forever around the magnetic field

Internal geometry

On average, the magnetization lies only along the z-direction. In order to observe NMR, we must perturb the system!

Classical description of NMR
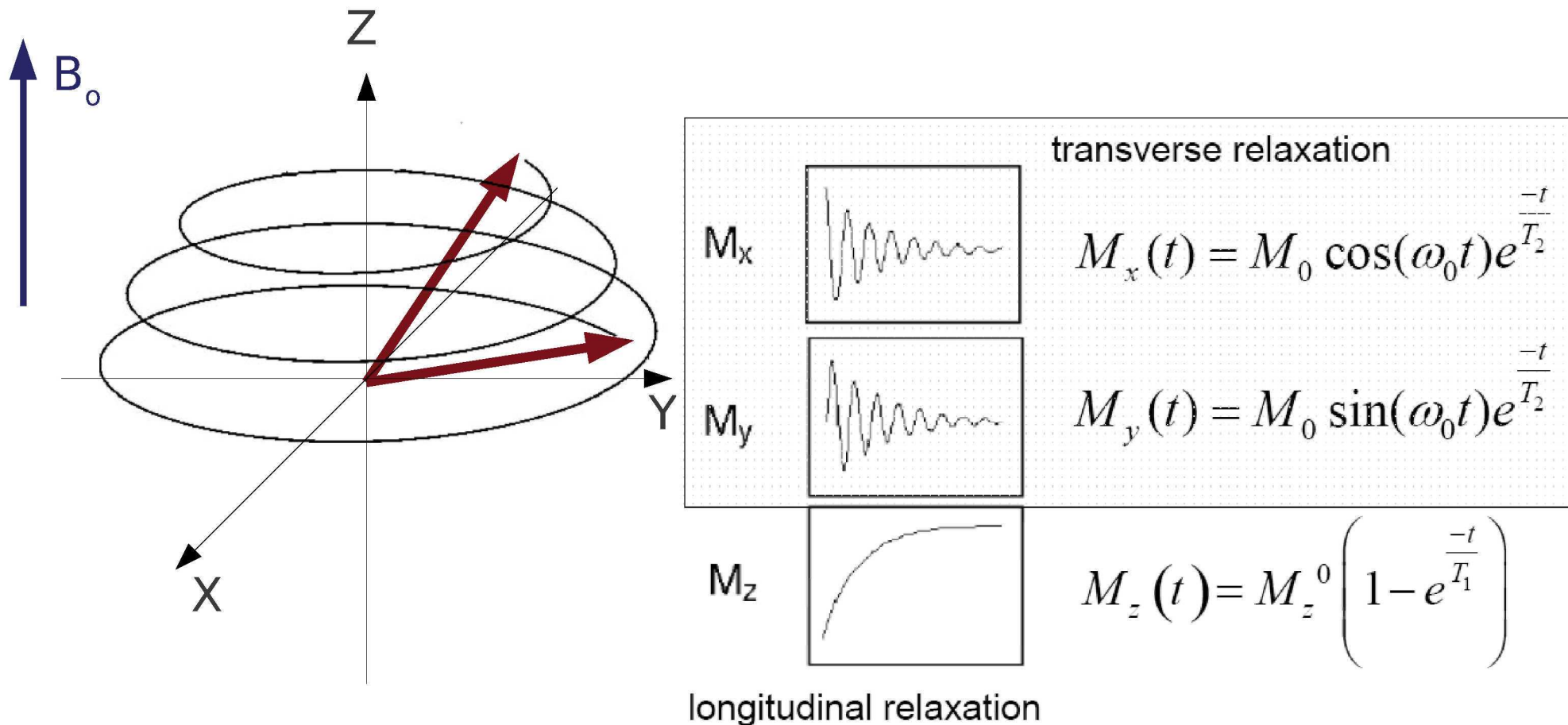
We send a RF pulse to by 90° the precession axis ...

Internal geometry

... and we start recording the spin relaxing back to the initial state.

Classical description of NMR

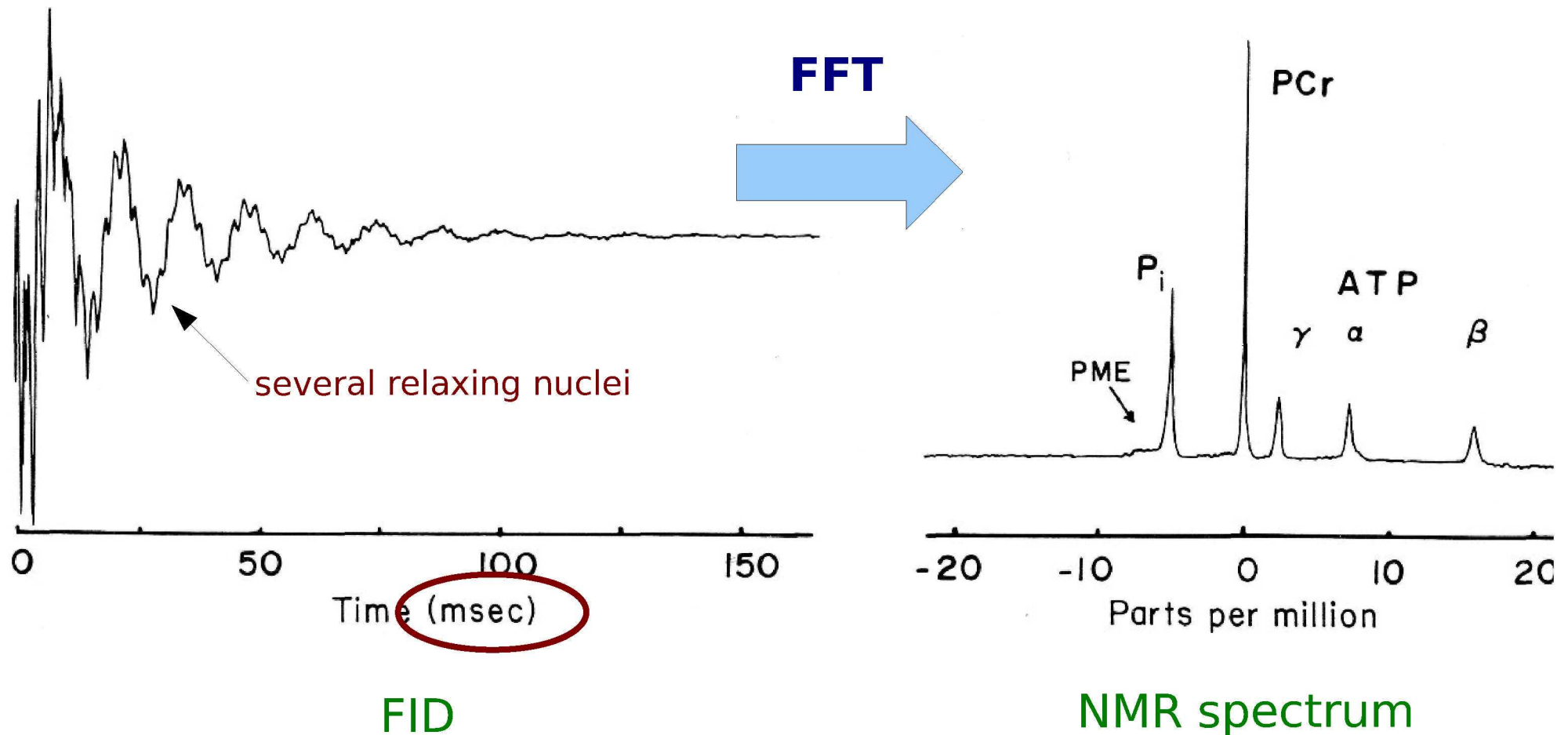... and we start recording the spin relaxing back to the initial state.

$$M_x(t) = M_0 \cos(\omega_0 t) e^{\frac{-t}{T_2}}$$

$$M_y(t) = M_0 \sin(\omega_0 t) e^{\frac{-t}{T_2}}$$

$$M_z(t) = M_z^0 \left(1 - e^{\frac{-t}{T_1}}\right)$$

T_1 = longitudinal (spin-lattice) relaxation time
T_2 = transverse (spin-spin) relaxation time

Free Induction Decay

Signal recorded after the pulse is called Free Induction Decay (FID).
The Fourier transform of the FID yields the NMR spectrum.
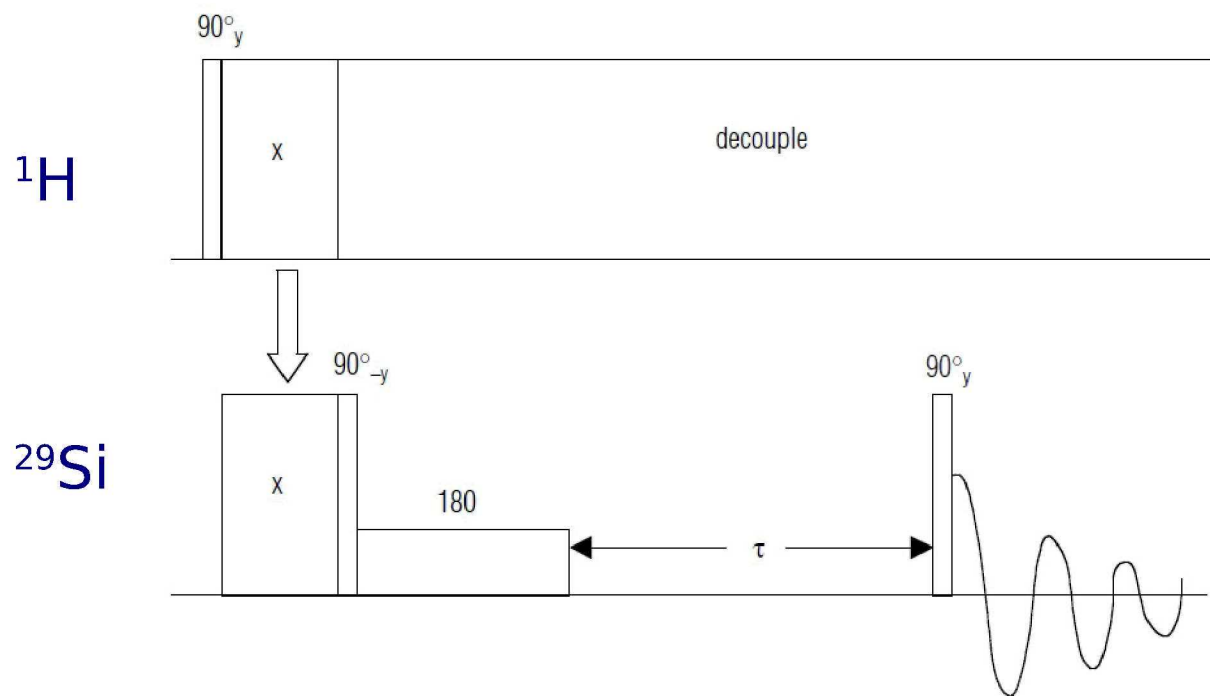

FID

NMR spectrum

Pulse sequences

The NMR spectrometer is a programmable machine!
Pulse sequences have been designed to:
- increase resolution and sensitivity, decouple spins
- find correlations between neighboring nuclei (2D and 3D NMR)

Cross-polarization (CP) pulse sequence

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Chemical shift

- Different nuclei/isotopes resonate at different Larmor frequencies.
- The resonance frequency is modified by the chemical environment.
- Every nucleus experiences a different local magnetic field.

Definition: shielding tensor σ

$$\mathbf{B}_{\text{eff}} = \mathbf{B}_{\text{ext}}\left(1 - \overset{\leftrightarrow}{\sigma}\right)$$

- σ independent of magnetic field
- usually σ << 1
- measured in ppm (1 ppm = 10^{-6})

Definition: chemical shift δ

$$\delta = -\left(\sigma - \sigma_{\text{ref}}\right)$$

- δ given as deviation from a <u>reference</u> compound
- measured in ppm (1 ppm = 10^{-6})

Reference compounds can be liquids, solutions, solids.

Chemical shift

In practice δ is obtained from the resonance frequencies:

$$\delta = \frac{\omega - \omega_{\mathrm{ref}}}{\omega_{\mathrm{ref}}} \cdot 10^6$$

TMS

Some reference compounds:
- ^1H, ^{13}C, ^{29}Si → tetramethylsilane (TMS)
- ^{15}N → liquid NH_3
- ^{17}O → liquid H_2O
- ^{19}F → liquid $CFCl_3$
- ^{27}Al → $AlCl_3$ in D_2O
- ^{43}Ca → $CaCl_2$(aq) 1 mol/L

It is possible to use a secondary reference if you know its chemical shift from the primary reference.
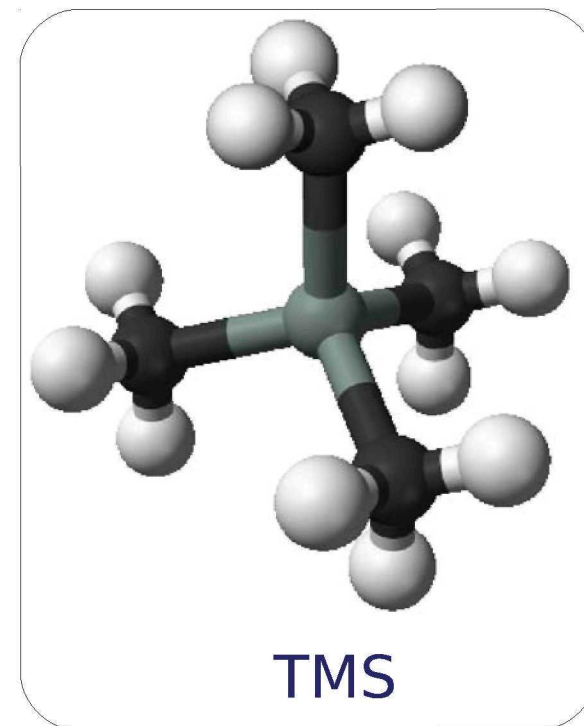
Chemical shift

The origin of the chemical shift are the orbital currents induced by the external magnetic field.

The shielding σ can be decomposed into a diamagnetic ($\sigma_d > 0$) and paramagnetic ($\sigma_p < 0$) term:

σ_d depends on the density of circulating electrons
increases with electronegativity of substituents

σ_p depends on the hindering free circulation
dominates in presence of p and d orbitals, anysotropic chemical bond, positive charges, low lying electronic states, high atomic number elements
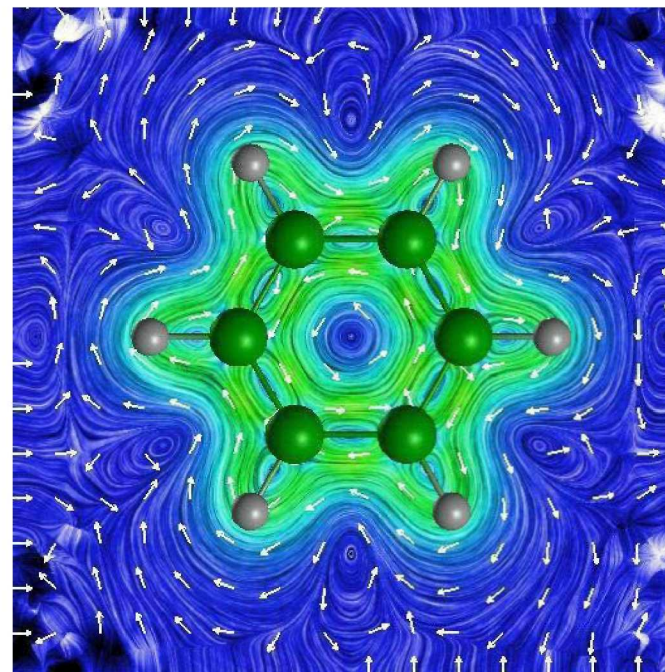
Electronic current in benzene, induced by a perpendicular magnetic field
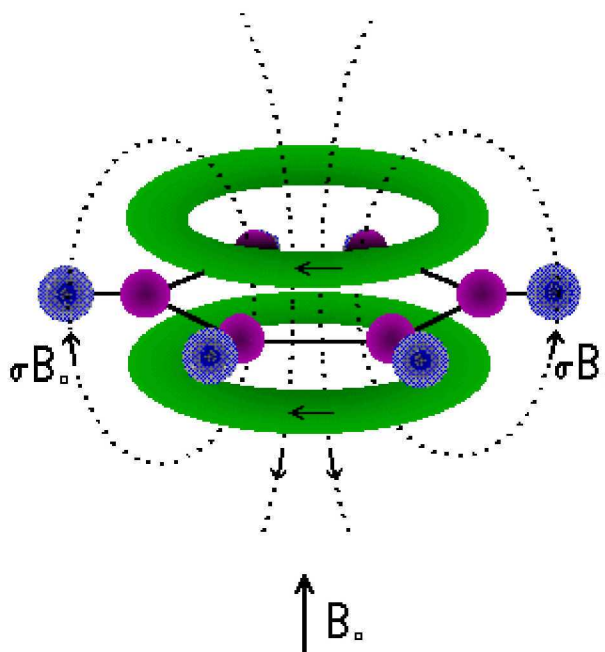
NMR terminology

$$\mathbf{B}_{\text{eff}} = \mathbf{B}_{\text{ext}}(1 - \overset{\leftrightarrow}{\sigma})$$
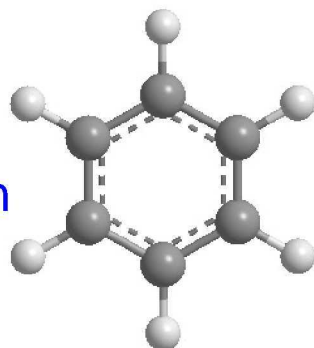
$$\delta = -(\sigma - \sigma_{\text{ref}})$$

TMS

CHCl$_3$

7.27

0 ppm

increasing δ
low field
high frequency
low shielding
paramagnetic

decreasing δ
high field
low frequency
high shielding
diamagnetic
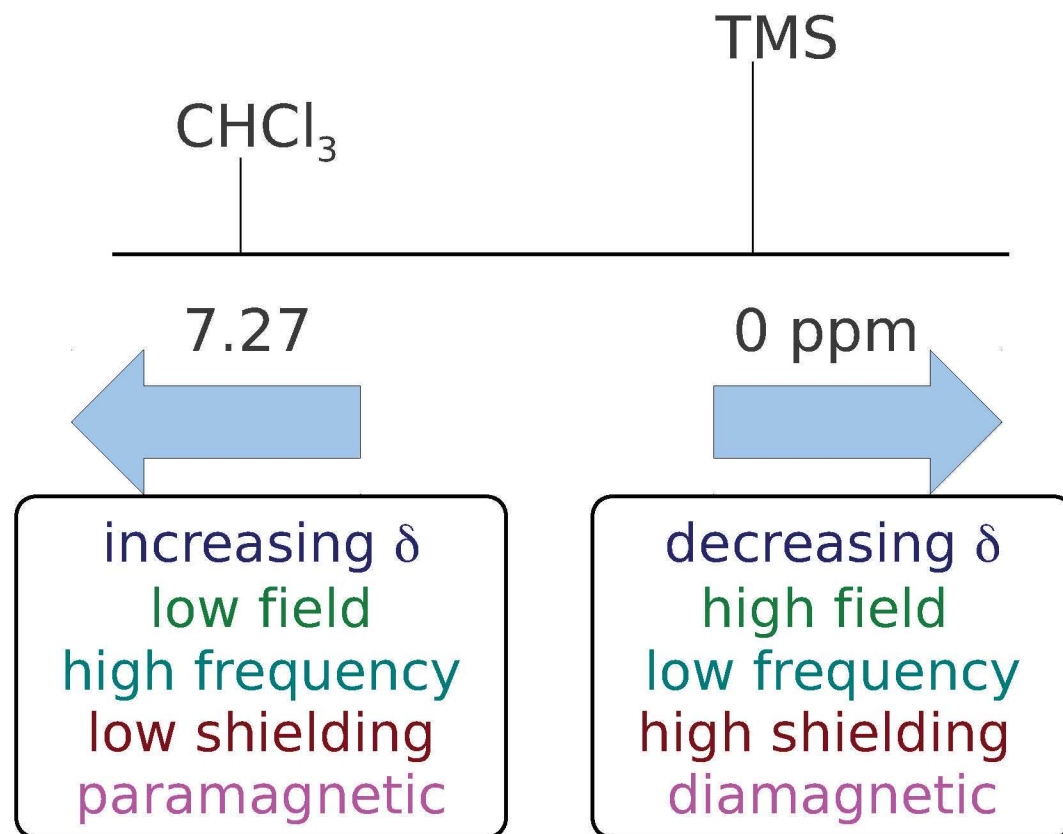
Ring current effect

Atoms on the equatorial plane are strongly de-shielded (higher δ).

Benzene:
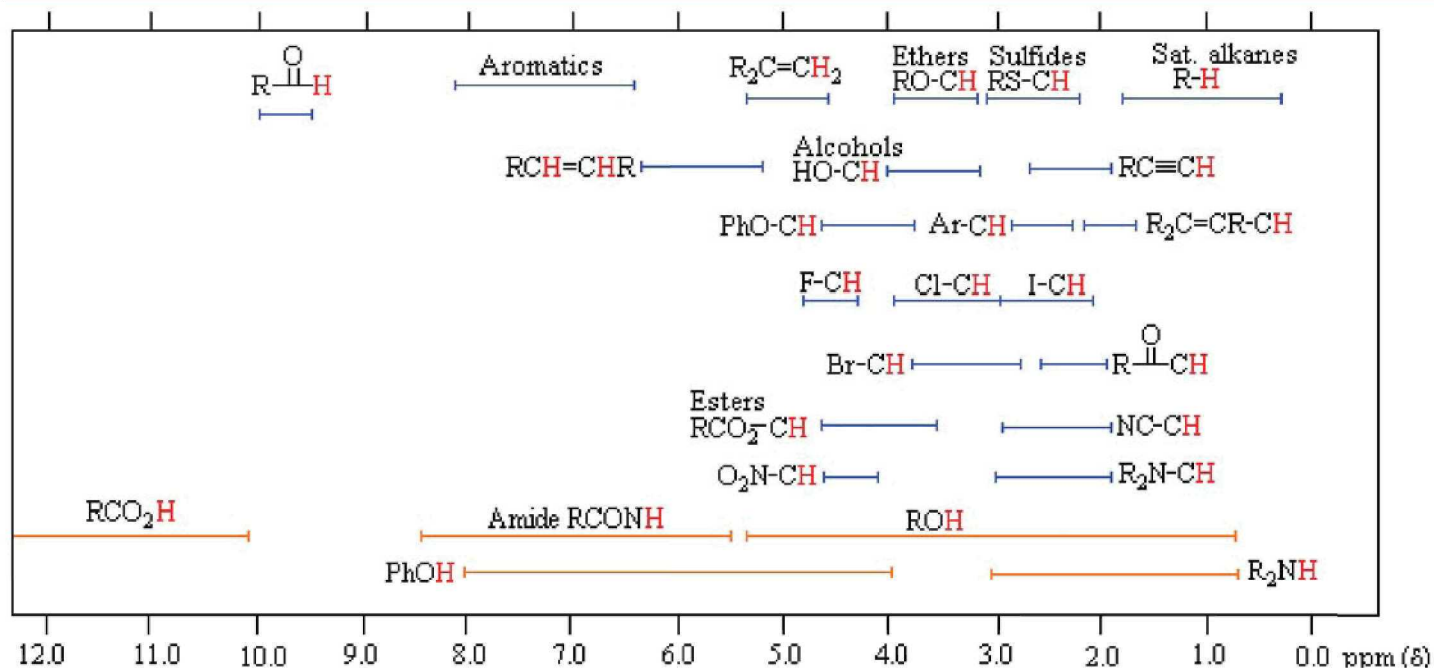^{1}H : 7.16 ppm
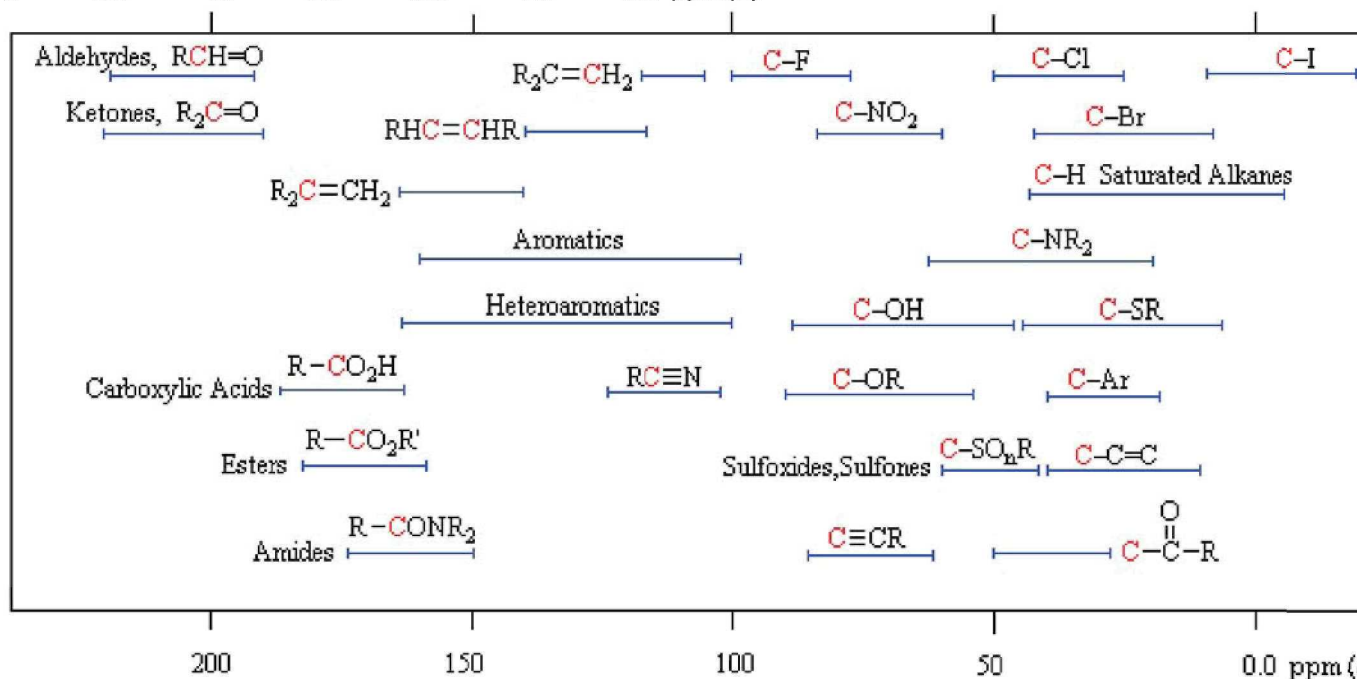^{13}C: 128.39 ppm

Cyclohexane:
^{1}H : 1.38 ppm
^{13}C: 26.43 ppm
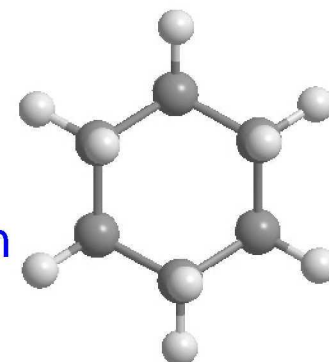
Chemical shift tables

Interpretation of NMR spectra

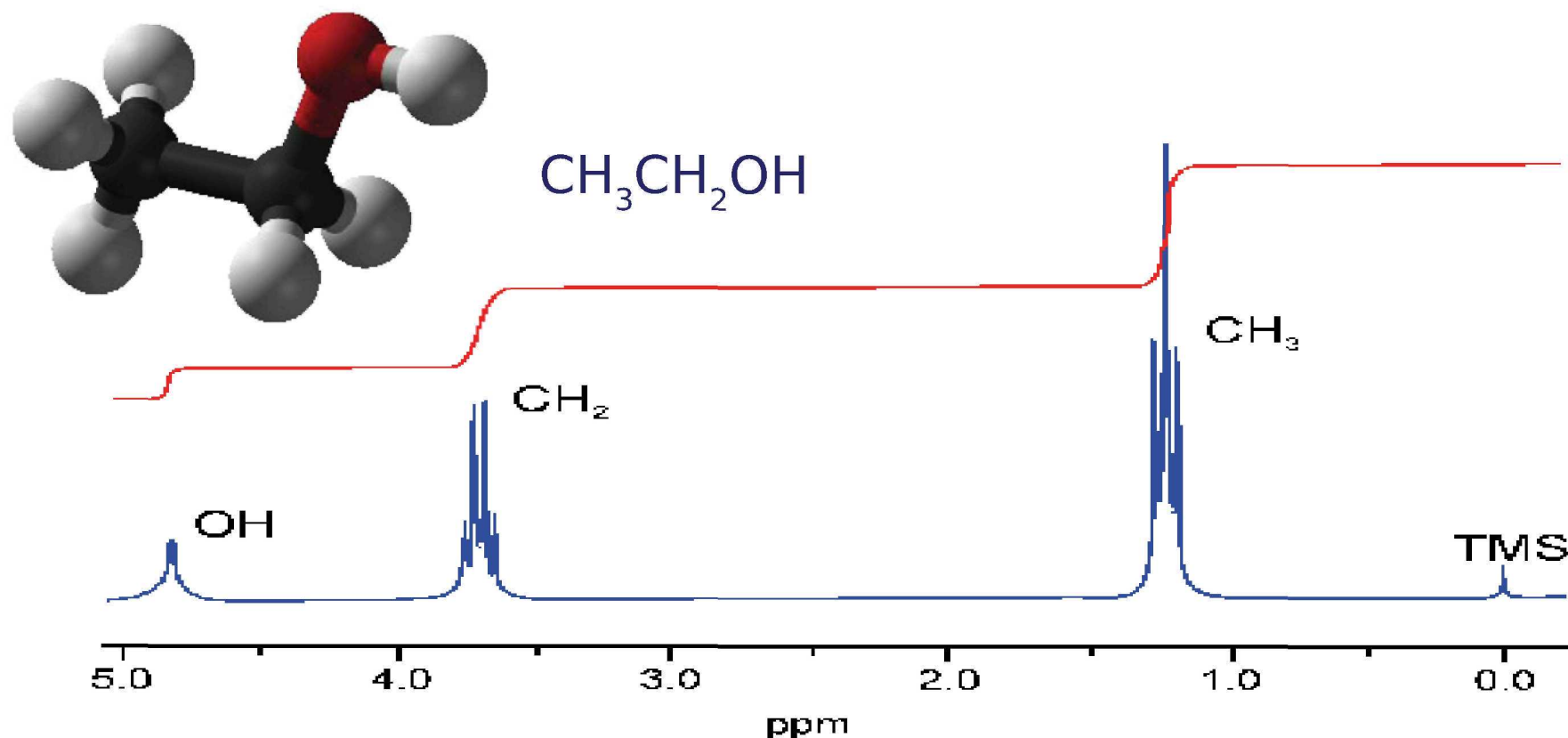Area of the peaks (red curve) → number of equivalent nuclei
Chemical shift table → possible chemical group
Splitting (J-coupling) → connectivity between groups

nuclei are coupled Heisenberg-like: $-J\, S_i \cdot S_j$

The "exchange" coupling J decays as $1/r_{ij}^3$

J is independent of the magnetic field (higher B → better resolution)

CH_3CH_2OH

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Solid-state NMR

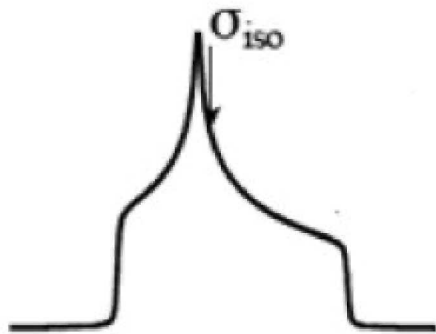Molecules in liquids move very fast w.r.t. NMR time, averaging over all orientations:

→ sharp NMR lines (isotropic chemical shift)

In solids nuclei are fixed in the lattice, no averaging:

→ broad NMR peaks (anysotropy)

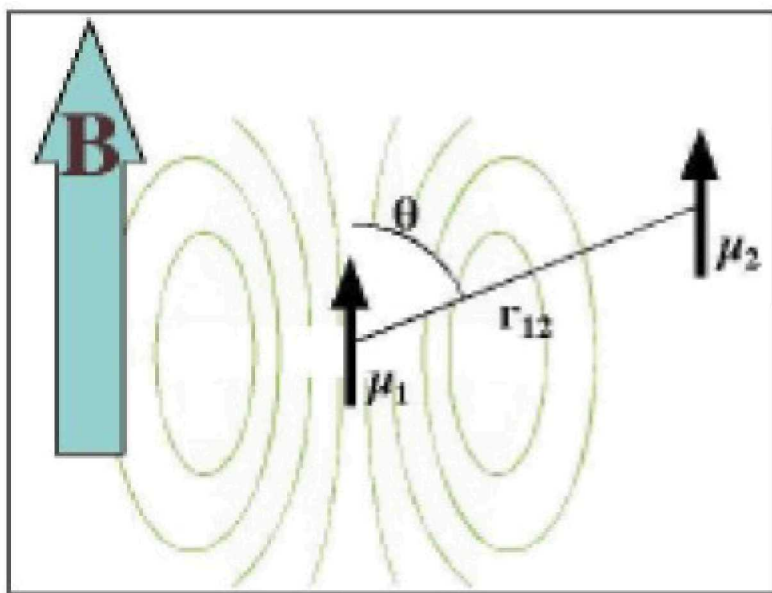→ interactions between spins are not averaged-out (broader lines)

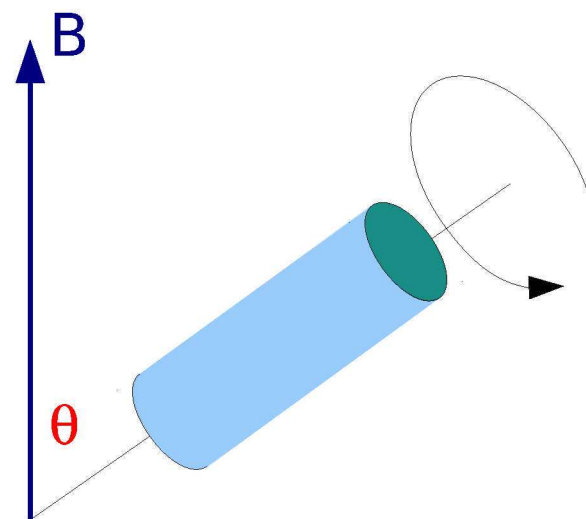→ long T_1 relaxation time (which implies longer experiments)

σ_{iso}

typical poly-crystalline line-shape

Magic Angle Spinning

The magnetic dipole interaction goes like $(3\cos^2 \theta - 1)$, where θ is the angle with the magnetic field.
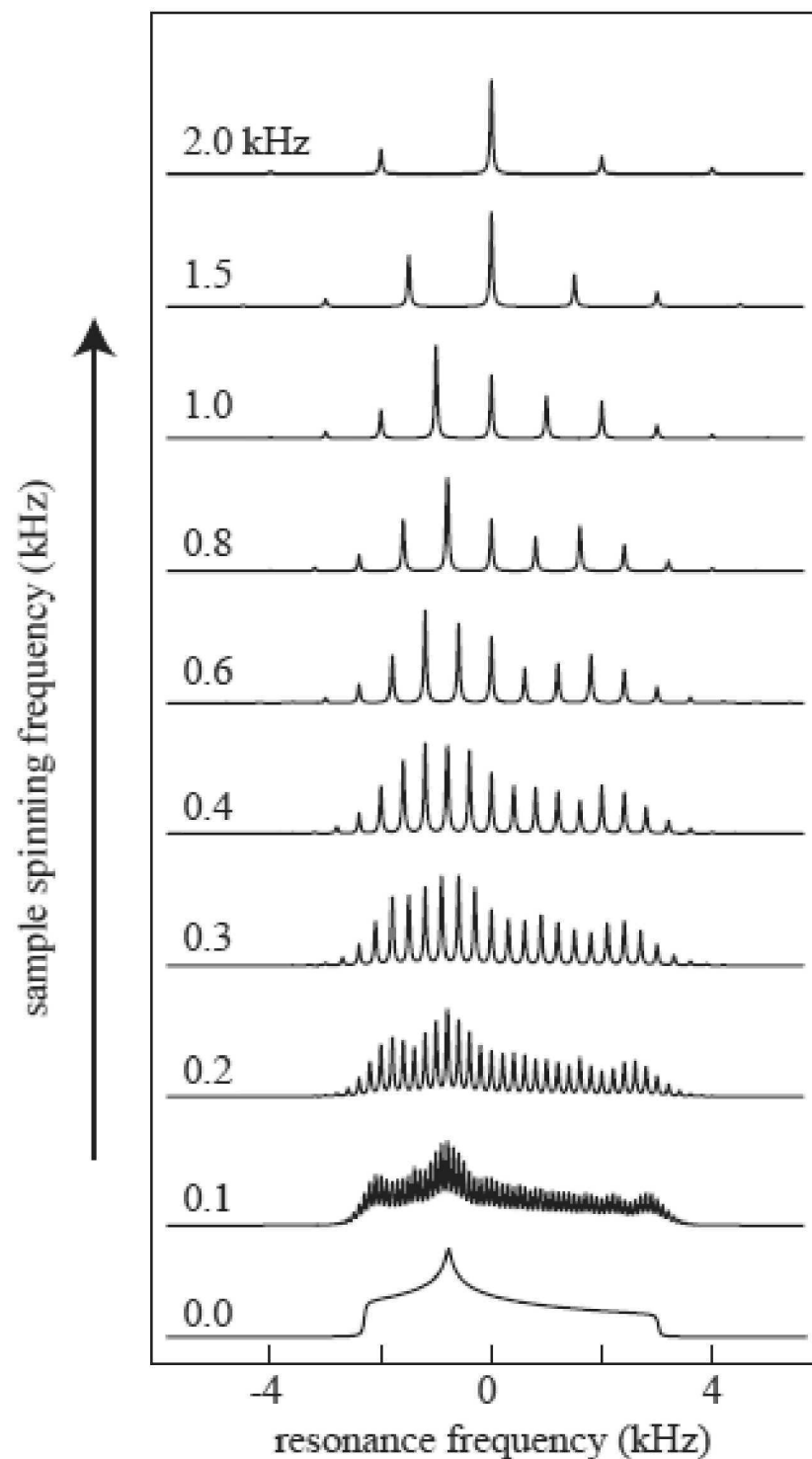

Solution: spin the sample at the magic angle $\theta \sim 54.74°$

MAS reduces effect of chemical shift anisotropy and dipolar interactions.

Magic Angle Spinning

ss-NMR:
- sophisticated pulse sequences
- peak assignment more difficult
- need for calculations and simulations

Summary

- NMR uses radio-frequency radiation to induce transitions between different nuclear spin states of samples in a magnetic field.

- NMR can be used for quantitative measurements, but it is most useful for determining the structure of molecules.

- Different atoms in a molecule experience slightly different magnetic fields and therefore resonate at different frequencies (chemical shift).

- Splittings of the spectra lines (J-coupling) provide information about the proximity of different atoms in a molecule.

Advanced NMR topics (not covered in these notes):
- multidimensional NMR
- relaxation time, nuclear Overhauser effect