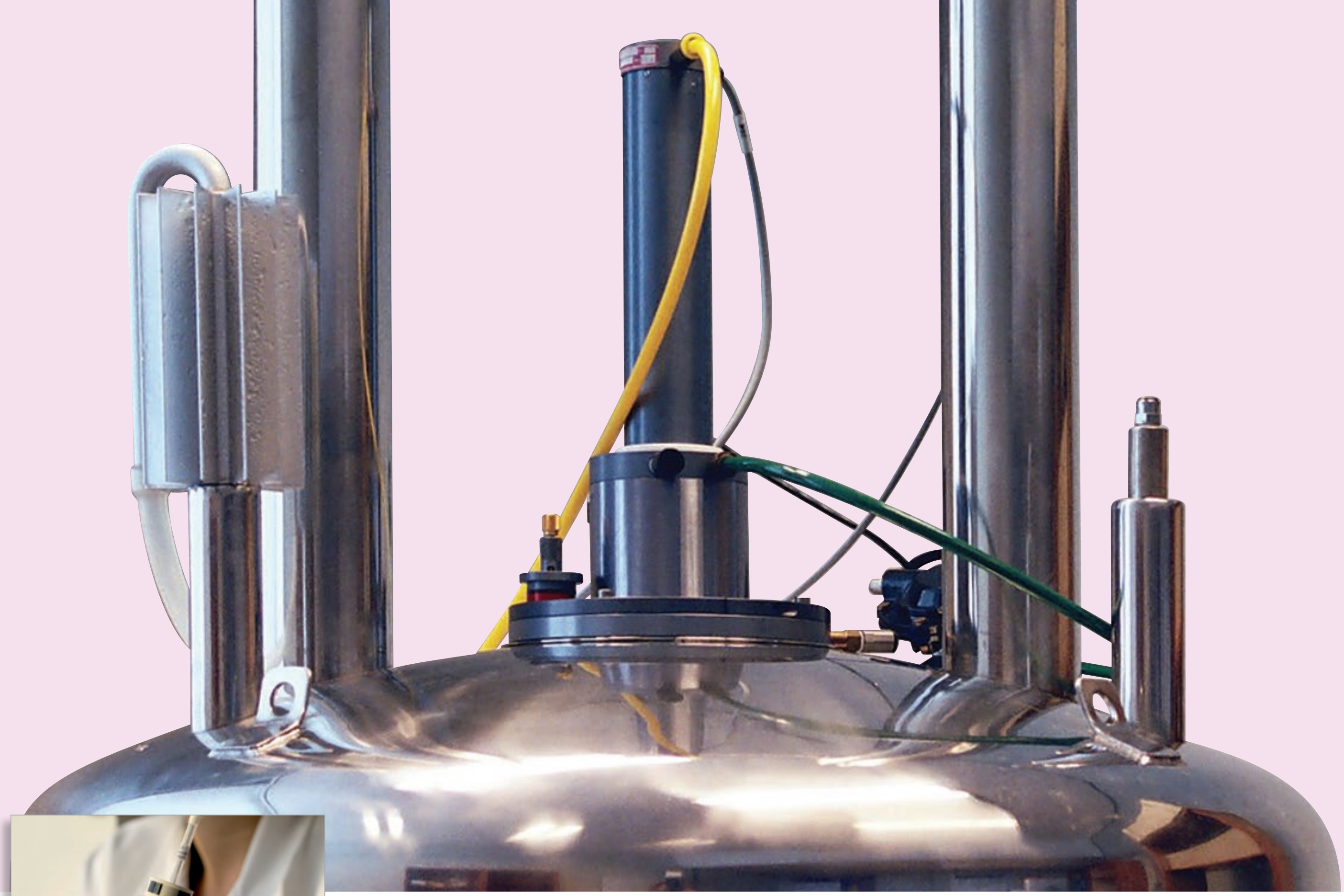

Nuclear Magnetic Resonance

(NMR)

- molecular analysis
- structure determination
- quantitative analysis
- non-destructive analysis
- reaction kinetics
- macroscopic polymer properties
- diffusivity, viscosity, porosity
- metabolic profiling

NMR spectroscopy is a flexible non-destructive analytical technique that gives access to numerous chemical and physical properties of materials. Sampled material is placed in a magnetic field and subjected to a broad spectrum of radio frequency waves (10 – 900 MHz). From this spectrum narrow lines are absorbed by atomic nuclei. These absorption bands are recorded as signals in the NMR spectrum.

A well-known application of NMR is Magnetic Resonance Imaging (MRI), which is used for medical diagnostics. Typical applications in material sciences are quantitation and molecular characterization of main chemical components and/or contaminants. More sophisticated applications are complete molecular structure elucidation, assessment of (polymerization) reaction kinetics, and determination of diffusion constants.

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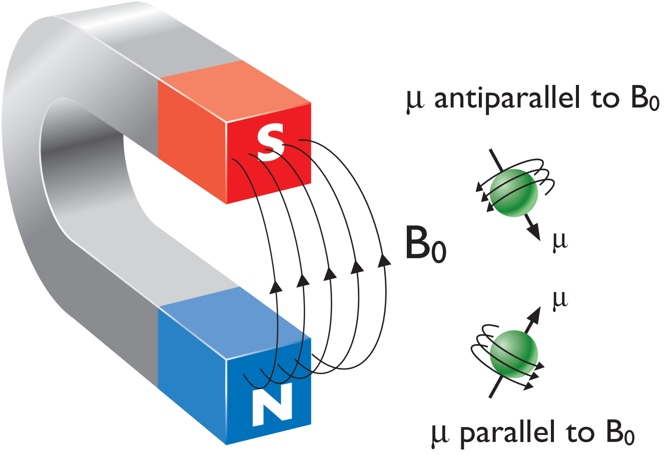

Fig. 2: Schematic representation of the two allowed orientations (parallel and antiparallel) of a nuclear spin with magnetic moment μ in an external magnetic field B_0.

Basic principle of NMR

Most atomic nuclei such as ^1H, ^{13}C, ^{19}F, ^{31}P, ^{29}Si, and ^{199}Hg possess a physical property known as spin. This can be envisaged as a rotation of the nucleus around its own axis (fig. 2). As a result of its electrical charge, the spinning nucleus possesses a magnetic moment μ. It therefore acts as a tiny bar magnet (e.g. a compass needle) with its axis along the axis of rotation. This becomes apparent when the nucleus is placed in an external magnetic field B_0. Like a compass needle in the earth magnetic field, the energetically most favorable state is reached when the magnetic moment is oriented parallel to B_0. Unlike a classical magnetic moment, however, the orientation of nuclear spins is quantitized. In the case of an isolated ^1H nucleus only two orientations are possible, one parallel to B_0, which is energetically favorable, and one antiparallel to B_0. The energy difference ΔE between both orientations is given by

$$E = E_{antiparallel} - E_{parallel} = \gamma h B_0$$

Here, h is Planck's constant and γ is the gyromagnetic ratio, which has a characteristic value for every atomic nucleus.

In a typical NMR experiment, a sample (e.g. water in the case of ^1H-NMR) is brought into a magnetic field. In equilibrium, the nuclear spins are not evenly distributed over both energy levels. According to Boltzmann's law, the lower energy level is slightly more populated than the higher energy level. Radio frequency (RF) waves, when transmitted to the sample, induce transitions between the energy levels only if the RF frequency ν matches exactly the energy difference ΔE according to Planck's law ($\Delta E = h\nu$). This is called the 'resonance frequency' of a nucleus, $\nu_{resonance}$.

$$\nu_{resonance} = \gamma B_0$$

As a result of these transitions, the population of the higher energy level is slightly increased. This process is called excitation. In modern NMR techniques, nuclei are usually excited with a short RF pulse containing a continuum of frequencies. Only nuclei with a resonance frequency within the frequency bandwidth of the RF pulse are excited. Immediately after full excitation, the nuclear spins are distributed evenly over both energy levels. Subsequently, the spins return slowly to the equilibrium distribution by emitting an RF signal at the resonance frequency, which is detected by the NMR spectrometer (fig. 3).

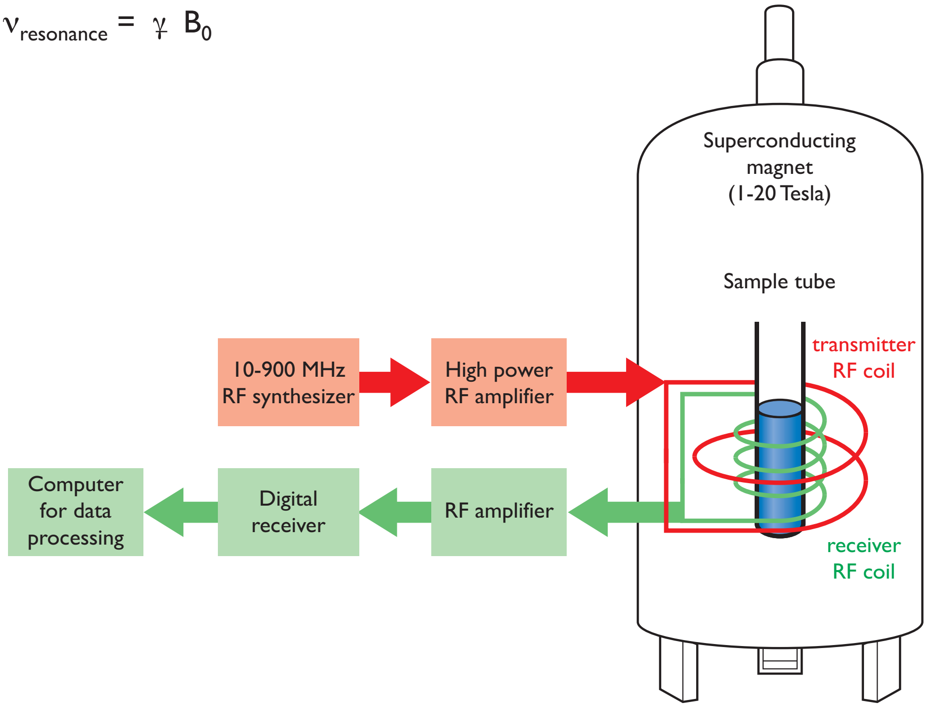

Fig. 3: Schematic representation of the main components of a modern NMR spectrometer.

The NMR spectrum

The basic NMR spectrum is a plot of intensity versus frequency of the RF signal detected by the NMR spectrometer. As an example, the ^{1}H-NMR spectrum of ethanol (alcohol) is shown in figure 4. Four different spectral features can be distinguished, each of which contains valuable information about chemistry and molecular structure.

1. Chemical shift.

For the ethanol molecule three NMR signals are observed at different resonance frequencies. These correspond to the three chemically different types of hydrogen atoms in OH, CH_2, and CH_3, respectively. The differences in resonance frequency originate from additional magnetic fields generated locally in the molecule by electrons circling around the nucleus. These fields slightly change the local magnetic field. The accompanying shift in resonance frequency $\nu_{resonance}$ is highly characteristic of the direct chemical environment of the nucleus and is called 'chemical shift'. Chemical shifts of nuclei in numerous chemical compounds have been tabulated. Therefore, chemical shifts can be used to identify or verify the presence of specific compounds in a sample.

2. Signal Intensity.

The intensity of an NMR signal is proportional to the concentration of the corresponding atom in the sample. Therefore, NMR signal intensities can be used to determine relative concentrations of mixture constituents or the number of equivalent atoms in a molecule. In the ^{1}H-NMR spectrum of ethanol the peaks have relative intensities of 1 : 2 : 3, which indicates the number of equivalent hydrogen atoms in OH, CH_2, and CH_3 respectively.

3. J-splitting.

In the ^{1}H-NMR spectrum of ethanol, the OH signal actually consists of three subsignals with relative intensities 1:2:1 (fig. 5). The frequency separation between adjacent subsignals, 4.96 Hz, is defined as the J-splitting. J-splitting is caused by interactions between the ^{1}H atoms of the OH group and those of the chemically bound CH_2 group. Experimentally obtained J-splitting patterns yield quantitative information about the number of equivalent ^{1}H atoms connected to a carbon atom, the number of chemical bonds between different ^{1}H atoms, and the three-dimensional configuration of H-C-C-H (or H-C-O-H) fragments in a molecule.

4. Line width.

If a significant amount of water (H_2O) is present in the ethanol sample, the line width of the ethanol OH hydrogen signal is significantly increased. This is caused by chemical exchange of the OH hydrogen atom between ethanol and H_2O during the detection of the NMR signal. The NMR line width can be used to quantitate the rate of chemical exchange processes.

More sophisticated variants of NMR can be performed, which yield various types of additional information, such as interatomic distances, diffusion constants, reaction kinetics, polymer backbone dynamics, and many more physico-chemical details of the sample.

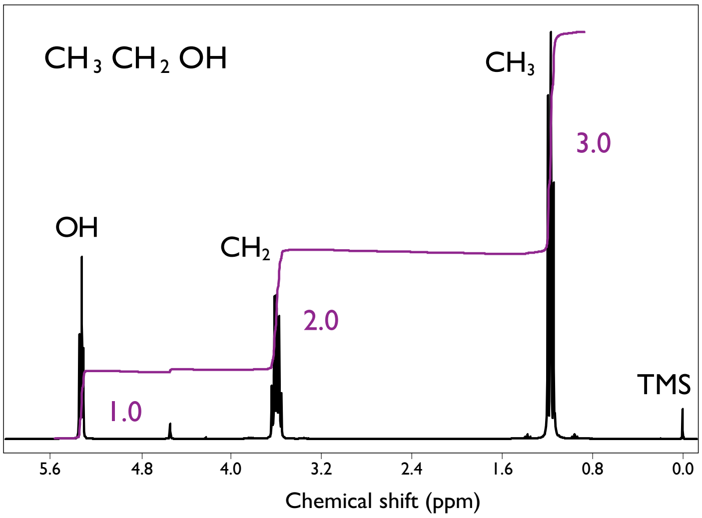

Fig. 4: ^{1}H-NMR spectrum of ethanol, showing the signals of all hydrogen atoms in the molecule. The integral of the spectrum is indicated in purple. In practice, the chemical-shift scale is used for the horizontal axis instead of the actual resonance frequency: chemical shift (ppm) = resonance frequency (Hz) * 10^6 / γB_0. Chemical shift, in contrast to resonance frequency, is independent of the magnetic-field strength. This facilitates comparison between NMR spectra acquired on different spectrometers.

A small amount of tetramethylsilane (TMS) was added to the sample. TMS, giving rise to a single signal at 0 ppm by standard, is the universal chemical-shift reference for ^{1}H, ^{13}C, and ^{29}Si NMR.

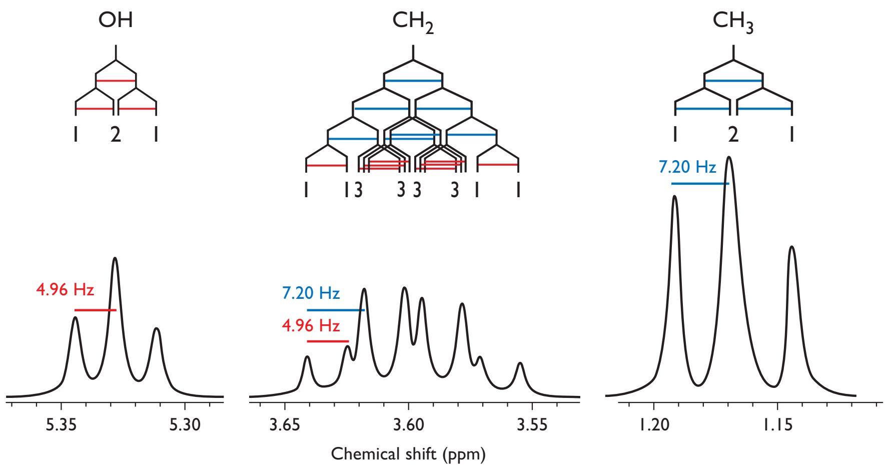

Fig. 5: Details of the OH, CH$_2$, and CH$_3$ signals in the ^{1}H-NMR spectrum of pure ethanol (fig. 4). Explanations of the experimentally observed J-splitting pattern are schematically drawn on top of the corresponding signals. J-splittings between OH and CH$_2$ (4.96 Hz) are indicated in red; J-splittings between CH$_2$ and CH$_3$ (7.20 Hz) are indicated in blue. J-splittings are commonly expressed in Hz instead of ppm, because they are independent of the magnetic field strength.

Applications

- routine chemical identification and quantification of organic compounds in solutions or liquid mixtures
- molecular structure elucidation
- coordination of atoms in poly- or low-crystalline materials
- polymer characterization (chemical structure, chain length, cross linking, curing conditions, etc.)
- kinetics of chemical reactions (e.g. curing of polymers and sol-gel coatings)
- determination of diffusion constants
- size distribution of liquid droplets in emulsions and porous media
- imaging of biological tissues (MRI)
- screening of MRI contrast agents
- metabolic profiling, screening of inborn metabolic diseases, molecular diagnostics
- quality control of food and beverages (purity, integrity, authenticity)

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Technical Note 15
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Characteristics

Obtained information (chemical)

- chemical composition (including trace constituents)
- absolute concentration
- detailed molecular structure
- reaction kinetics
- molecular interaction/ordering
- metabolic profile

Obtained information (physical)

- diffusion constants
- (polymer) viscosity
- (polymer) glass transition temperature
- porosity

Sample type

- liquids or solutions
- solids (amorphous or crystalline)
- (combined) organic and inorganic compounds
- biological tissues
- cell cultures

Analytical range

- 0.1 - 500 mg (strongly depending on application)
- -20 to +90°C

Accuracy

- 0.1 - 10 % relative (strongly depending on application)

Self service

- possible (depending on application)

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