Fundamental principles of Nuclear Magnetic Resonance (NMR)

Physics	Modern Physics	Quantum physics	
Chemistry	Analytical Chemistry	Nuclear magnetic resonance	
Biology	Modern Imaging Methods in Biology		
Applied Science	Medicine	The Nervous System	
Applied Science	Medicine	Radiology & Ultrasonic Diagnostics	Magnetic resonance imaging (MRT)

Difficulty level	Group size	Preparation time	Execution time
hard	2	10 minutes	45+ minutes

This content can also be found online at:

http://localhost:1337/c/5f0ed5e6b6127b00030449bb

General information

Application

Set-up of the MRT training unit

Nuclear Magnectic Resonance spectroscopy is widely used to determine the structure of organic molecules in solution and study molecular physics, crystals as well as non-crystalline materials. NMR is also routinely used in advanced medical imaging techniques, such as in magnetic resonance imaging (MRI).

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Other information (1/2)

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Prior knowledge

The relationship is expressed as ν = *Ve/h,* in which *e* is the charge of the electron and *h* is Planck's constant. This law is sometimes called the inverse photoelectric equation.

Scientific principle

The fundamental experiments include the adjustment of the system frequency that is applied perpendicularly to the magnetic $\overrightarrow{B_0}$ field as an HF pulse to the Larmor frequency, the determination of the deflection angle of the magnetisation vector via the duration of the HF pulse, the effects of the substance quantity on the so-called FID signal (free induction decay), the effects of special magnetic field inhomogeneities, the measurement of a spin echo signal, and an averaging procedure for maximising the signal-to-noise ratio. The adjustment of all these parameters is essential for a high-quality MR image.

Other information (2/7)

PHYWE

Learning objective

The aim of these experiments is to demonstrate and study the fundamental principles of nuclear magnetic resonance (NMR). The experiments are performed directly with the MRT training unit.

This unit enables the direct examination of small samples in a sample chamber. The unit is controlled via the supplied software.

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Other information (3/7)

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Tasks

A: Tuning of the system frequency to the Larmor frequency v_L

1. Study the effects of varying system frequencies on the FID signal (free induction decay).
2. Calculate the magnetic field strength B0B0 of the permanent magnet with the aid of the system frequency that is attuned to the Larmor frequency (use $\gamma(hydrogen) \approx 26.75 \cdot 10^7 rad/sT$).
3. Study the influence of external interference factors on the magnetic field $\overline{B_0}$. Comment on your observations.

Other information (4/7)

PHYWE

Tasks

4. Are there any differences between the Larmor frequency of oil and that of water? Comment on your observations.

5. Remember that the FID signal is a complex signal in a mathematical sense. Why is it so important to consider the real part and the imaginary part of the FID signal and not only the absolute value?

B: Adjustment of the HF pulse duration for defining the MR excitation angle

1. Study the effect of the HF pulse duration on the FID signal (free induction decay).
2. Find the two pulse durations that generate a 90° and 180° pulse.

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Other information (5/7)

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Tasks

C: Influence of the substance quantity on the FID signal

1. Study the effect of the substance quantity on the FID signal amplitude.
2. Study the effect of the repetition time, i.e. the time between two consecutive measurements, on the FID signal amplitude and explain why a repetition time of at least 5 seconds is important for determining the signal amplitude in the case of tap water. Why is this long repetition time not necessary in the case of oil?

D: Minimisation of magnetic field inhomogeneities

1. Study the effect of an additional magnetic field (shim) on the FID signal amplitude.
2. Adjust the shim in all three spatial directions so that you obtain an FID signal that is as long as possible.

Other information (6/7)

PHYWE

Tasks

E: Restoration of the relaxed FID signal via a spin echo

1. Study the effect of a second HF pulse on the received signal. Adjust the pulse duration of the second pulse to a value that causes the nuclear spins to be flipped by 180° (optimum spin echo signal).
2. Study the effect of the pulse duration of the first pulse on the FID signal (see B) as well as on the spin echo signal.
3. Study the effect of the point of time of the second HF pulse on the spin echo signal (echo time). Analyse the spin echo amplitude at different echo times.
4. Observe the measurement signal at the point of time of the second HF pulse while at the same time varying the pulse duration of the first HF pulse.

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Other information (7/7)

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Tasks

F: Maximisation of the signal-to-noise ratio

1. Study the effect of the repetition time, i.e. the time between two consecutive measurements, and the number of averages on the FID signal.
2. Try to achieve a good signal-to-noise ratio as quickly as possible.

Safety instructions

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Read the supplied operating instructions thoroughly and completely prior to starting the unit. Ensure that all of the safety instructions that are listed in the operating instructions are strictly followed when starting the unit.

Only use the unit for its intended purpose.

Pregnant women as well as people with cardiac pacemakers must keep a distance of at least 1 m from the magnet.

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Theory (1/35)

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Today, MRI (Magnetic Resonance Imaging) or MRT (Magnetic Resonance Tomography) is a fundamental imaging method that is used very frequently. MR scanners can display structures and functions of bodily tissues and organs in a non-invasive manner. This is why its main area of application is clinical diagnostics. However, this method can also be used for the chemical analysis of mixtures.All types of MRI methods are based on nuclear magnetic resonance (NMR). The nuclear spin is a measure of the total angular momentum of an atomic nucleus and, thereby, of a purely quantum-mechanical nature (see Fig. 11).

The fundamental components of an atomic nucleus are protons and neutrons (nucleons). As fermions, they exhibit the nuclear spin $\frac{1}{2}$. From this it follows that the nuclear spin I is a general integer if the number of nucleons is even (e.g. $I({}^{14}_{7}\mathrm{N} = 1)$ and a half-integer if the number of nucleons is odd (e.g. $I({}^{15}_{7}\mathrm{N} = \frac{1}{2})$.

Theory (2/35)

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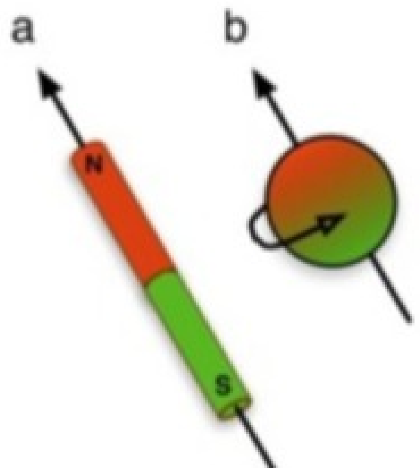

Figure 11

Two protons or two neutrons form pairs with an antiparallel spin (see Fig. 12). In the ground state, this arrangement result in the nuclear spin $I = 0$ (paired elementary particles, Pauli exclusion principle). ${}^{12}_{6}\mathrm{C}$ or ${}^{16}_{8}\mathrm{O}$, for example, do not have a nuclear spin.

In the case of the element ${}^{14}_{7}\mathrm{N}$, however, a neutron and a proton exist in the unpaired state and the resulting nuclear spin is $I = 1$ (see Fig. 12). Due to quantum-mechanical energy splitting, the nuclear spin I can take values between 0 and $\frac{15}{2}$. For example, the following applies: $I^{1}_{1}\mathrm{H}) = \frac{1}{2}$, $I^{13}_{6}\mathrm{C}) = \frac{1}{2}$, $I({}^{17}_{8}\mathrm{O}) = \frac{3}{2}$, $I({}^{19}_{9}\mathrm{F}) = \frac{1}{2}$ and $I({}^{31}_{15}\mathrm{P}) = \frac{1}{2}$.

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Theory (3/35)

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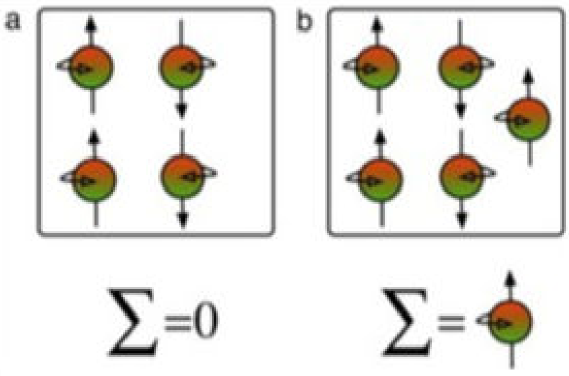

Figure 12

In accordance with the Pauli exclusion principle, the atomic nuclei of elements with an even number of protons and neutrons do not have any resulting nuclear spin (a) and, thereby, neither a magnetic moment.

Atomic nuclei with an odd number of nuclear particles have a resulting nuclear spin and a magnetic moment (b).

Theory (4/35)

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Due to the intrinsic angular momentum, atomic nuclei with a nuclear spin have a magnetic moment $\overrightarrow{\mu}$ (see Fig. 11). This is why they align in an external static magnetic field $\overrightarrow{B_0}$. Unlike common "bar magnets", however, they do this in a parallel and antiparallel manner based on the energy quantisation. The energy difference between the two states is

$\Delta E = \hbar\omega_L$ (1)

The slightly different energetic states are not occupied equally in thermal equilibrium. In accordance with the Boltzmann distribution, the following applies:

$\frac{N\downarrow}{N\uparrow} = exp(\frac{-\hbar\omega_L}{kT}) \approx 1 - \frac{\hbar\omega_L}{kT}$ (2)

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Theory (5/35)

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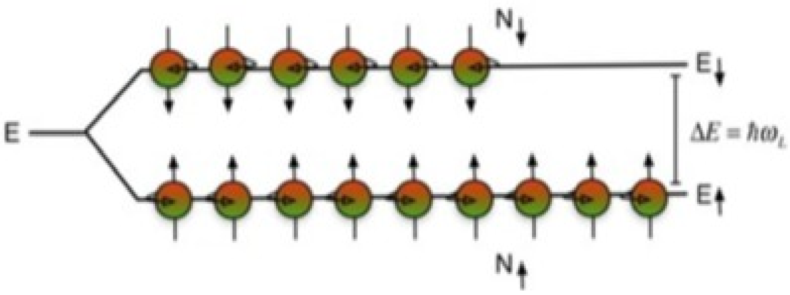

Figure 13

Energy splitting of the nuclear spins in a magnetic field. Parallel $(N\uparrow)$ and antiparallel $(N\downarrow)$ spin orientations correspond to two different energy states. The energy difference of these states is exactly $\hbar\omega_L$.

The lower-energy state is slightly more occupied than the higher-energy state $(N\uparrow > N\downarrow)$. This leads to a "spin excess" of parallel spin orientations and an effective magnetisation in the direction of the external magnetic field.

Theory (6/35)

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Consequently, the parallel spin $N\uparrow$ is slightly favoured. In the ensemble average (ensemble = all of the nuclear spins), this leads to a macroscopic effective magnetisation in the direction of the magnetic field $\overrightarrow{B_0}$ (longitudinal magnetisation $\overrightarrow{M_{L0}}$. The fact that the effective magnetisation can actually be measured is due to the large number of hydrogen protons, for example, in a volume that is to be analysed. Among 10^6 protons at one Tesla, there is only a surplus of approximately 6 protons in the lower-energy state. However, one cubic millimetre of water includes approximately $6.7 \cdot 10^{19}$ hydrogen protons and, thereby, also a surplus of approximately $400 \cdot 10^{12}$ protons in the lower-energy state compared to the higher-energy state.

The magnetisation $\overrightarrow{M_{L0}(t)}$ that is evoked by these excess nuclear spins precesses around the static field vector $\overrightarrow{B_0}$ with a nucleus-specific frequency that is also dependent on the strength of the magnetic field. This frequency is the so-called Larmor frequency v_L (see Fig. 14). The following applies:

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Theory (7/35)

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$\nu_L = \frac{\omega_L}{2\pi} = \frac{\gamma}{2\pi} B_0$ (3)

The precession movement is described by the Landau-Lifshitz equation

$\frac{d}{dt}\overrightarrow{M_{L0}(t)} = 2\pi \cdot \overrightarrow{\nu_L} \times \overrightarrow{M_{L0}(t)}$ (4)

with $\overrightarrow{\nu_L} \parallel \overrightarrow{B_0}$ (see Fig. 14).

It is important that, in the ground state, all of the nuclear spins precess out of phase, i.e. their effect in the plane perpendicular to $\overrightarrow{B_0}$ is zero (see Fig.15).

Theory (8/35)

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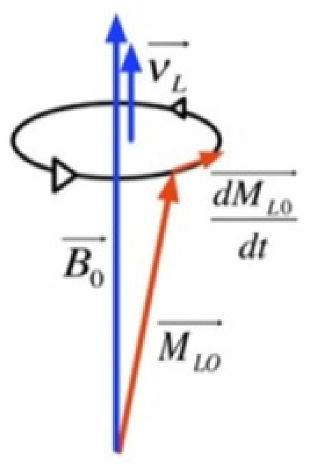

Fig. 14

Fig. 14: Vectorial representation of the precession of a magnetisation vector around an external magnetic field. The dynamic precession movement is described by the Landau-Lifshitz equation.

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Theory (9/35)

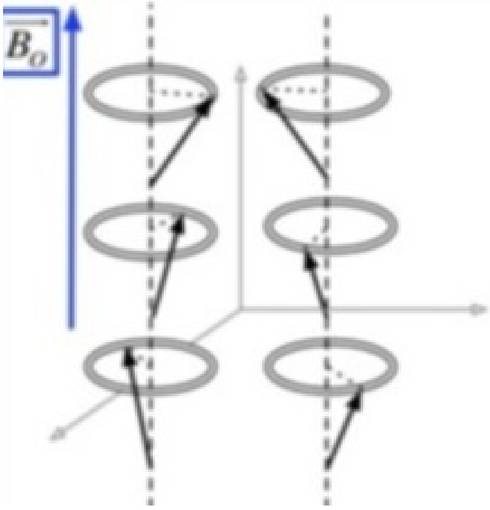

Fig. 15

Fig. 15: Precession movement of all of the spins around an external magnetic field. The individual spins precess out of phase and, therefore, do not have any effect perpendicular to the magnetic field.

Theory (10/35)

After the application of an HF pulse (high frequency) via an HF coil that is perpendicular to the static magnetic field $\overrightarrow{B_0}$, the nuclear spins flip precisely in the moment when the resonance condition (3) is fulfilled, i.e. when the frequency of the HF pulse (system frequency) matches the Larmor frequency ν_L of the nuclei that are to be analysed (usually hydrogen protons). This is clear, since alternating current in the HF coil generates an oscillating magnetic field $\overrightarrow{B_1(t)}$ that is perpendicular to $\overrightarrow{B_0}$. Every oscillating magnetic field can be described as being formed by two field components that rotate in opposite directions.

The field component that rotates opposite to the Larmor frequency ν_L has no effect on the magnetic moment $\overrightarrow{\mu}$. Caused by the HF pulse, the nuclear spins sense a magnetic field $\overrightarrow{B_1(t)}$ that rotates in phase with their precession frequency, i.e. the Larmor frequency ν_L.

Theory (11/35)

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This means that during the HF pulse, there are two magnetic fields, the static magnetic field $\overrightarrow{B_0}$ and the rotating magnetic field $\overrightarrow{B_1(t)}$. In order to understand the effect of these magnetic fields in greater detail, we now use a system of coordinates that co-rotates with $\overrightarrow{B_1(t)}$.

We select a system of coordinates in which the static magnetic field $\overrightarrow{B_0}$ points in the z-direction and the magnetic field $\overrightarrow{B_1(t)}$ that rotates around the z-axis points in the x'-direction (see Fig. 16). In accordance with these conditions, the system of coordinates x'-y'-z rotates around the z-axis with the frequency of the HF pulse (system frequency).

If the nuclear spins also rotate around the z-axis with the system frequency, i.e. if the system frequency equals the Larmor frequency ν_L (resonance condition), the effective axis of the magnetic field $\overrightarrow{B_1(t)}$ appears to be static.

Theory (12/35)

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The nuclear spins also precess around this new effective axis, which leads to a deflection of the magnetisation vector and, thereby, to a magnetisation in the x'-y'-plane. As a result, a magnetisation vector $\overrightarrow{M_\varphi(t)}$ that is deflected by the angle φ rotates around the z-axis with the Larmor frequency ν_L in the x-y-z system of coordinates (see Fig. 16). φ is determined by the pulse amplitude and duration of the HF pulse.

Regardless of the system of coordinates that is used, the following equation of motion applies to $\overrightarrow{M_\varphi(t)}$:

$$\frac{d}{dt}\overrightarrow{M_\varphi(t)} = 2\pi \cdot \overrightarrow{\nu_{eff}} \times \overrightarrow{M_\varphi(t)} \qquad (5)$$

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Theory (13/35)

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$\overrightarrow{\nu_{eff}}$ is given by the strength of the HF frequency field and by the deviation from the Larmor frequency $\overrightarrow{\nu_L}$ in the co-moving system of coordinates x'-y'-z (see Fig. 17).

The following applies:

$$\overrightarrow{\nu_{eff}} = \nu_1 \overrightarrow{e'_x} + (\nu_L - \nu)\overrightarrow{e_z} = -\frac{y}{2\pi} B_1 \overrightarrow{e'_x} + (\nu_L - \nu)\overrightarrow{e_z} \qquad (6)$$

with

$$\varphi = tan^{-1} \frac{\nu_1}{\nu_L - \nu} [/tex]and[tex] \nu_{eff} = \sqrt{((\nu_L - \nu)^2 + \nu_1^2)} \qquad (7)$$

Theory (14/35)

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$\overrightarrow{M_\varphi(t)}$ can be resolved into a component that is parallel to the static magnetic field $\overrightarrow{B_0}$ (longitudinal magnetisation $\overrightarrow{M_L(t)}$) and into a perpendicular component (transverse magnetisation $\overrightarrow{M_Q(t)}$) that rotates in a plane perpendicular to $\overrightarrow{B_0}$ with the Larmor frequency ν_L.

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Theory (15/35)

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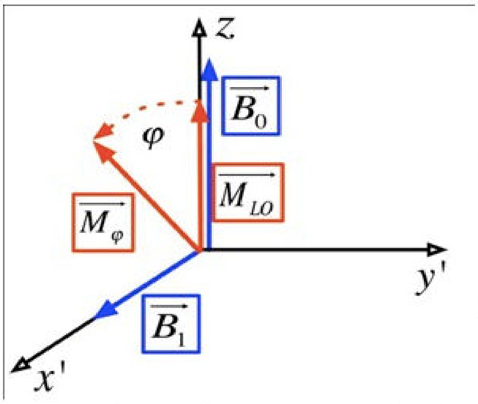

Fig. 16: Deflection of the magnetisation from the z-direction in the rotating system of co-ordinates x`-y`-z. (B_0 ⃗)always acts in the z-direction, while the magnetic field (B_1 ⃗)that is produced by way of the HF pulse always points in the x`-direction.

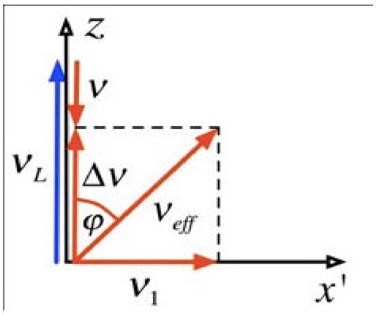

Fig. 17: Resolution of frequencies in the co-rotating system of coordi-nates.

Theory (16/35)

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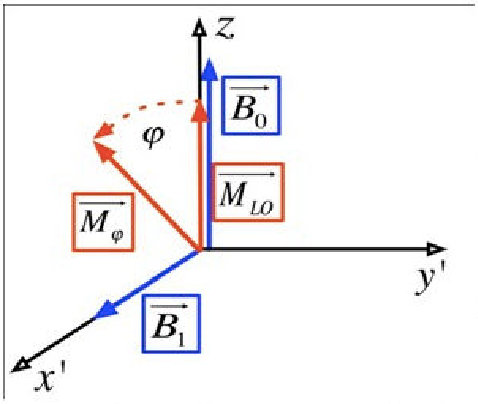

Fig. 16: Deflection of the magnetisation from the z-direction in the rotating system of co-ordinates x`-y`-z. (B_0 ⃗)always acts in the z-direction, while the magnetic field (B_1 ⃗)that is produced by way of the HF pulse always points in the x`-direction.

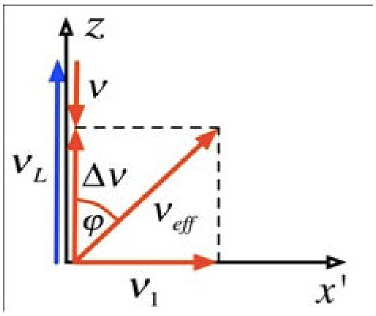

Fig. 17: Resolution of frequencies in the co-rotating system of coordi-nates.

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Theory (17/35)

As a consequence, the following applies:

$\overrightarrow{M_\varphi(t)} = \overrightarrow{M_L(t)} + \overrightarrow{M_Q(t)}$ (8)

A 90° pulse synchronises the phases of the spins, which results in a complete magnetisation in the transverse direction $(|\overrightarrow{M_Q(0)}| = |\overrightarrow{M_{L0}}|; |\overrightarrow{M_L(0)}| = 0)$ (see Figs. 18 and 20). Transverse magnetisations act like rotating magnets and, in accordance with the law of induction, they induce an alternating voltage in a coil. It should also be mentioned that the course of this voltage over time is the MR signal that is to be studied. As the receiver coil, the same coil is used that has already applied the HF signal (transmitter/receiver coil).

A 180° pulse transfers so much energy to the excess $N\uparrow$ spins that they move from the lower-energy state to the higher-energy state.

Theory (18/35)

The result is a complete magnetisation inversion, i.e. a magnetisation that is antiparallel to the original static magnetic field vector $\overrightarrow{B_0} \cdot (|\overrightarrow{M_Q(0)}| = 0; \overrightarrow{M_L(0)} = \overrightarrow{M_{L0}}$ (see Figs. 19 and 21). In this case, there is no magnetisation in the plane of the receiver coil. This means that the magnetisation vector that precesses around \(\overrightarrow{B_0\) and that has an opposite orientation can no longer induce voltage and the MR signal amplitudes decreases back to zero.

Bigger deflection angles will again provide a signal. For the initial amplitude after the HF excitation pulse, the following relationship applies:

$A(\tau) = A_{max} sin(\gamma \cdot B_1 \cdot \tau)$ (9)

with γ as the particle-specific gyromagnetic ratio and τ as the duration of the HF excitation pulse.

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Theory (19/35)

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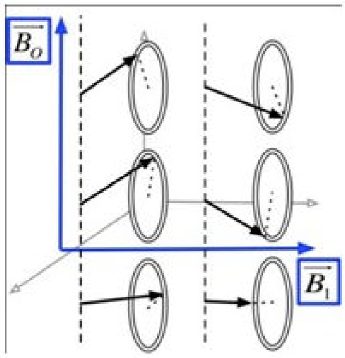

Fig. 18: Precession movement of all of the spins around the rotating magnetic field (B_1) that is generated by a 90° HF pulse.

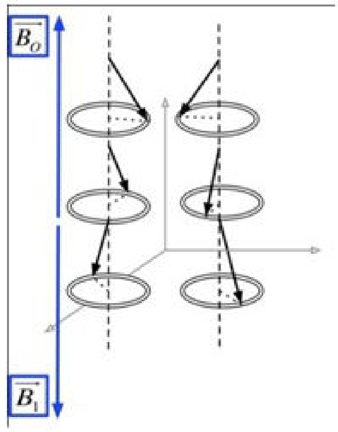

Fig. 19: Precession movement of all of the spins around the magnetic field (B_1)that is generated by a 180° pulse

Theory (20/35)

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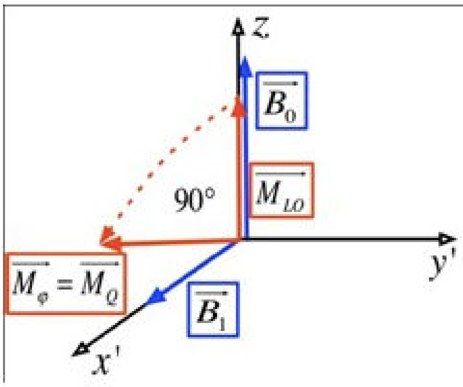

Fig. 20: 90° deflection of the magnetisation from the z-direction in the rotating system of coordinates x'-y'-z (see Fig. 16).

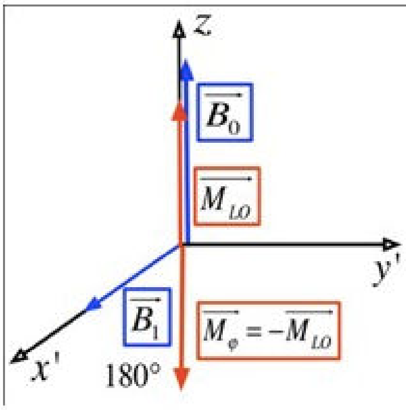

Fig. 21: 180° deflection of the magnetisation from the z-direction in the rotating system of coordinates x'-y'-z (see Fig. 16).

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Theory (21/35)

The greater the rotating magnetic moment $\vec{\mu}$ and the higher the rotation frequency is, the higher the MR signal is that is generated, for example by an exact 90° pulse. Both are proportional to the static magnetic field $\overrightarrow{B_0}$ so that a magnetic field that is as strong as possible is used for a good signal-to-noise ratio (standard magnetic fields for clinical imaging are between 0.2 T and 3 T, for biomedical research purposes they are between 1.5 T and 7 T, and for high-resolution spectroscopy they are between 7 T and 21 T).

For a strong MR signal, it is also important to keep the external magnetic field as constant as possible over time. Even slight changes in the magnetic field strength will automatically lead to changes of the resonance condition (3), and a system frequency that has been attuned to the Larmor frequency will lose its full deflection potential. A spin deflection can only occur in those places where the resonance condition is fulfilled when an HF pulse is applied. This spin deflection ultimately leads to a transverse magnetisation and, thereby, to an MR signal.

Theory (22/35)

Last but not least, the MR signal, of course, also depends on the sample itself. If we look at the MR signal of hydrogen protons, we can see that with a higher proton density also the number of excitable nuclear spins and, therefore, also the strength of the MR signal increases in the resonance condition (3).

After every interference of the spin ensemble that is caused by an HF pulse, the spins strive to resume their energetic state of equilibrium (relaxation) in the static external magnetic field. During this process, the transverse magnetisation decays more quickly than the original longitudinal magnetisation can build up again. The exponential restoration of the longitudinal magnetisation $\overrightarrow{M_L(t)}$ is described by the relaxation time T_1, while the exponential decay of the transverse magnetisation $\overrightarrow{M_Q(t)}$ is described by the relaxation time T_2.

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Theory (23/35)

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The following applies:

$M_L(t) = M_{L0}(1 - ce^{-t/T1})$ (10)

$M_Q(t) = M_Q(0)e^{-t/T2}$ (11)

with M_{L0} as the strength of the initial longitudinal magnetisation, the constant c as the state of the spin ensemble at the beginning of the relaxation $(c = 1 : saturation, c = 2 : inversion)$, and $M_Q(0)$ as the strength of the transverse magnetisation directly after the HF pulse that was applied with the Larmor frequency. The transverse magnetisation that decreases exponentially is the actual MR signal that can be detected by way of the receiver coils. This signal is called an FID signal (free induction decay) (see Fig. 23).

Theory (24/35)

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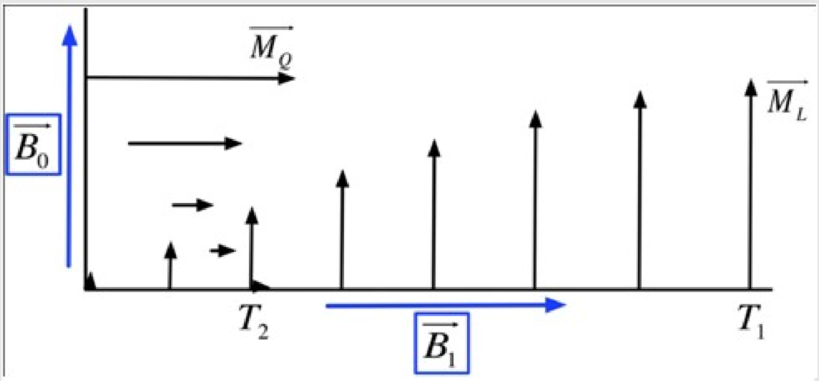

Figure 22

Fig. 22: Longitudinal and transverse relaxation after a 90° HF pulse. The transverse magnetisation decays more quickly than the longitudinal magnetisation builds up (T_2)

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Theory (25/35)

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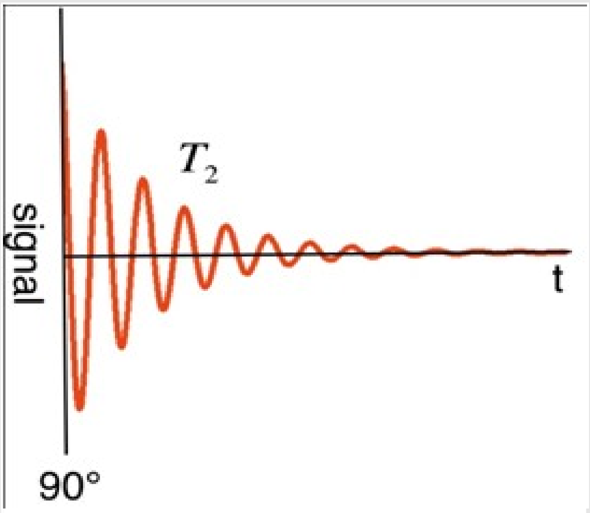

Figure 23

Fig. 23: FID signal after a 90° HF pulse. The signal decays with a characteristic relaxation time T_2. T_2 is based on local, time-dependent field inhomogeneities (spin-spin interactions, spin-lattice interactions). The additional temporally and spatially constant field inhomogeneities finally lead to the real, measurable relaxation time 〖T_2〗^* that is even much shorter than T_2 (see below).

Theory (26/35)

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The dynamic motion of the transverse magnetisation vector $\overrightarrow{M_Q(t)}$ during the FID signal relaxation actually describes an exponentially damped oscillation. If the excitation frequency of the HF pulse (system frequency) that is generated by the transmitter/receiver coil is used as a reference, the oscillations of the FID signal indicate the difference between the Larmor frequency and the system frequency.

If they are small, this means that the system frequency has been perfectly attuned to the Larmor frequency in accordance with the resonance condition (3). This is why a separate consideration of the real and imaginary parts of the signal is absolutely essential for the fine tuning of the system frequency to the Larmor frequency. This is the only way to make the oscillations of the FID signal actually visible.

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Theory (27/35)

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The actual dynamic motion of the total magnetisation vector $\overrightarrow{M_\varphi(t)}$ after the HF pulse (no separate consideration of the longitudinal and transverse relaxation), while taking the Larmor precession and relaxation into consideration, occurs on a three-dimensional spiral path. The more this spiral path rotates out of the deflection plane, the more it approaches the static magnetic field vector $\overrightarrow{B_0}$.

The associated exact equation of motion can be found in the literature (Landau-Lifshitz equation Bloch equation). In the end, the total magnetisation vector $\overrightarrow{M_\varphi(t)}$ precesses again around $\overrightarrow{B_0}$ with the Larmor frequency ν_L and the Landau-Lifshitz equation (4) applies with $\overrightarrow{M_\varphi(t)} = \overrightarrow{M_{L0}(t)}$.

Theory (28/35)

PHYWE

The fact that T_2 is normally smaller than T_1 is based on various mechanisms of interaction. The nuclei (e.g. hydrogen protons), whose spin describes the effective magnetisation, sense locally fluctuating magnetic fields based on molecular movements. These magnetic fields superimpose the external magnetic field. In the case of a certain position and oscillation, they can lead to a natural "spin flip". The probability and speed of these "nuclear spin flips" depends on the surrounding substance, which leads to different T_1 relaxations in different media. Since a nucleus transfers energy to its surroundings (often called a lattice) during the longitudinal relaxation, the T_1 process is also referred to as "spin-lattice relaxation". The T_2 relaxation is also based on the spin-lattice interaction.

However, the loss of coherence between the gyrating spins and, thereby, the dephasing, also result in an additional interaction, the so-called "spin-spin interaction". Every spin flip automatically leads to a minimal local change of the magnetic field. This change is sensed by the neighbouring spins and their precession frequencies shift $(\sim 40kHz)$.

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Theory (29/35)

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As a result, the nuclei in the sample precess at different locations with different frequencies and, thereby, also induce signal voltages with different frequencies in the receiver coil. The observed signal is a superimposition of all of these individual signals. This dephased total signal decays very quickly and the transverse magnetisation of the spin ensemble disappears even before the longitudinal magnetisation has rebuilt. Therefore, local field inhomogeneities determine the duration of the FID signal.

In the following sections, we will have a closer look at the essential quantity in MR technology, the FID signal, i.e. the temporal course of the decaying transverse magnetisation. We have already explained that the FID signal reflects the temporal course of the voltage that is induced in the transmitter/receiver coil that is arranged perpendicular to the external magnetic field. It is particularly strong when a particularly large number of nuclear spins are deflected in a phase-synchronous manner in a direction that is perpendicular to the external magnetic field. Due to spin-spin interactions, it decays much more quickly than the longitudinal magnetisation can rebuild.

Theory (30/35)

PHYWE

Spin-spin interactions are local, time-dependent field inhomogeneities that lead to a very quick dephasing of the nuclear spin ensemble. These field inhomogeneities cannot be avoided, which is why the duration of the measurable FID signal is highly limited.

There are also purely static field inhomogeneities that are constant in terms of time and space. These are mainly local field variations that are caused by the body of the patient, for example, as well as technical inhomogeneities of the magnet. These variations in the magnetic field also contribute to the fanning-out of the nuclear spins. As a result, the nuclear spin ensemble dephases during a time T_2^* and, therefore, is even more rapid than the relaxation time $T_2 (T_2^* < T_2 < T_1)$. However, it is possible to partially compensate for temporally and spatially constant field inhomogeneities and, thereby, to artificially extend the duration of the FID signal T_2^*. In order to increase the homogeneity of the static magnetic field, for example, it is often superimposed by a magnetic field that is generated by electrical coils. This magnetic field is the so-called "magnetic field shim".

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Theory (31/35)

Furthermore, the phase coherence of the spins is not irreversibly destroyed during the time T_2^*, since the dephasing process follows a well-defined pattern in the case of temporally and spatially constant field inhomogeneities. We can reverse the influence of the field inhomogeneities with a sort of trick.

Immediately after a 90° pulse, the nuclear spins precess in a phase-synchronous manner in the plane that is perpendicular to the static magnetic field $\overrightarrow{B_0}$. However, the spins diverge in a relatively systematic manner based on temporally and spatially constant field variations, i.e. spin 1 precesses with maximum speed, while spin n precesses with minimum speed. This results in a well-defined phase sequence. Spin 1 is always the first and spin n always the last spin in the rotational movement around $\overrightarrow{B_0}$ (see Fig. 24). If then, after a time T_S, the reversing command is given by way of a 180° pulse, i.e. if the entire fanned-out spin ensemble is flipped by 180° (compare "flipped omelette"), spin 1 will suddenly be the last spin and spin n the first spin in the rotational movement around $\overrightarrow{B_0}$.

Theory (32/35)

However, since spin 1 rotates more quickly, it catches up with spin n after the time $2 \cdot T_S$. Precisely at this point of time, the initial phase synchronicity of the spin ensemble is restored. The restored MR signal is called spin echo (see Fig. 24). The spin echo can be envisioned as runners on a race track. After the time T_S, the runners are commanded to reverse their direction while maintaining their original speed. After the time $2 \cdot T_S$, all of the runners will meet again on the starting line.

The spin echo signal increases prior to the time $2 \cdot T_S$, since all of the nuclear spins precess in an increasingly phase-synchronous manner around $\overrightarrow{B_0}$ and, thereby, are eliminated to a lower extent by averaging. It reaches its maximum precisely in the time $2 \cdot T_S$, since the full phase synchronicity is reached, before it then decreases after the time $2 \cdot T_S$ in the same manner as it had increased beforehand. Thereafter, the spin ensemble spreads out again. The time $2 \cdot T_S$ is also called echo time T_E (see Fig. 25).

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Theory (33/35)

The spin echo signal itself decreases with T_2^* , while its amplitude decreases with T_2 (see Fig. 25). This is clear since the dephasing cannot be reversed due to the spin-spin interactions that are described above. Consequently, the application of a 180° pulse leads to the generation of a detectable spin echo only in the time between T_2^* and T_2. The question that remains is why the recording and evaluation of a spin echo signal is so advantageous compared to the recording and evaluation of the FID signal that decreases with T_2^* and that is generated immediately after the 90° HF pulse.

This simply results from the fact that the strength of the FID signal is difficult to measure, since it appears suddenly and, therefore, does not provide any absolutely reliable information as to whether a relaxation process has already started. Since the maximum of the spin echo can be identified easily, this uncertainty can be avoided. In addition, when the spin echo is recorded, the time for applying certain information to the signal in order to use this information for later analyses is

Theory (34/35)

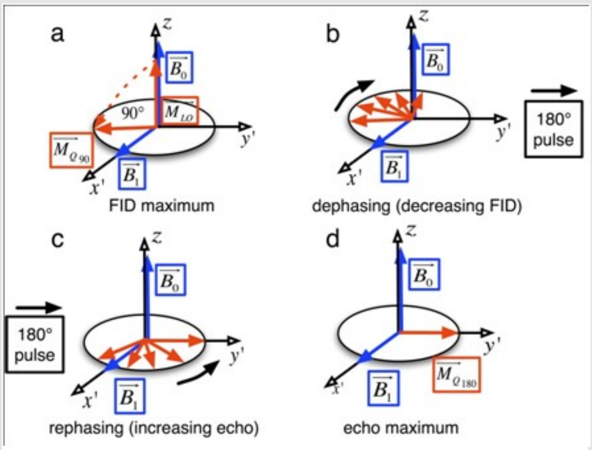

Figure 24

Fig. 24: Restoration of the relaxed FID signal via a spin echo that flips the individual nuclear spins by 180° ("flipped omelette"). Representation of the co-moving system of coordinates x'-y'-z. (a) All of the nuclear spins are in phase and tilted by 90° out of the initial precession around (B_0) ⃗. Here, the FID signal is at its maximum. (b) Based on static field inhomogeneities, the spins get out of phase. The resulting FID signal decreases. (c) A 180° pulse after the time T_S inverses all of the phase positions. The nuclear spins get increasingly back in phase until a signal can be measured once again. (d) All of the nuclear spins are back in phase. After the echo time T_E=2T_S, the amplitude of the echo signal is maximal.

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Theory (35/35)

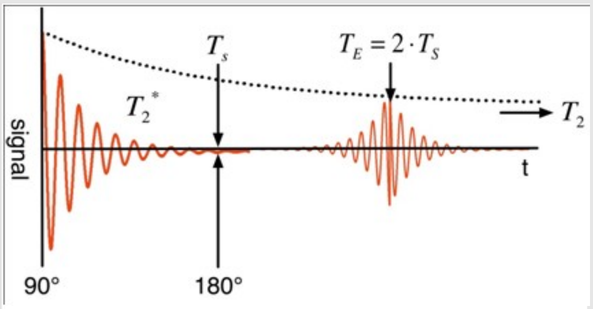

Figure 25

Fig. 25: Spin echo signal. The FID signal that has relaxed during the time 〖T_2〗^* has not completely vanished. It can be restored by way of a 180° pulse after the time T_S. The resulting spin echo signal reaches its maximum after the time T_E=2·T_S. Precisely at this point of time, all of the nuclear spins precess once more in a phase-synchronous manner in the plane perpendicular to (B_0). The amplitude of the restored spin echo signal decreases with T_2. This is based on the irreversible "dephasing" due to spin-spin interactions.

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Equipment

Position	Material	Item No.	Quantity
1	PHYWE Compact magnetic resonance tomograph (MRT)	09500-99	1

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Setup and procedure

Setup (1/3)

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Set the MR unit up as shown in Fig. 1. Ensure that the unit is used in a dry and dust-free room. Ensure that the unit is set up in a vibration-free manner. The mains power switch and the device connector must be freely accessible. Ensure that the ventilation slots are not blocked or covered. Keep a suitable safety distance from other technical equipment and storage media, since they may be damaged by strong magnets. Remove any metallic objects in the direct vicinity of the unit.

Ensure that the POWER switch of the control unit is set to off (see Fig. 3).
Connect the control unit via the power supply connector (12 V DC, 2 A) to the power supply. It is absolutely necessary to use the power supply unit that is intended for this purpose (see Fig. 3).

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Setup (2/3)

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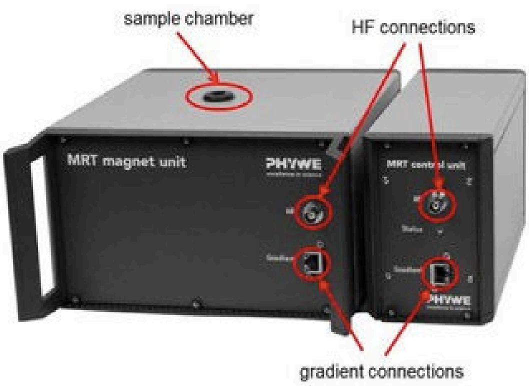

Fig. 2: Magnet and control unit connectors

Fig. 3: Connectors at the back of the control unit

Setup (3/3)

PHYWE

Connect the control unit and the magnet by way of the gradient and BNC cables that are intended for this purpose (see Fig. 2). Then, connect the USB interfaces of the control unit and measurement computer via a USB 2.0 high-speed cable (see Fig. 3). Switch the unit on via the POWER rocker switch (the MR unit should only be switched on for performing experiments). When the unit is started for the first time, the operating system of the computer will recognise the control unit. Then, install the device driver and measurement software (see the installation instructions). Start the "measure MRT" software.

Note:

Details concerning the operation of the MR unit as well as the handling of samples in the MR sample chamber can be found in the corresponding operating instructions.

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Procedure (1/12)

When the "measure MRT" software is started, a window will open automatically as shown in Fig. 4. In area 1, experiments can be selected (experiments area). The associated parameters are displayed in area 2 (parameters area). Area 3 shows a sequence representation of the selected experiment (sequence area). Finally, the results are displayed in area 4 (results area). All of these areas can be arranged as desired in the window. An individual arrangement can be saved for future measurements via the "program settings".

Note:

The following experiments (A-F) should be performed in chronological order. Since the experiment conditions may change over time (e.g. small fluctuations of the magnetic field), it may be useful to repeat a certain experiment in order to readjust the corresponding parameters. The last parameter setting will be saved.

Procedure (2/12)

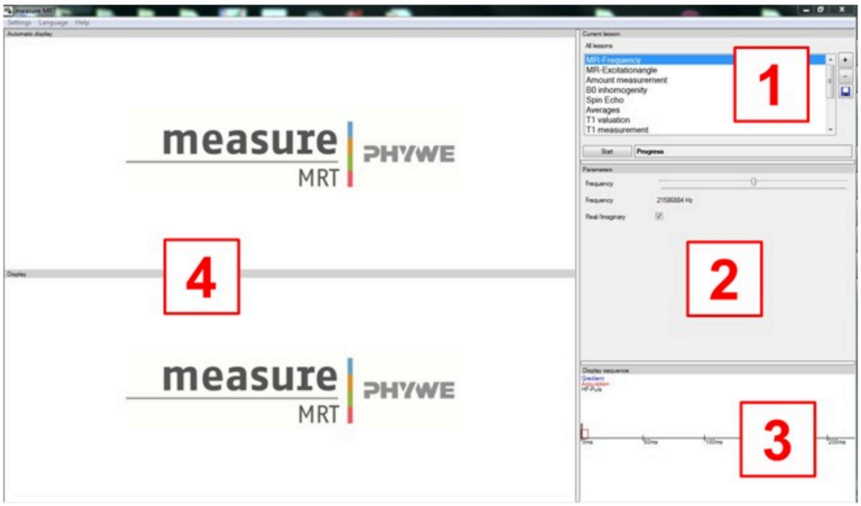

Fig. 4: Areas of the "measure MRT" program

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Procedure (3/12)

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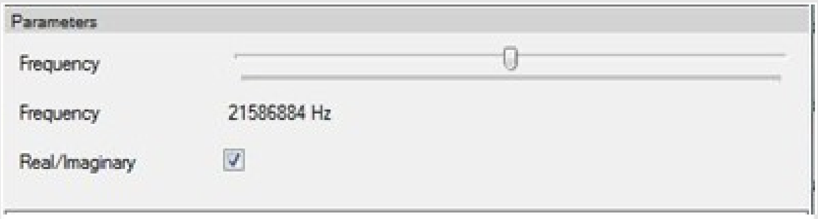

Fig. 5: MR frequency - parameters

A: Tuning of the system frequency to the Larmor frequency

1. Place the 10 mm oil sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson named MR frequency. The parameters area shows the setting options Frequency and Real/Imaginary (see Fig. 5). Vary the system frequency of the MR unit via the Frequency slider.

Procedure (4/12)

PHYWE

2. Adjust a system frequency value that supplies the maximum FID signal. Continue to change the frequency until the signal shows only a few oscillations or none at all (fine tuning). The system frequency thus found corresponds to the Larmor frequency of hydrogen protons.

3. While the measurement is running, bring a piece of iron close to the magnet.

4. While the measurement is running, replace the 10 mm oil sample with the 10 mm water sample.

5. Activate or deactivate the option Real/Imaginary during the measurement. The real part, the imaginary part, and the absolute value of the signal at a specific measuring time can also be displayed separately by way of the option Evaluation (right-click in the results area).

Note: At the end of this experiment part, adjust the system frequency in accordance with task 2. This frequency will be adopted for the remaining experiment parts.

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Procedure (5/12)

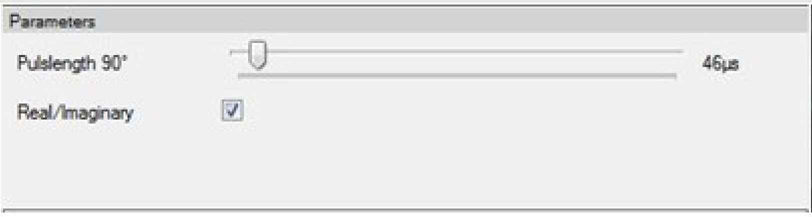

Fig. 6: MR excitation angle - parameters

B: Adjustment of the HF pulse duration for defining the MR excitation angle

1. Place the 10 mm oil sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson MR excitation angle. The parameters area shows the setting options Pulse length 90° and Real/Imaginary (see Fig. 6). Vary the pulse duration of the HF pulse by way of the slider Pulse length 90°.

Procedure (6/12)

2. Start with the minimum pulse duration of the slider and increase it until the FID signal reaches its maximum. The pulse duration thus found generates a 90° pulse. Increase the pulse duration further until it becomes minimal again. The pulse duration thus found generates a 180° pulse. This process can be repeated as desired.

Note: Observe the sequence area in order to view the course of the exciting HF pulse over time. At the end of this experiment part, adjust

C: Influence of the substance quantity on the FID signal

1. Place the 10 mm water sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson Amount measurement. The parameters area shows the setting options Repetition time and Real/Imaginary (see Fig. 7). Observe the signal amplitude. Repeat the experiment with the 5 mm water sample and compare the signal amplitudes.

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Procedure (7/12)

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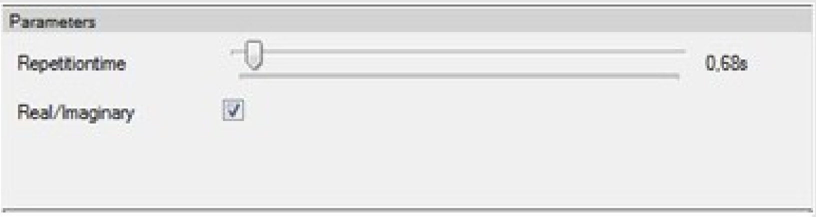

Fig. 7: Substance quantity - parameters

2. Use the 10 mm water sample again. Vary the repetition time, i.e. the time between two consecutive measurements, via the slider Repetition time. Compare the FID signal amplitudes with repetitions times of 0.5 seconds, 1 second, and 5 seconds. Repeat this experiment part with the 10 mm oil sample.

Note: This experiment part uses the sequence of A. The repetition time simply indicates the time between two consecutive sequences.

Procedure (8/12)

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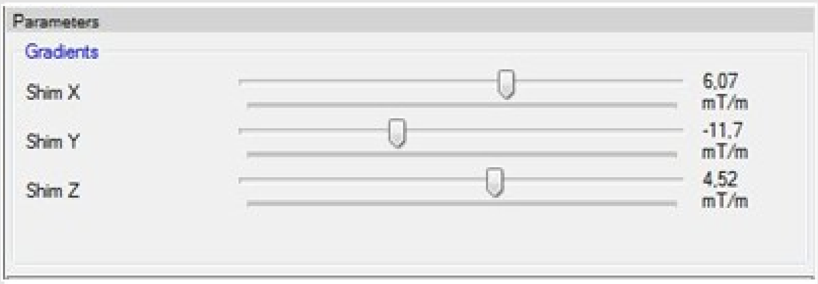

Fig. 8: B_0 inhomogeneity - parameters

D: Minimisation of magnetic field inhomogeneities

1. Place the 10 mm oil sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson inhomogeneity. The parameters area now shows the setting options Shim X, Shim Y, and Shim Z (see Fig. 8). Vary the shim strength in all three spatial directions by way of the corresponding sliders.

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Procedure (9/12)

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2. Set all of the shim sliders to zero. Start with the Shim X slider and adjust a value with which the FID signal decays as slowly as possible. Then, change the setting of the Shim Y slider until the FID signal reaches its maximum length. The same applies to the Shim Z slider. Repeat this process until the length of the FID signal cannot be maximised any further. Note these values down.

Note: As the last setting, adjust an optimum shim. These settings will be automatically adopted for all of the experiments.

E: Restoration of the relaxed FID signal via a spin echo

1. Place the 10 mm oil sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson Spin echo. The parameters area shows the setting options Pulse length 90°, Length 2^{nd} pulse, Real/Imaginary, and Echo time (see Fig. 9). Vary the length of the second HF pulse by way of the slider Length 2^{nd} pulse. Adjust this length until the spin echo signal becomes maximal and then maintain this setting. The adjusted HF pulse duration causes a 180° nuclear spin flip.

Procedure (10/12)

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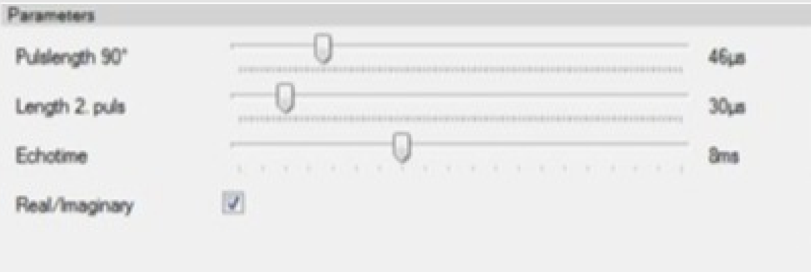

Fig. 9: Spin echo - parameters

2. Vary the pulse duration of the first HF pulse by way of the slider Pulse length 90°. As of a certain value, the strength of the FID signal becomes maximal and the signal shows hardly any oscillations or even none at all. This is the 90° HF pulse that causes all of the nuclear spins to flip by 90° (see part B). Maintain this setting. The influence on the spin echo signal can be seen rather easily.

3. Vary the echo time with the Echo time slider and, at the same time, analyse the spin echo amplitude.

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Procedure (11/12)

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4. Vary the pulse duration of the first HF pulse once more with the slider Length 2^{nd}pulse and observe at which values the signal disappears nearly completely directly after the second HF pulse. At these values, the nuclear spins seem to precess in a plane that is perpendicular to the static magnetic field B_0 .

Note: Observe the sequence area in order to view the course of the exciting HF pulses over time. At the end of this experiment, adjust the pulse durations for the 90° pulse and for the 180° pulse in accordance with task 1. These settings will be adopted for the remaining experiments.

F: Maximisation of the signal-to-noise ratio

1. Place the 5 mm oil sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson Averages. The parameters area shows the setting options Repetition time, Averages, and Real/Imaginary (see Fig. 10). At first, set the number of averages to one and vary the repetition time between consecutive measurements. Then, also vary the number of measurements.

Procedure (12/12)

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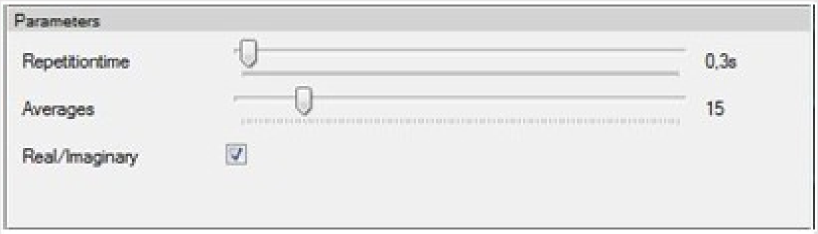

Fig. 10: Averages - parameters

2. Adjust the sliders Repetition time and Averages until you obtain a relatively stable signal as quickly as possible. Note down the corresponding settings and results.

Note: This experiment uses the sequence of A. The repetition time simply indicates the time between two consecutive sequences.

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Evaluation (1/32)

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A: Tuning of the system frequency to the Larmor frequency νL

1. Study the effects of varying system frequencies on the FID signal (free induction decay).

Figs. 26 a-c show the measurement signal of the 10 mm oil sample for three different system frequencies. In Fig. 26 a, the system frequency is much lower than the Larmor frequency for hydrogen protons. This does not lead to any deflection of the nuclear spins and, therefore, it also does not lead to any transverse magnetisation $\overrightarrow{M_Q(t)}$. As a result, it is impossible to induce voltage in the receiver coil and, thereby, to record a signal. (Please remember that only the transverse magnetisation $\overrightarrow{M_Q(t)}$ and not the longitudinal magnetisation $\overrightarrow{M_L(t)}$ is described by the FID signal.)

Evaluation (2/32)

PHYWE

In Fig. 26 b, the system frequency is nearly attuned to the exact Larmor frequency. We observe a signal because of the resulting transverse magnetisation $\overrightarrow{M_Q(t)}$. However, this signal oscillates very strongly, i.e. the rotation frequency of the transverse magnetisation vector still differs slightly from the system frequency. (Please remember that the frequency that can be observed in the FID signal is not the Larmor frequency but rather the difference between the Larmor frequency and system frequency.) The frequency adjustment in Fig. 26 b has not yet effectively led to the exact tuning of the system frequency to the Larmor frequency for hydrogen protons.

Fig. 26 c shows a nearly perfect fine tuning of the system frequency to the Larmor frequency of hydrogen protons. With this setting, the FID amplitude is maximal and we can detect a signal nearly without any oscillations. The FID signal decreases exponentially over the time T_2^*. The time T_2^* is characteristic for hydrogen protons in oil.

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Evaluation (3/32)

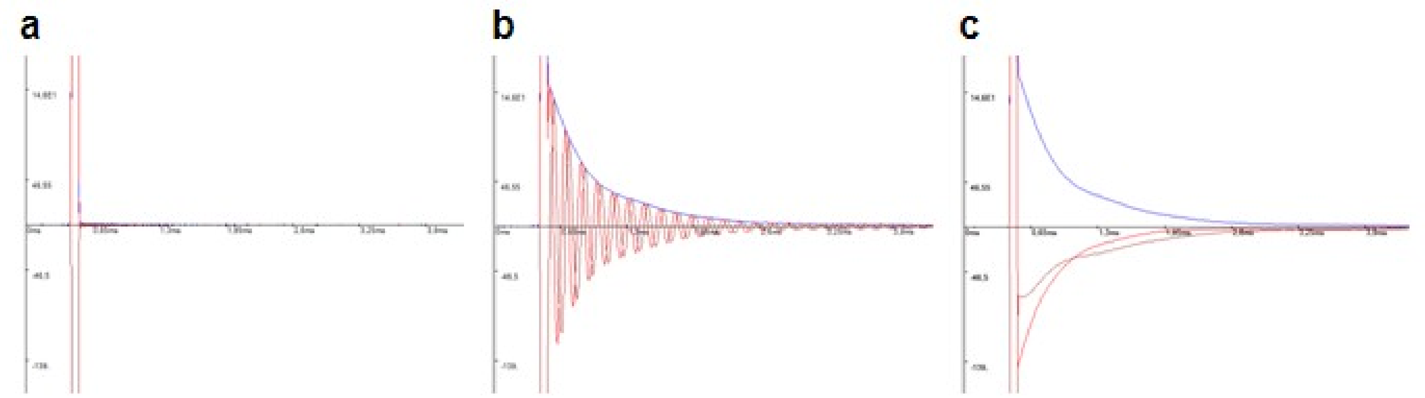

Fig. 26: Measurement signal of the 10 mm oil sample for three different system frequencies.

Evaluation (4/32)

Fig. 26: Measurement signal of the 10 mm oil sample for three different system frequencies. (a) 21.653371 MHz (b) 21.671714 MHz (c) 21.677039 MHz. In (a), the system frequency is much lower than the actual Larmor frequency for hydrogen protons and there is no deflection of the corresponding nuclear spins. As a result, there is hardly any transverse magnetisation (M_Q (t)) ̃ and it is not possible to detect a signal in the receiver coil. In (b), the system frequency is nearly attuned to the Larmor frequency.

Since the rotation frequency of the transverse magnetisation vector still differs slightly from the system frequency, the signal shows numerous oscillations. In (c), the system frequency is attuned nearly perfectly to the Larmor frequency of hydrogen protons. The FID signal hardly shows any oscillations. The absolute value of the signal decreases with the time 〖T_2〗^* that is characteristic of hydrogen protons in oil

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Evaluation (5/32)

2. Calculate the magnetic field strength B_0 of the permanent magnet with the aid of the system frequency that is attuned to the Larmor frequency (use $\gamma(hydrogen) \approx 26.75 \cdot 10^7 rad/sT$).

We use the formula for the resonance condition (3) of hydrogen protons and rearrange it based on B_0. The following applies:

$$\frac{2\pi\nu_L}{\gamma(hydrogen)} = B_0$$

By putting in the frequency of 1c, we obtain the field strength of the static magnetic field:

$$B_0 \approx 509mT$$

(compare 500 mT from device specifications)

Evaluation (6/32)

3. Study the influence of external interference factors on the magnetic field $\overrightarrow{B_0}$. Comment on your observations.

Iron that is placed close the static magnet influences its magnetic field. This automatically changes the resonance condition (3) and the system frequency that was adjusted beforehand (see task 1) no longer corresponds exactly to the Larmor frequency. The FID signal is subject to oscillations and the signal amplitude decreases (see task 1). Figs. 27 a and b illustrate this effect (Fig. 27 a corresponds exactly to Fig. 26 c).

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Evaluation (7/32)

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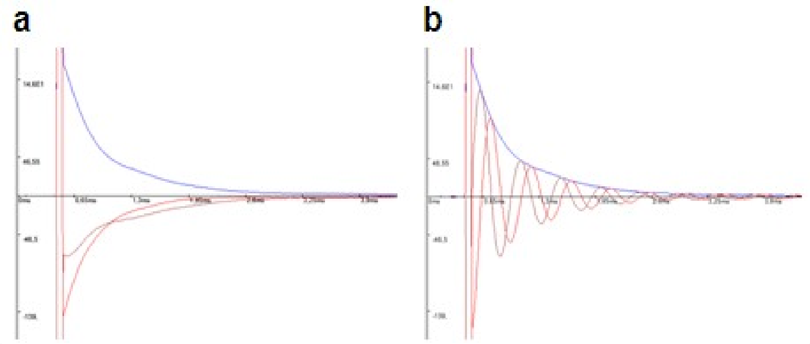

Fig. 27: Measurement signal of the 10 mm oil

Fig. 27: Measurement signal of the 10 mm oil sample. In (a), the system frequency is perfectly attuned to the Larmor frequency in accordance with the resonance condition (3) (21.677039 MHz). (b) uses the same system frequency as (a), but in this case an iron rod was positioned close to the static magnet. This iron rod automatically changes the magnetic field and, thereby, also the resonance condition (3). The perfect tuning is lost.

Evaluation (8/32)

PHYWE

4. Study the effect of the sample substance on the Larmor frequency ν_L.

Are there any differences between the Larmor frequency of oil and that of water? Comment on your observations.

Figs. 28 a-c show the measurement signal of the 10 mm water sample for the three different system frequencies of task 1. It is obvious that in Fig. 28 c the system frequency has been attuned perfectly to the Larmor frequency. As a result, there are no differences between the Larmor frequency of the oil sample and the Larmor frequency of the water sample. This makes sense since in both cases the nuclear spins of the hydrogen protons are deflected. As a result, the resonance condition is the same for both media (oil and water).

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Evaluation (9/32)

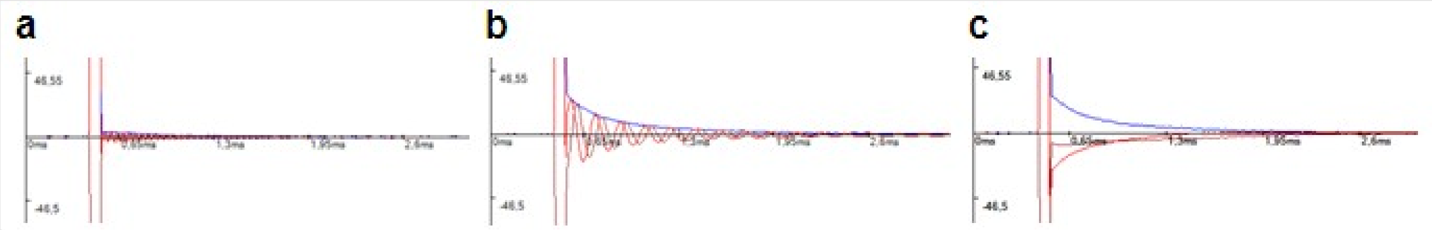

Fig. 28: Measurement signal of the 10 mm water sample for three different system frequencies. (a) 21.653371 MHz (b) 21.671714 MHz (c) 21.677039 MHz (see task 1). Obviously, there is no difference between the Larmor frequency of the water sample and that of the oil sample. In both cases, a perfect FID signal can be obtained with the system frequency that is adjusted in (c). Only the amplitudes of the FID signal differ from each other, which is due to different repetition times and hydrogen proton densities of oil and water. The repetition time will be discussed in greater detail in part C.

Evaluation (10/32)

5. Remember that the FID signal is a complex signal in a mathematical sense. Why is it so important to consider the real part and the imaginary part of the FID signal and not only the absolute value?

At all times, the recorded FID signal is characterised by a well-defined amplitude and a well-defined phase that describes the difference between the system frequency and the Larmor frequency. Such a signal is mathematically described by a complex number in polar coordinates:

$$FID = A \cdot e^{i\theta} = A \cdot (cos\theta + i \cdot sin\theta) \qquad (12)$$

The absolute value of the signal is defined by $|FID| = \sqrt{FID \cdot FID^*}$, whereby * stands for the complex, conjugate of the FID. As a result, $|FID| = A$ applies. However, the absolute value provides only information about the amplitude of the signal but not about its phase position. However, the phase position is essential for attuning the system frequency as exactly as possible to the Larmor frequency. If there are still many oscillations in the recorded FID, then the difference between the system frequency and Larmor frequency is unequal to zero and a finer tuning of the system frequency is indispensable.

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Evaluation (11/32)

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Please bear in mind that the real part of the FID precedes the imaginary part by $\pi/2$. The following applies:

$RE[FID] = A \cdot cos(\theta)$ and $IM[FID] = A \cdot sin(\theta)$ (13)

B: Adjustment of the HF pulse duration for defining the MR excitation angle

1. Study the effect of the HF pulse duration on the FID signal (free induction decay).

Figs. 29 a-c show the FID signal for various pulse durations and under a system frequency that has been perfectly attuned to the Larmor frequency. The pulse duration of the exciting HF pulse determines the angle φ (MR excitation angle) by which the magnetisation vector will be deflected from its original precession around the static magnetic field $\overrightarrow{B_0}$.

Evaluation (12/32)

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Since the receiver coil can only measure the rotating transverse magnetisation $\overrightarrow{M_Q(t)}$, i.e. the part of the magnetisation vector in the plane perpendicular to $\overrightarrow{B_0}$, the FID signal is particularly strong when $|\overrightarrow{M_Q(t)}| = |\overrightarrow{M_L 0}|$, i.e. when the initial magnetisation vector $\overrightarrow{M_L 0}$ has completely tilted into the plane perpendicular to $\overrightarrow{B_0}$. This is the case for the angles $\varphi = (2n-1) \cdot \pi/2$with $n \epsilon \mathbb{N}$. The amplitude of the FID signal increases with an increasing pulse duration (a) until it reaches a first maximum (b). This pulse duration corresponds to a 90° pulse. Then, the amplitude of the FID signal decreases again (c) until it ideally disappears completely at a pulse duration that generates a 180° pulse. If the pulse duration increases further, the FID amplitude increases again. It reaches a second maximum at a pulse duration that generates a 270° pulse. The described up and down of the FID signal amplitude as a function of a varying pulse duration can be continued as desired. However, it must be taken into consideration that the variance of the individual nuclear spin tilt angles also increases when the angles φ increase, which actually leads to a decrease of the FID signal strength at very large MR deflection angles.

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Evaluation (13/32)

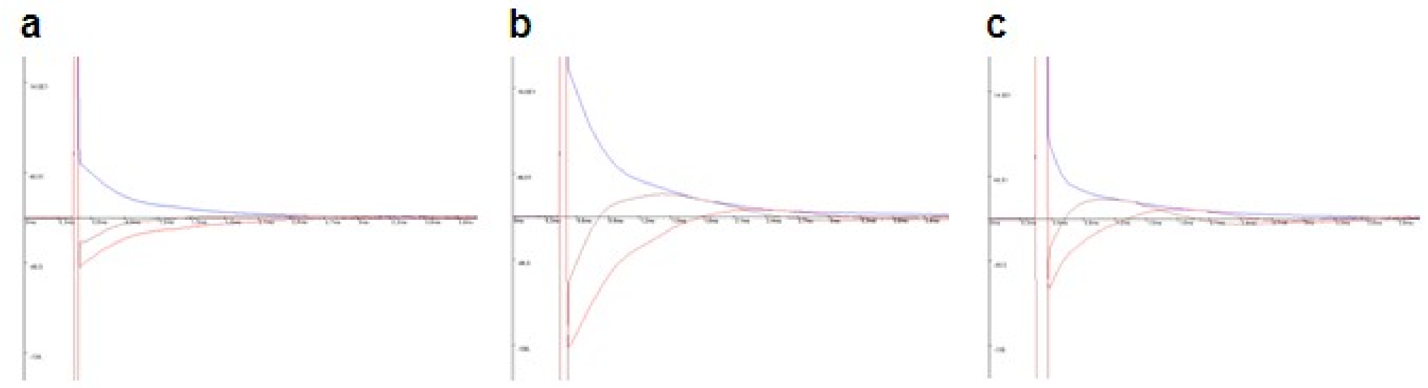

Fig. 29: Measurement signal of the 10 mm oil sample for three different pulse durations.

Evaluation (14/32)

Fig. 29: Measurement signal of the 10 mm oil sample for three different pulse durations. (a) 9 µs. (b) 53 µs. (c) 80 µs. For all three measurements, the system frequency has been perfectly attuned to the Larmor frequency (see part A). The FID signal increases with longer pulse durations (a) until it reaches a first maximum at a 90° pulse (b). Here, the magnetisation vector has been completely deflected into the plane perpendicular to the static magnetic field $\vec{B_0}$ and all that is left is a transverse magnetisation $\vec{M_Q(t)}$. For longer pulse durations, the FID signal decreases again (c) until it reaches a minimum (or until it ideally becomes zero) at a pulse duration that corresponds to a 180° pulse, before it increases again afterwards. Consequently, FID signal maxima exist in the case of deflection angles $\varphi=(2n-1)\cdot\pi/2$ with $n\in N$, and FID signal minima in the case of $\varphi=n\cdot\pi$ with $n\in N$.

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Evaluation (15/32)

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2. Find the two pulse durations that generate a 90° and 180° pulse.

In accordance with task 1, a pulse duration of approximately 53 μs generates a 90° pulse. After this excitation, the magnetisation vector rotates with $|\overrightarrow{M_Q(t)}|=|\overrightarrow{M_{L0}}|$ in the plane perpendicular to the static magnetic field $\overrightarrow{B_0} \cdot (|\overrightarrow{M_L(t)}|=0)$. A pulse duration of approximately 100 μs generates a 180° pulse. In this case, $|\overrightarrow{M_Q(t)}|=0$ and $\overrightarrow{M_L(t)}=-\overrightarrow{M_{L0}}$ apply.

Evaluation (16/32)

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C: Influence of the substance quantity on the FID signal

1. Study the effect of the substance quantity on the FID signal amplitude.

Figs. 30 a and b show the FID signal for the 10 mm water sample (a) and for the 5 mm water sample (b) with the settings of tasks A and B (system frequency = Larmor frequency, 90° pulse). The repetition time was set to approximately 5 seconds.

Obviously, the FID signal of the 5 mm water sample is weaker (smaller FID amplitude) than the corresponding signal of the 10 mm water sample. This makes sense, since the number of excitable hydrogen protons in the 10 mm water sample is higher than in the 5 mm water sample. However, it is the nuclear spins of these hydrogen protons that determine the absolute value of the magnetisation vector $\overrightarrow{M_Q(t)}$ and, thereby, the strength of the FID signal. The same explanation also applies to the comparison of the two oil samples.

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Evaluation (17/32)

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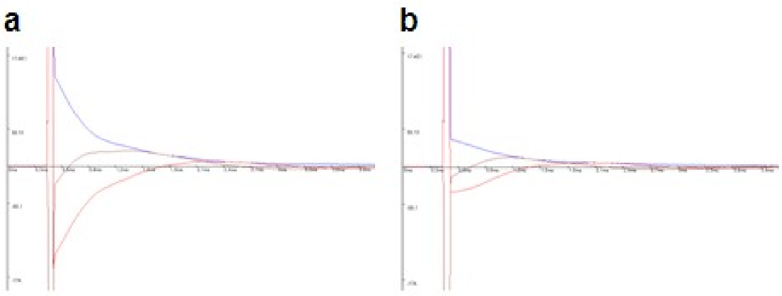

Figure 30

Fig. 30: FID signal of the 10 mm water sample (a) and of the 5 mm water sample (b). For both measurements, the system fre-quency has been perfectly at-tuned to the Larmor frequency (see part A). The pulse duration corresponds to the excitation by way of a 90° HF pulse (see part B).

Evaluation (18/32)

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2. Study the effect of the repetition time, i.e. the time between two consecutive measurements, on the FID signal amplitude and explain why a repetition time of at least 5 seconds is important for determining the signal amplitude in the case of tap water. Why is this long repetition time not necessary in the case of oil? Figs. 31 a-c show the FID signal of the 10 mm water sample for repetition times of 0.5 s (a), 5 s (b), and 10 s (c). Obviously, the signal for long repetition times is much stronger than the signal for very short repetition times.

Fig. 31: FID signal of the 10 mm water sample for three different repetition times. (a) 0.5 s. (b) 5 s. (c) 10 s. For all three measurements, the system frequency has been perfectly attuned to the Larmor frequency (see part A). The pulse duration corresponds to the excitation by way of a 90° HF pulse (see part B). The FID signal in (a) is considerably weaker than the FID signals in (b) and (c), since the very short repetition time of 0.5 s does not provide the magnetisation vector with sufficient time to relax back to its state of equilibrium (parallel position with regard to (B_0 ⃗). The time that is required for a nearly complete relaxation depends on the medium that is analysed. The relaxation time T_1 of water, for example, is considerably longer than that of oil.

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Evaluation (19/32)

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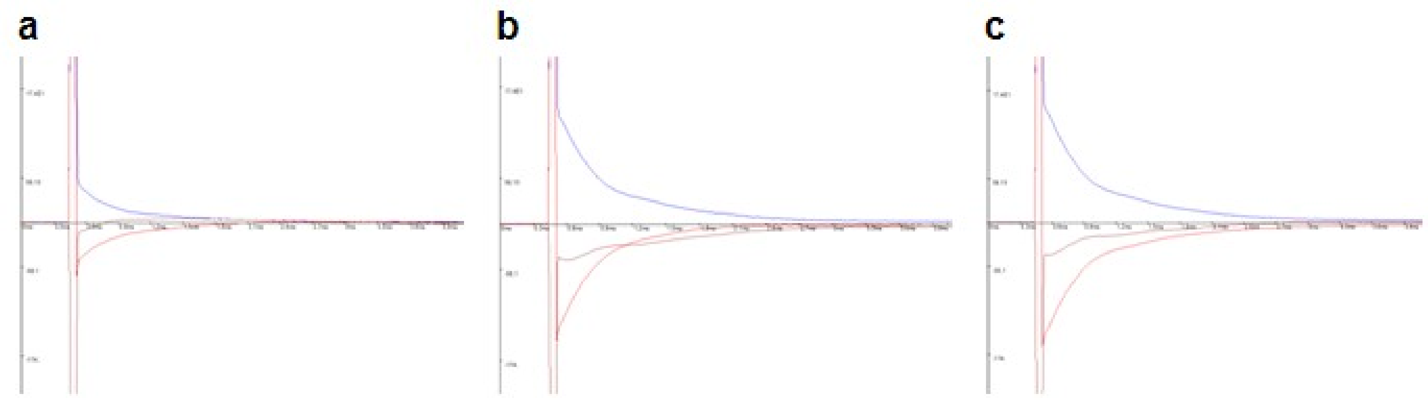

Fig. 31: FID signal of the 10 mm water sample for three different repetition times.

Evaluation (20/32)

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The repetition time is the time that passes after a measurement before a new measurement commences. It is one of the most important parameters in MR technology. Let us assume that, after a 90° HF pulse, a magnetisation vector has been tilted into the plane perpendicular to the static magnetic field vector $\overrightarrow{B_0}$. After the pulse, this tilted vector $\overrightarrow{M_Q(t)}$ (pure transverse magnetisation vector) strives for its state of equilibrium. In this state, the magnetisation vector points again into the same direction as the static magnetic field $\overrightarrow{B_0}$ and the transverse magnetisation part is nearly zero.

However, the state of equilibrium is reached during a relaxation time T_1' that is characteristic for the analysed medium. (Please note that T_1' is greater than T_1, since the latter indicates the point of time at which the longitudinal magnetisation has been restored only by approximately 63%. T_1' is usually selected between $2 \cdot T_1$ and $3 \cdot T_1$, since at this point of time the longitudinal magnetisation is restored by approximately 86-95%.)

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Evaluation (21/32)

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It is not until this relaxation time T_1' has elapsed that the nuclear spin ensemble has nearly completely resumed its initial precession movement around $\overrightarrow{B_0}$. If a new measurement is started after the elapsed relaxation time T_1', another FID signal can be recorded. This signal is nearly identical with the one of the first measurement (repetition time > T_1'). If, however, the relaxation time T_1' is not allowed to elapse and if a new 90° pulse is applied before the state of equilibrium is reached, the strength of the recorded FID signal decreases, since after the new 90° pulse the incompletely relaxed magnetisation vector no longer rotates precisely in the plane perpendicular to the static magnetic field $\overrightarrow{B_0}$ (repetition time < T_1').

Since the relaxation time T_1' of water is in the range of approximately 5 s, a repetition time of at least 5 s is essential for determining the FID signal amplitude of water (see Fig. 31 a-c). The relaxation time T_1' of oil is much shorter than that of water. It is in the range of approximately 300 ms. This is why the exact FID signal amplitude of oil can already be determined at very short repetition times.

Evaluation (22/32)

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D: Minimisation of magnetic field inhomogeneities

1. Study the effect of an additional magnetic field (shim) on the FID signal amplitude.

If the static magnetic field is superimposed by an additional magnetic field (shim), static field inhomogeneities that exhibit a certain directional preference and that are due to the special "setting" can be partly eliminated. The magnetic field becomes increasingly homogeneous. As a result, the effective relaxation time T_2^* of the FID signal increases, since the nuclear spin ensemble dephases less quickly. Figs. 32 a-c show the absolute values of the FID signal for three different magnetic field shims.

2. Adjust the shim in all three spatial directions so that you obtain a FID signal that is as long as possible.

In Fig. 32 c, the shim is adjusted so that it maximises the relaxation time T_2^* of oil. As a result, the deflected nuclear spin ensemble remains in phase for a comparably long period of time.

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Evaluation (23/32)

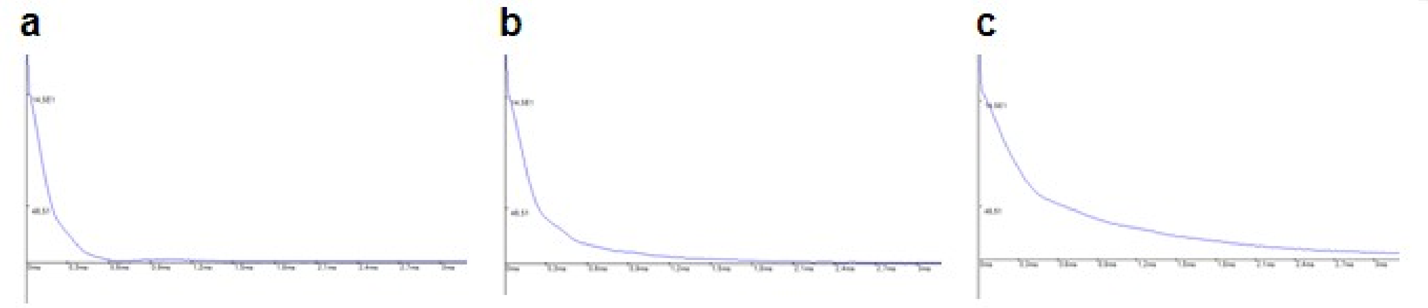

Fig. 32: Absolute values of the FID signal of the 10 mm oil sample for three different magnetic field shims. (a) shim X: -1.53 mT/m; shim Y: 4.90 mT/m; shim Z: 9.04 mT/m. (b) shim X: 5.52 mT/m; shim Y: 10.30 mT/m; shim Z: 9.04 mT/m. (c) shim X: 3.64 mT/m; shim Y: 10.90 mT/m; shim Z: 4.81 mT/m. The settings in (c) lead to a rather long FID signal, which means that a constant, system-caused magnetic field inhomogeneity of the external magnet in a certain direction has been reduced to a minimum.

Evaluation (24/32)

E: Restoration of the relaxed FID signal via a spin echo

1. Study the effect of a second HF pulse on the received signal. Adjust the pulse duration of the second pulse to a value that causes the nuclear spins to be flipped by 180° (optimum spin echo signal).

After the relaxation time T_2^*, a large part of the nuclear spin ensemble still rotates in the plane perpendicular to the static magnetic field $\overrightarrow{B_0}$. The only reason why a transverse magnetisation $\overrightarrow{M_Q}(t)$ cannot be measured is that the nuclear spin ensemble has dephased after a certain pattern. This directly results from the different rotational speeds of the individual nuclear spins, i.e. the faster ones have basically outrun the slower ones. If, after a time T_S, the command concerning the inversion of the direction is issued by way of a 180° pulse, the individual spins rejoin each other and rephase completely after the echo time $T_E = 2 \cdot T_S$. If this rephasing takes place within the time T_2, a signal can be measured. This signal is called spin echo. The spin echo itself decreases with the time T_2^*.

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Evaluation (25/32)

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Its amplitude, however, decreases with the time T_2. Only a 180° pulse leads to complete rephasing after the time T_E and to an optimum spin echo signal (maximum spin echo amplitude). In Fig. 33, the pulse duration of the second pulse is adjusted so that it generates an optimum 180° pulse. The FID signal was generated with an ideal 90° pulse.

2.

Study the effect of the pulse duration of the first pulse on the FID signal (see B) as well as on the spin echo signal.

In Fig. 34, the pulse duration of the first pulse has been decreased while the pulse duration for a 180° pulse (see task 1) has been maintained. The first HF pulse deflects the magnetisation vector by an angle φ that is smaller than 90°. Of course, this reduces the FID signal amplitude (see part B). Since the echo signal is simply a rephased FID signal, the echo amplitude also decreases.

Evaluation (26/32)

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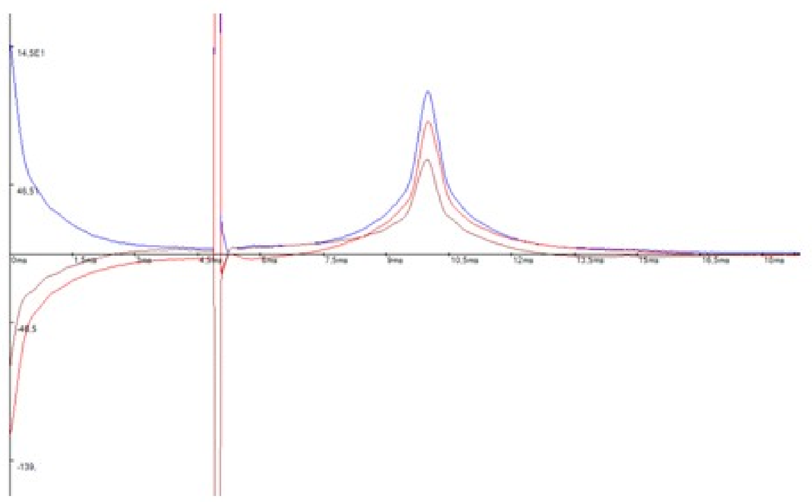

Fig. 33: Spin echo signal after an ideal 90° HF pulse (53 µs).

Fig. 33: The system frequency has been perfectly attuned to the Larmor frequency (see part A). The result is a maximum spin echo signal, since after the time T_S=5 ms a nearly ideal 180° pulse was applied (100 µs). This pulse causes the individual nuclear spins of the hydrogen protons to rephase completely. Rephasing is completed after the echo time T_E=2·T_S=10 ms. Here, the spin echo amplitude is at maximum. The spin echo itself decreases with the time 〖T_2〗 ^*. Its amplitude, however, decreases with the time T_2.

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Evaluation (27/32)

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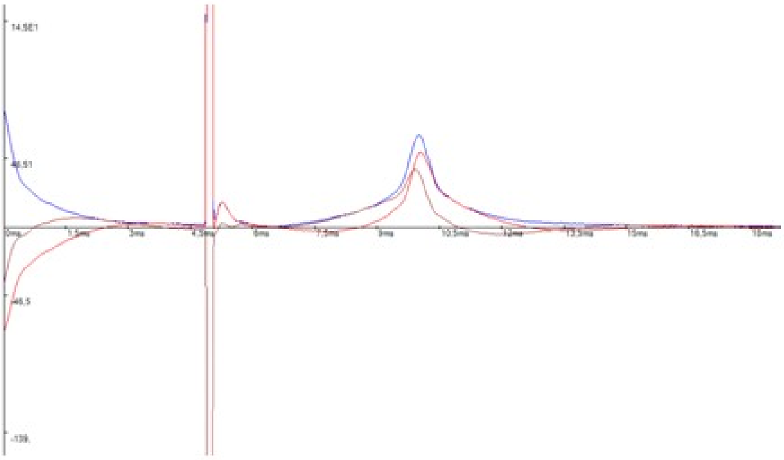

Fig. 34: Spin echo signal after an HF pulse that deflects the magnetisation vector by an angle of φ

3. Study the effect of the point of time of the second HF pulse on the spin echo signal (echo time). Analyse the spin echo amplitude at different echo times.

The point of time of the second 180° HF pulse determines the echo time. If the 180° pulse is applied after the time T_S, the echo signal will be obtained after the time $T_E = 2 \cdot T_S$. For $T_S = 6s$, for example, the echo time is $T_E = 12s$.

Evaluation (28/32)

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4. Observe the measurement signal at the point of time of the second HF pulse while at the same time varying the pulse duration of the first HF pulse.

The signal at the point of time of the application of the second HF pulse is another characteristic for the adjustment of an optimum first 90° HF pulse. When the signal disappears, an ideal 90° pulse has been adjusted. This becomes directly clear, since the nuclear spins only continue to rotate in the plane perpendicular to the static magnetic field $\overrightarrow{B_0}$ after the second 180° pulse if the first HF pulse has actually been a 90° pulse. Otherwise, the second 180° pulse would lead to a further tilting of the nuclear spin ensemble with regard to the static magnetic field vector $\overrightarrow{B_0}$ with the direct consequence of a forced phase coherence. As a result, a signal would be measurable at the point of time of the application of the 180° pulse.

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Evaluation (29/32)

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F: Maximisation of the signal-to-noise ratio

1. Study the effect of the repetition time, i.e. the time between two consecutive measurements, and the number of averages on the FID signal. In part C, we have already observed the influence of the repetition time on the FID signal amplitude. A small value for the repetition time can only be used if the relaxation time of the sample medium is also small. This is why the repetition time for oil can be significantly smaller than the repetition time for water.

Consequently, the effective measuring time in MR technology depends strongly on the repetition time. Another time factor is the number of averages taken over various measurements. Since a measured signal is inevitably accompanied by a certain level of noise, averaging is indispensable in MR technology. It must be taken into consideration that in order to double the signal-to-noise ratio (SNR) four averages are necessary, which means that the SNR improvement is proportional to the root of the number of averages.

Evaluation (30/32)

PHYWE

2. Try to achieve a good signal-to-noise ratio as quickly as possible. A good setting is reached if, with a short repetition time, the signal between several total measurements (every total measurement comprises a defined number of individual measurements) no longer shows any considerable fluctuations. The exact number of averages is to be decided by the person performing the experiment. The MR imaging quality can be considerably improved by way of a large number of averages.

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Evaluation (31/32)

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Fill in the missing words

Today, MRI (Magnetic Resonance Imaging) or MRT (Magnetic Resonance ______) is a fundamental imaging method that is used very frequently. MR scanners can display structures and functions of bodily tissues and organs in a ______ manner.This is why its main area of application is clinical diagnostics. However, this method can also be used for the chemical analysis of mixtures. All types of MRI methods are based on nuclear magnetic resonance (NMR). The ______ ______ is a measure of the total angular momentum of an atomic nucleus and, thereby, of a purely quantum-mechanical nature.

Check

Evaluation (32/32)

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True or False?

The greater the rotating magnetic moment $\vec{\mu}$ and the higher the rotation frequency is, the higher the MR signal that is generated.

- True
- False

Check

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Questions (1/6)

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A: Tuning of the system frequency to the Larmor frequency v_L

1. Why do hydrogen protons in an external magnetic field $\overrightarrow{B_0}$ behave differently than oxygen nuclei?
2. How do hydrogen protons differ from standard dipole magnets? Why is it actually possible to measure a total magnetisation in a certain volume with hydrogen protons? Discuss these questions using the keywords "energy quantisation (parallel and antiparallel spin orientation)" and "excess spins".
3. What kind of dynamic movement do nuclear spins perform in an external magnetic field $\overrightarrow{B_0}$? With which frequency do the nuclear spins of hydrogen protons precess in the Earth's magnetic field? How can nuclear spins be deflected from their dynamic precession around an external magnetic field $\overrightarrow{B_0}$?
4. Why does an HF pulse (high frequency) that is perpendicular to the external magnetic field $\overrightarrow{B_0}$ cause a deflection of the nuclear spins?

Questions (2/6)

PHYWE

B: Adjustment of the HF pulse duration for defining the MR excitation angle

1. Why does a 90° pulse that flips all of the nuclear spins by 90° lead to a maximum signal in the receiver coil, and a 180° pulse that flips all of the nuclear spins by 180° to a minimum signal (or ideally none at all)? When answering this question, remember that the receiver and transmitter coils are identical and that via these coils a rotating magnetic field $\overrightarrow{B_1}$ is generated in the plane perpendicular to $\overrightarrow{B_0}$.
2. What other MR excitation angles also lead to a maximum signal in the receiver coil? (Please bear in mind that the variance of the nuclear spins that are deflected by a certain angle increases over the excitation duration while the FID signal decreases.)

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Questions (3/6)

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C: Influence of the substance quantity on the FID signal

1. Why does a smaller substance quantity in the sample chamber of the MR unit decrease the FID signal amplitude?
2. What are the other factors that affect the FID signal amplitude?
3. Why is it impossible to deduce the hydrogen proton density of the sample substance with certainty based on the FID signal amplitude in the case of a short repetition time T_R between consecutive measurements?

D: Minimisation of magnetic field inhomogeneities

1. Why is a homogeneous static magnetic field so important for MR analyses and MR imaging?
2. What are the exact effects of magnetic field inhomogeneities on the FID signal and why do they have these effects?

Questions (4/6)

PHYWE

E: Restoration of the relaxed FID signal via a spin echo

1. What exactly happens with the nuclear spins after a 180° HF pulse if they were deflected by 90° beforehand? Answer this question based on the keyword "additional dephasing" that leads to an effective relaxation time T_2^* of the FID signal ($T_2^* < T_2$) and bear in mind that the second 180° HF pulse is applied within the relaxation time T_2.
2. T_S is defined as the time between the 90° HF excitation pulse and the 180° HF pulse. Why does the spin echo signal appear only after $2 \cdot T_S = T_E$?
3. Why does the strength of the spin echo signal decrease when the echo time T_E increases?

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Questions (5/6)

F: Maximisation of the signal-to-noise ratio

1. Apart from the number of averages, why is it necessary to take the repetition time [tex]T_R\), which describes the time between two consecutive measurements, also into consideration in order to obtain an adequate signal (see part C)?

Questions (6/6)

2. The standard deviation of the basic population of a sample is given by

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2} \approx \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})^2},$$

with as the number of measurements and $\overline{X}$ as the average of the random variable X_i. X_i. is the noise that happens to be included in an MR signal during a measurement i. In order to reduce the noise by half during a measurement, four consecutive measurements are required in accordance with the formula. The included MR signal simply adds up since it is identical in every individual measurement. As a result, the following applies to the signal-to-noise ratio:

$$SNR = \frac{|MR_{signal}|}{\sigma_{noise}} \approx \frac{MR_{signal}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(noise_i - \overline{noise})^2}}$$

How many averages are needed in order to achieve a tenfold SNR?

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Slide	Score / Total
Slide 93: Evaluation 31	0/4
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