Fundamental principles of nuclear magnetic resonance (NMR) (Item No.: P5942100)

Overview

Short description

Fundamental principles of nuclear magnetic resonance (NMR) (Item No.: P5942100)

Curricular Relevance

Area of Expertise: Physics → **Education Level:** University → **Topic:** Modern Physics → **Subtopic:** Quantum Physics → **Experiment:** Fundamental principles of nuclear magnetic resonance (NMR)

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Very difficult	10 Minutes	2 Hours	2 Students

Additional Requirements:

- PC (Windows)

Experiment Variations:

Keywords:

Nuclear spins, Atomic nuclei with a magnetic moment, Precession of nuclear spins, Magnetisation, Resonance condition, MR frequency, MR flip angle, FID-Signal (Free Induction Decay), Spin echo, Relaxation times (T1: longitudinal magnetisation, T2: transverse magnetisation), Signal-to-noise ratio

Related Topics

Nuclear spins, atomic nuclei with a magnetic moment, quantum physics versus classical physics, Pauli exclusion principle, precession movement of the nuclear spins, Landau-Lifshitz equation, Bloch equation, magnetisation, resonance condition, MR frequency, HF pulse technology (high frequency), FID signal (free induction decay), MR excitation angle, spin echo, relaxation times (T_1 : longitudinal magnetisation, T_2 : transverse magnetisation), signal-to-noise ratio, spectroscopy, magnetic resonance imaging (MRI), and magnetic resonance tomography (MRT).

Principle

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. 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.

Fig. 1: Set-up of the MRT training unit

Safety instructions

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.

Note

The experiment group "Fundamental principles of nuclear magnetic resonance (NMR)" (P5942100) is part of the set "Compact MRT" and covers the fundamental principles that are required for understanding a magnetic resonance tomography scanner. All of the experiments are integrated in the courses "Basic Course" and "Fundamental Principles". They can be selected via these courses by way of the "measure MRT" software. Many of the parameters that are set here are fundamental for numerous other TESS expert experiment sets.

Equipment

Position No.	Material	Order No.	Quantity
1	Compact MRT	09500-99	1

Tasks

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

1. Study the effects of varying system frequencies on the FID signal (free induction decay).
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 $\gamma(hydrogen) \approx 26.75 \cdot 10^7 \, rad/sT$).
3. Study the influence of external interference factors on the magnetic field $\overline{B_0}$. Comment on your observations.
4. Study the effect of the sample substance on the Larmor frequency υ_L.
   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.

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.

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.

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.

Setup and Procedure

Setup

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).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.

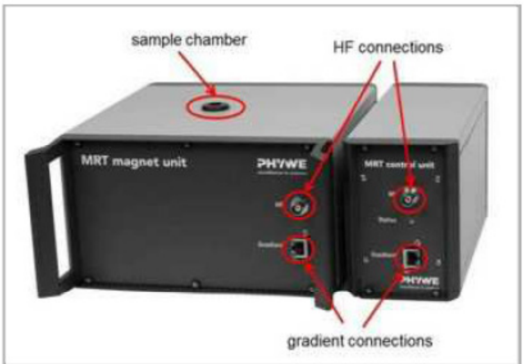

Fig. 2: Magnet and control unit connectors

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

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.

Questions

A: Tuning of the system frequency to the Larmor frequency υ_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?

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.)

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?

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?

F: Maximisation of the signal-to-noise ratio

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

Procedure

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".