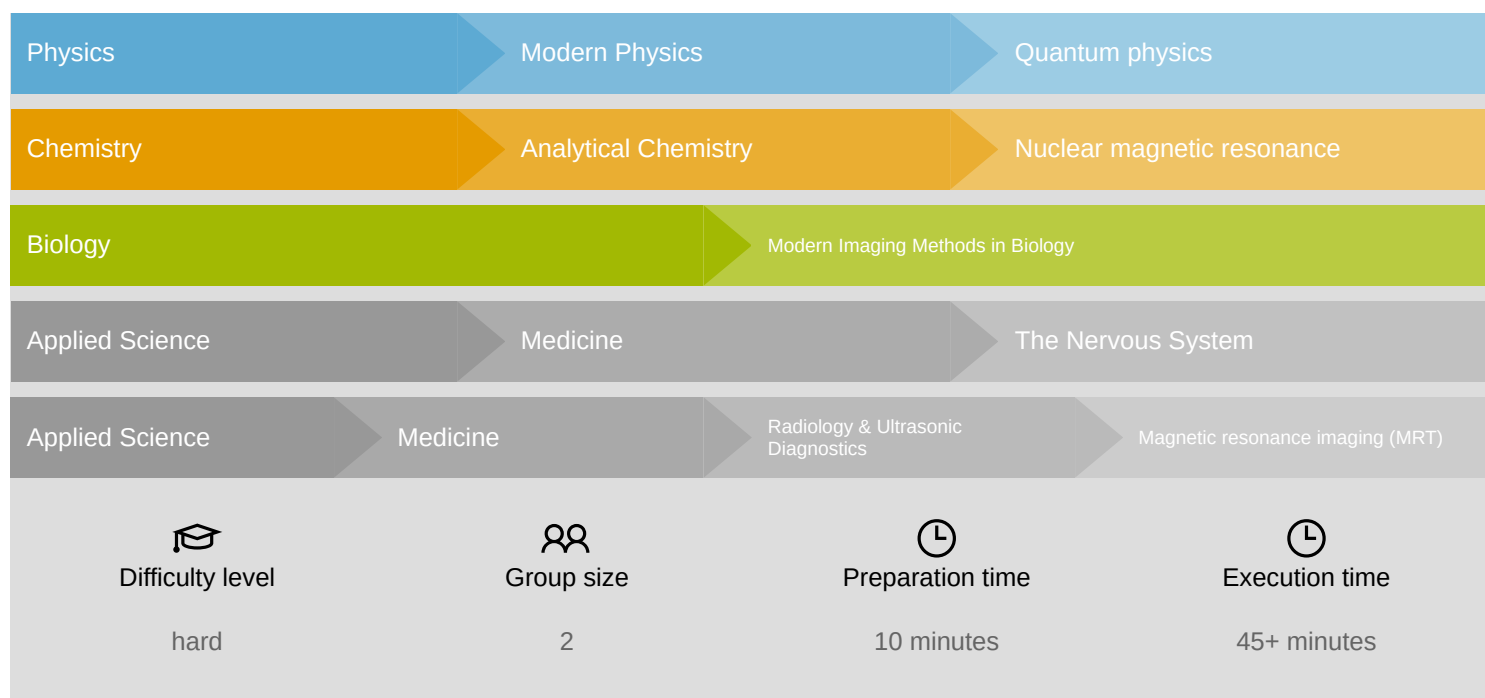
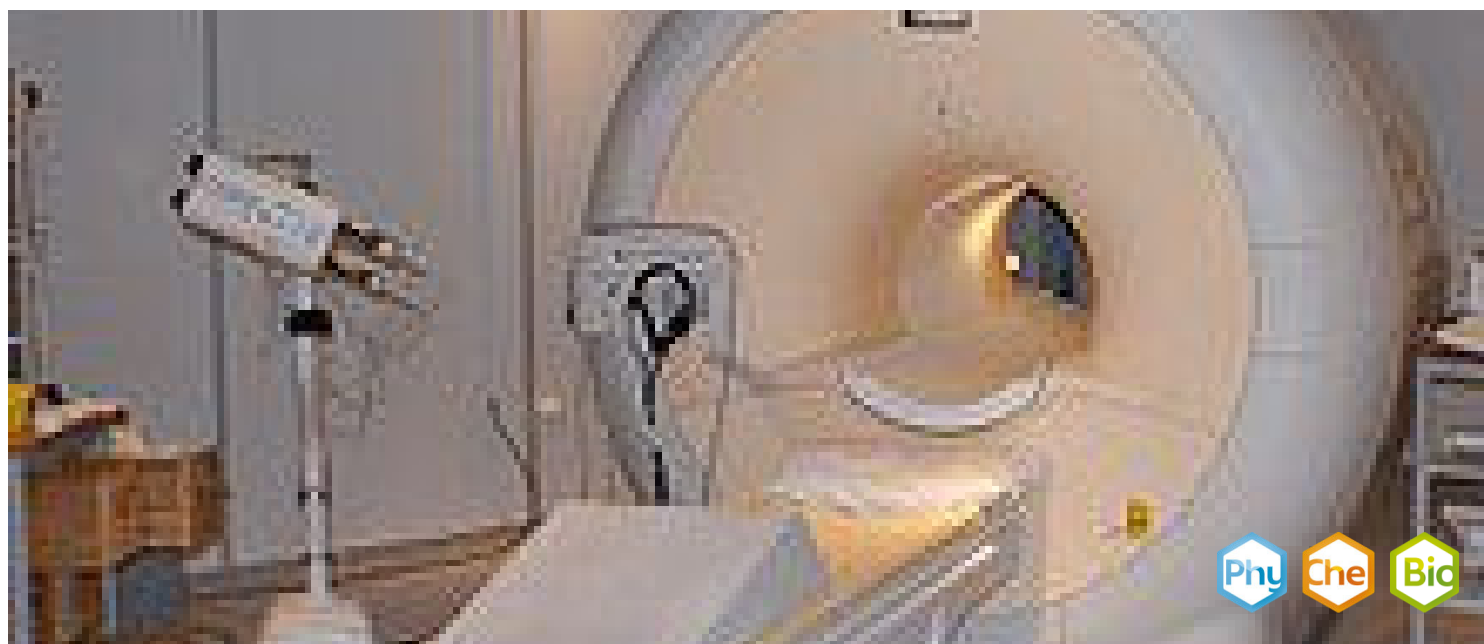


# Relaxation times in Nuclear Magnetic Resonance



This content can also be found online at:



<http://localhost:1337/c/5f0ed66bb6127b00030449f7>

PHYWE



## General information

### Application

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Medical MRI

Nuclear magnetic resonance (NMR) technique are applied in:

- **Medicine:** Based on the principles of NMR, magnetic resonance imaging (MRI) is used for medical diagnosis without exposing the body to radiation.
- **Biomedical:** NMR is used to study and determine structures and functions of important biological molecules, such as drugs.
- **Food industry:** The technique provides the information about the chemical composition and the structure of components in food without destroying the sample.

## Other information (1/5)

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## Prior knowledge



In the presence of a magnetic field, nuclei will align themselves either with or against the applied magnetic field. The energy difference between the two states results in a net spin magnetization along the  $B_0$  direction. The information in NMR is delivered by the precession of the spin magnetization around the magnetic field at the nucleus, with the angular frequency  $\omega = -\gamma B$ , where  $\gamma$  is the gyromagnetic ratio.

## Other information (2/5)

PHYWE

## Scientific principle



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  $\vec{B}_0$  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 (3/5)

PHYWE

Learning  
objective

The aim of these experiments is to demonstrate and understand the fundamental principles of nuclear magnetic resonance (NMR).

## Tasks

**A: Estimation of the relaxation time  $T_1$** 

1. Study the effects of the repetition time between two  $90^\circ$  HF pulses on the recorded signal.
2. Reduce the repetition time until the recorded signal amplitude corresponds approximately to half of the maximum amplitude and use the approximate spin-lattice half-life to calculate the approximate relaxation time of water.
3. Compare the estimated relaxation times of water and oil and then comment on your results.

## Other information (4/5)

PHYWE

## Tasks

**B: Measurement of the relaxation time  $T_1$** 

1. Record the exponential  $T_1$  relaxation curve of oil. Study the influence of the repetition time, time step, and number of points on this relaxation curve.
2. Record an ideal  $T_1$  relaxation curve and fit the signal course with the FIT routine that is implemented in the software. Read the relaxation time  $T_1$  of oil and print the graph.
3. Repeat these measurements for water. Read the relaxation time  $T_1$  of water on the corresponding FIT curve and print the graph.

## Other information (5/5)

PHYWE

### Tasks



#### C: Measurement of the relaxation time $T_2$

1. Study the effect of the echo time and number of echoes on the exponential  $T_2$  relaxation curve of oil.
2. Record an ideal  $T_2$  relaxation curve and fit the signal course with the FIT routine that is implemented in the software. Read the relaxation time  $T_2$  of oil and print the graph.
3. Repeat these measurements for water. Read the relaxation time  $T_2$  of water on the corresponding FIT curve and print the graph.

## Safety instructions

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For this experiment the general instructions for safe experimentation in science lessons apply.

For H- and P-phrases please consult the safety data sheet of the respective chemical.

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

## Theory (1/20)

PHYWE

The experiment ensemble "Fundamental principles of nuclear magnetic resonance (NMR)" concentrated mainly on the generation of the actual, measurable signal, as the so-called FID signal.

We have demonstrated how the individual nuclear spins contribute to the total magnetisation that aligns itself parallel to an external static magnetic field  $\vec{B}_0$ . The nuclear spins then precess around this static magnetic field vector with a frequency that is highly specific for the nucleus. This frequency is called the Larmor frequency. The following applies:

$$\nu_L = \frac{\omega_L}{2\pi} = \frac{\gamma}{2\pi} B_0 \quad (1)$$

An HF pulse in the resonance condition (1) that is applied perpendicularly to the external static magnetic field  $\vec{B}_0$  deflects the total magnetisation by an angle  $\phi$ . This excitation angle strongly depends on the pulse duration.

## Theory (2/20)

PHYWE

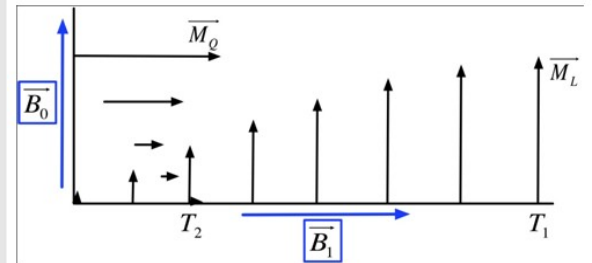
After every excitation at an angle  $\phi$ , the magnetisation vector can be divided into a part that is parallel to the static magnetic field and that is called longitudinal magnetisation  $\vec{M}_L(t)$ , and into a perpendicular part that is called transverse magnetisation  $\vec{M}_Q(t)$  and that precesses around the field vector in a plane perpendicular to  $\vec{B}_0$ .

A 90° HF pulse, for example, converts the initial longitudinal magnetisation  $\vec{M}_{L0}(t)$  completely into a transverse magnetisation  $\vec{M}_Q(0)$ . It is important to note that transverse magnetisations  $\vec{M}_Q(t)$  in a sample are the result of the phase synchronicity of the nuclear spin ensemble. If this phase synchronicity decays, a transverse magnetisation can no longer be measured.

## Theory (3/20)

PHYWE

Every deflection means that the state of equilibrium, i.e. the precession of the magnetisation vector around the static magnetic field  $\vec{B}_0$ , is abandoned. The relaxation describes the natural, dynamic restoration of the original state of equilibrium. The exponential restoration of the longitudinal magnetisation  $\vec{M}_L(t)$  is described by the relaxation time  $T_1$ , while the exponential decay of the transverse magnetisation  $\vec{M}_Q(t)$  is described by the relaxation time  $T_2$ .



Longitudinal and transverse relaxation after a 90° HF pulse.

## Theory (4/20)

PHYWE

The following applies:

$$M_L(t) = M_{L0}(t)(1 - ce^{-t/T_1}) \quad (2)$$

$$M_Q(t) = M_Q(0)e^{-t/T_2} \quad (3)$$

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.

Based on geometrical considerations, the constant  $c$  can be defined as

$$c = 1 - \cos\phi \quad (4)$$

## Theory (5/20)

PHYWE

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).  $T_2$  is normally smaller than  $T_1$ .

The  $T_1$  relaxation is caused by the so-called spin-lattice interaction. Because of the random molecular motion, the individual nuclear spin dipoles interact with their environment and transfer energy, e.g. kinetic energy, to the lattice atoms of the surrounding substance. (We will call the environment of a nuclear spin dipole a lattice rather often in the following, although this term is actually only permissible for solid bodies). The temporal change of these interactions is accompanied by a temporal local change of the magnetic field.

If the frequency of these magnetic field fluctuations corresponds to the approximate Larmor frequency, they act as small HF pulses and cause the spins to flip. As a result, the old state of equilibrium is reached again quickly in accordance with the Boltzmann distribution. The probability and speed of these "nuclear spin flips" depends on the surrounding substance, which leads to different  $T_1$  relaxations in different media.

## Theory (6/20)

PHYWE

Let us now once again have a look at the hydrogen protons that are essential for MR technology. Within a fat molecule with relatively low mobility, the protons sense the magnetic field fluctuations rather strongly.

As a result, the probability of a "proton spin flip" is comparably high, i.e. fat tissue is associated with a relatively short  $T_1$  relaxation time. Of course, the same reasoning also applies to other media with low mobility, e.g. for protons that are attached to a protein.

The situation in liquids is different, since the molecular motion of water is much quicker than most magnetic field fluctuations. This leads to a lower probability of resonances of the individual nuclear spins with these magnetic field fluctuations. If they do occur, they are usually weaker. As a result, the probability of a "proton spin flip" is comparably low. This is why pure water or cerebrospinal fluid are characterised by a relatively long  $T_1$  relaxation time.

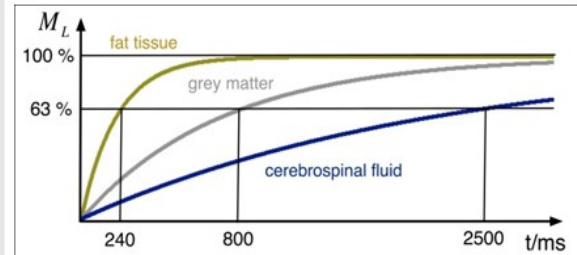
## Theory (7/20)

PHYWE

The curves correspond to the temporal course of the absolute value of the longitudinal magnetisation after a  $90^\circ$  HF pulse.

It can be seen that fat returns very quickly to its state of equilibrium (magnetisation vector parallel to the static magnetic field  $\vec{B}_0$ , which means that the  $T_1$  relaxation time is comparatively short.

Cerebrospinal fluid, on the other hand, has a considerably longer  $T_1$ . The relaxation curve of oil is similar to the one of fat and the relaxation curve of water is similar to the one of cerebrospinal fluid.



$T_1$  relaxation curves for different substances

## Theory (8/20)

PHYWE

As a summary, it can be stated that the relaxation time  $T_1$  that corresponds to the time that is needed for the restoration of approximately 63% of the original absolute value of the longitudinal magnetisation strongly depends on the size and structure of the molecules that surround the hydrogen protons as well as on their mobility and viscosity (temperature-dependent).

With the aid of a  $T_1$  weighting, it is, therefore, possible to create an image contrast with which the different types of tissue can be clearly identified. In a typical,  $T_1$ -weighted MR image, cerebrospinal fluid (water) is much darker than fat (oil). This contrast can be improved even further, since electron shell dipoles also affect the relaxation time  $T_1$ .

Paramagnetic contaminations, for example, lead to a shortening of  $T_1$ , since the electron shell dipoles are much stronger magnets than the nuclear dipoles. As a result, they produce stronger and more far-reaching interferences. In clinical applications, this "shell effect" is mainly used for the visualisation of blood vessels (angiography). Gadolinium complex compounds are mainly used for this purpose.

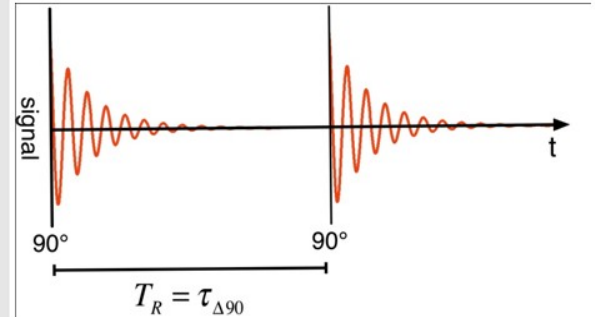
## Theory (9/20)

PHYWE

Now, the question is how the described spin-lattice relaxation times  $T_1$  can actually be measured. A suitable means would be a sequence of two  $90^\circ$  HF pulses that are separated by a certain time  $\tau_{\Delta 90}$ .

After the first  $90^\circ$  excitation pulse that generates the FID signal, a second  $90^\circ$  pulse is applied after the time  $T_R = \tau_{\Delta 90}$ . The signal strength after the second pulse is directly proportional to the longitudinal magnetisation  $\vec{M}_L(t)$ .

By varying  $\tau_{\Delta 90}$ , the  $T_1$  relaxation curve can be scanned. An exponential FIT of this curve leads to the relaxation time  $T_1$  of the substance that is examined.



Pulse sequence for the measurement of the  $T_1$  relaxation curve

## Theory (10/20)

PHYWE

The first deflection pulse moves the magnetisation vector to the plane that is perpendicular to the static magnetic field  $\vec{B}_0$ . After a short period of time ( $T_2^*$ ), there is a dephasing of the nuclear spins in the perpendicular plane, and later ( $T_1$ ) the state of equilibrium is re-established, i.e. there is a relaxation of the magnetisation vector in the direction of the static magnetic field  $\vec{B}_0$ .

The second  $90^\circ$  pulse after the time  $\tau_{\Delta 90}$  now scans to see how many nuclear spins precess once more in the state of equilibrium or, in other words, by what angle the magnetisation vector has tilted back. This means that the signal amplitude after the second  $90^\circ$  "detection pulse" is proportional to the longitudinal magnetisation  $\vec{M}_L(t)$  immediately prior to the  $90^\circ$  "detection pulse".

## Theory (11/20)

PHYWE

A low amplitude after a short  $\tau_{\Delta 90}$  implies a high proportion of the transverse magnetisation  $\overrightarrow{M_Q(t)}$  and a low proportion of the longitudinal magnetisation  $\overrightarrow{M_L(t)}$  in the total magnetisation  $\overrightarrow{M_\phi(t)}$  prior to the detection pulse

$$\overrightarrow{M_\phi(t)} = \overrightarrow{M_Q(t)} + \overrightarrow{M_L(t)}.$$

Correspondingly, a high amplitude after a long  $\tau_{\Delta 90}$  implies a low proportion of the transverse magnetisation  $\overrightarrow{M_Q(t)}$  and a high proportion of the longitudinal magnetisation  $\overrightarrow{M_L(t)}$  in the total magnetisation  $\overrightarrow{M_\phi(t)}$  prior to the detection pulse, i.e. a nearly complete relaxation.

## Theory (12/20)

PHYWE

This means that by varying the repetition time  $\tau_{\Delta 90}$ , it is possible to determine a typical  $T_1$  relaxation curve of a specific substance. A FIT routine that fits an exponential function to the amplitudes of the measured signals enables the calculation of the relaxation times  $T_1$ . For this purpose, the signals must be prepared beforehand (baseline correction, Fourier transformation) in order to ensure that the correct amplitude values are used for the FIT (the supplied measurement program will perform these preparations automatically).

The first estimation of the  $T_1$  relaxation time can be achieved with a very simple method. First, we select a rather long  $\tau_{\Delta 90}$  (e.g. 20 s) in order to obtain the approximate maximum amplitude after the second detection pulse, i.e. the amplitude that corresponds to the complete relaxation of the longitudinal magnetisation  $\overrightarrow{M_L(t)}$  prior to the second detection pulse.

## Theory (13/20)

PHYWE

If we now reduce  $\tau_{\Delta 90}$ , and look for a value at which the signal amplitude is only approximately half as high as the approximate maximum amplitude, this value corresponds to a rough estimation of the spin-lattice half-life  $TR_{1/2}$ . If we define the amplitude of the signal as  $A_{\beta}(t)$ , the typical law of decay applies:

$$A_{\beta}(t) = A_{\beta}^m(t) \exp\left(-\frac{t}{T_1}\right) \quad (5)$$

This enables the direct estimation of the relaxation time. The following applies:

$$T_1 = \frac{TR_{1/2}}{\ln 2} \quad (6)$$

## Theory (14/20)

PHYWE

The spin-lattice interaction is also responsible for the  $T_2$  relaxation that actually describes the exponential decay of the transverse magnetisation  $\overrightarrow{M_Q}(t)$ . This becomes directly obvious, since fluctuating magnetic fields close to the Larmor frequency change the spin states of the protons. As a result, the phase coherence of the spin ensemble and, thereby, the measurable transverse magnetisation  $\overrightarrow{M_Q}(t)$  also vanishes.

As far as the relaxation of the transverse magnetisation is concerned, there is also another interaction that is responsible for the generally shorter  $T_2$  relaxation time compared to the  $T_1$  relaxation time. This is the so-called spin-spin interaction. The change of a spin state always implies a small, local change of the magnetic field. The neighbouring protons sense this change ( $\approx 1$  mT) that leads to slight changes of their precession frequencies. In a local range, these frequencies scatter by approximately 40kHz around the normal Larmor frequency. The frequency variations of neighbouring nuclear spins drive the dephasing process and the measurable transverse magnetisation vanishes comparably quickly.

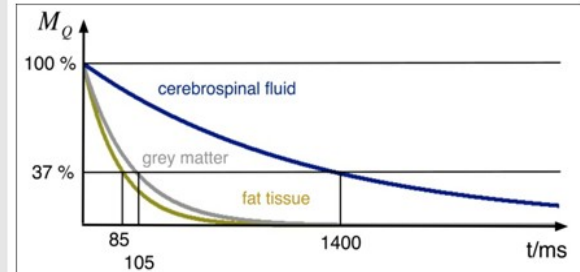
## Theory (15/20)

PHYWE

The additional dephasing based on spin-spin interactions depends on the surrounding substance, which leads to different  $T_2$  relaxations in different media.

In liquids (e.g. water or cerebrospinal fluid),  $T_2$  is relatively long (in the case of pure liquids, it is sometimes nearly as long as  $T_1$ ).

In solid or semi-solid materials (e.g. fat or biological tissue), on the other hand,  $T_2$  is in most cases clearly shorter than  $T_1$ .



$T_2$  relaxation curves for different substances

## Theory (16/20)

PHYWE

As a summary, it can be stated that the relaxation time  $T_2$  that corresponds to the time that is needed for the decay of approximately 63% of the original absolute value of the transverse magnetisation depends - just like the relaxation time  $T_1$  - strongly on the size and structure of the molecules that surround the hydrogen protons as well as on their mobility and viscosity (temperature-dependent).

With the aid of a  $T_2$  weighting, it is, therefore, possible to create an image contrast with which the different types of tissue can be clearly identified.

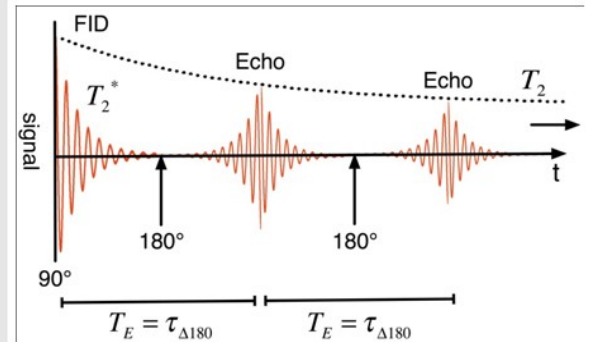
In a typical  $T_2$ -weighted MR image, for example, cerebrospinal fluid (water) is much lighter than fat tissue (oil). In the end, the question that remains is how spin-spin relaxation times  $T_2$  can actually be measured. Typically, a sequence of one  $90^\circ$  pulse and several  $180^\circ$  pulses is used for this purpose.

## Theory (17/20)

PHYWE

After the first  $90^\circ$  excitation pulse that generates the FID signal, a  $180^\circ$  pulse is applied after the time  $T_S$ . This pulse generates a spin echo signal after the time  $2T_S = T_E = \tau_{\Delta 180}$ . Its amplitude is proportional to the transverse magnetisation  $\overrightarrow{M_Q}(t)$ .

If a multi-echo sequence is used, the  $T_2$  relaxation curve can be scanned with one single measurement. An exponential FIT of this curve leads to the relaxation time  $T_2$  of the substance that is examined.



Pulse sequence for the measurement of the  $T_2$  relaxation curve

## Theory (18/20)

PHYWE

In this context, the purpose and effect of a  $180^\circ$  pulse should be explained again. In "Fundamental principles of nuclear magnetic resonance", we have seen that, after the phase-synchronous deflection into the plane perpendicular to the external static magnetic field vector  $\overrightarrow{B_0}$ , the nuclear spin ensemble dephases with  $T_2^* < T_2$  in the time  $T_2^*$ . This is due to purely static field inhomogeneities that are temporally and spatially constant. They cause the phases of the nuclear spin ensemble to diverge after a certain pattern.

However, this systematic dephasing can be reversed. If a  $180^\circ$  pulse is applied after the time  $T_S$ , i.e. if the entire fanned-out spin ensemble is flipped by  $180^\circ$  (compare the concept of a "flipped omelette"), the quickest spin 1 will catch up with the slowest spin  $n$  after the time  $2 \cdot T_S = T_E$ .

## Theory (19/20)

PHYWE

Precisely at this point of time, the initial phase synchronicity of the spin ensemble is restored. The restored MR signal is called a spin echo. The spin echo signal itself decreases with  $T_2$ , while its amplitude decreases with  $T_2$ . This means that dephasing due to a pure spin-spin and spin-lattice interaction can be observed directly based on the amplitude of the spin echo signal.

Now it is clear how the  $T_2$  relaxation curve can be determined. Instead of a second  $90^\circ$  pulse, we simply use a  $180^\circ$  pulse as the detection pulse (compare the  $T_1$  relaxation curve) and, thereby, the classic spin echo signal as a detection signal that indicates the value of the transverse magnetisation  $\overrightarrow{M_Q(t)}$  that has already decayed at the time  $T_E$  of the spin echo.

A variation of the echo time  $T_E$  then provides the typical  $T_1$  relaxation curve of a specific substance. A FIT routine that - just like in the case of the relaxation curve - fits an exponential function to the amplitudes of the measured signal at various echo times  $T_E$  enables the calculation of the relaxation times  $T_2$ .

## Theory (20/20)

PHYWE

In order to determine the  $T_2$  relaxation curve, it is not necessary to perform several measurements with varying  $T_E$  in order to obtain a large set of data points. One measurement with several echoes that repeat after the set echo time  $T_E = \tau_{\Delta 180}$  is perfectly sufficient. Such a sequence is known as a multi-echo sequence or turbo spin echo (TSE).

Every amplitude of a certain spin echo leads to a data point of the  $T_2$  relaxation curve when it appears ( $n \cdot T_E$ ). The exponential FIT routine can be used again to determine the relaxation time  $T_2$ .

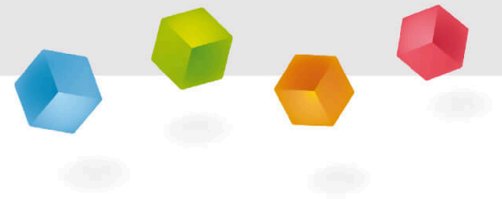
Analogous to the  $T_1$  estimation, it is sufficient for the  $T_2$  estimation to find the echo time  $TE_{1/2}$  at which the echo amplitude corresponds to half of the initial FID signal amplitude. Then, the following applies to the  $T_2$  estimation:

$$T_2 = \frac{TE_{1/2}}{\ln 2} \quad (7)$$

## Equipment

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

PHYWE



## Setup and procedure

### Setup (1/3)

PHYWE



Set-up of the MRT training unit

Set the MR unit up. 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.

## Setup (2/3)

PHYWE

Ensure that the POWER switch of the control unit is set to off. 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.

Connect the control unit and the magnet by way of the gradient and BNC cables that are intended for this purpose. Then, connect the USB interfaces of the control unit and measurement computer via a USB 2.0 high-speed cable. Switch the unit on via the POWER rocker switch (the MR unit should only be switched on for performing experiments).



Connectors at the back of the control unit

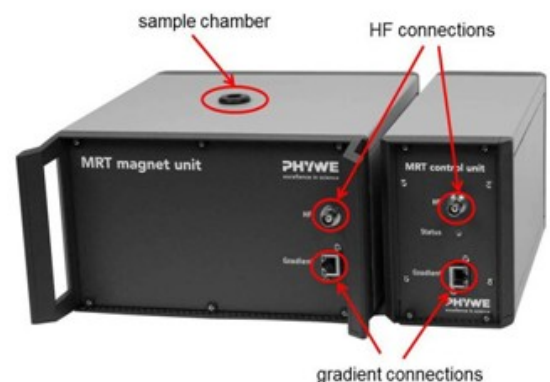
## Setup (3/3)

PHYWE

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.

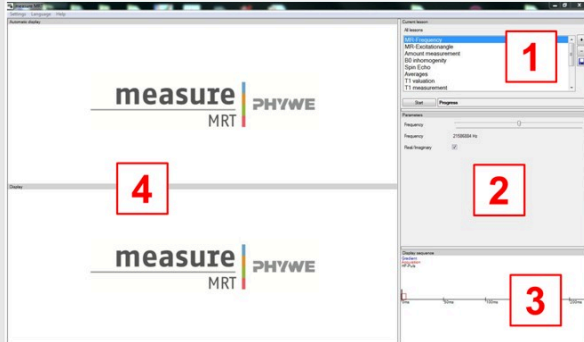
**Note:** Details concerning the operation of the MR unit as well as the handling of samples in the MR sample chamber can be found in the corresponding operating instructions.



Magnet and control unit connectors

## Procedure (1/7)

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Areas of the "measure MRT" program

When the "measure MRT" software is started, a window will open automatically.

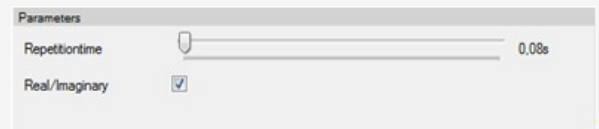
In area 1, experiments can be selected (experiments area). The associated parameters are displayed in area 2 (parameters area). Area 3 shows a sequence representation of the selected experiment (sequence area). Finally, the results are displayed in area 4 (results area).

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".

## Procedure (2/7)

### A: Estimation of the relaxation time $T_1$

- Place the 10 mm water sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson T1 valuation. The parameters area shows the setting options Repetition time and Real/Imaginary. Vary the repetition time between two 90° HF pulses by way of the slider Repetition time (interval between two measurements with one 90° HF pulse each).



T1 valuation - parameters

## Procedure (3/7)

PHYWE

- At first, set the repetition time to a very high value (e.g. 15 seconds) and measure the signal amplitude. Then, reduce the repetition time until the signal amplitude is only half. TIP: Reduce the repetition time from 15 seconds to approximately 2 seconds and then decide whether the repetition time must be increased or decreased from thereon. Calculate the relaxation time  $T_1$  of water based on the final value of the adjusted repetition time (corresponds to the spin-lattice half-life).
- Replace the 10 mm water sample with the 10 mm oil sample and repeat points 1 and 2. Calculate the relaxation time  $T_1$  of oil.

**Note:** Note down the  $T_1$  relaxation times of water and oil. These parameter estimations are highly useful for the correct performance of the other experiments.

## Procedure (4/7)

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### B: Measurement of the relaxation time $T_1$

- Place the 10 mm oil sample into the sample chamber of the unit. In the experiments area (lessons), select the lesson T1 measurement. The parameters area shows the setting options Repetition time, Time step, and Number of points. Vary the repetition time between two measurements (one measurement includes two consecutive 90° pulses) by way of the slider Repetition time, the incremental time step for increasing the interval between the two 90° HF pulses in consecutive measurements by way of the slider Time step, and the number of consecutive measurements by way of the slider Number of points.

Parameters		
Repetitiontime		0.3s
Timestep		15ms
Number of points		15

T1 measurement - parameters

## Procedure (5/7)

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- Adjust all of the sliders so that you can see an adequate exponential curve on the screen. This curve is part of the  $T_1$  relaxation curve of oil. TIP: Use the estimated relaxation time of part A. The repetition time should be set to at least three times the estimated  $T_1$  value of the sample. The time step and number of points should be set so that, at the end of the total measurement, the effective time between the two  $90^\circ$  pulses corresponds at least to the value of the estimated  $T_1$ . Note: A large number of data points and a small time step always provide a more trustworthy result.
- Fit the recorded signal course with the aid of an exponential curve  $\alpha - be^{-x/T_1}$ . To do so, right-click the graph and select "Evaluation/Absolute". Then, select the  $T_1$  FIT and click "Data fitting". The fitted parameters can be read directly in the diagram. Replace the 10 mm oil sample with the 10 mm water sample and repeat points 1 and 2. Compare the fitted parameters a, b, and  $T_1$  of oil and water.

**Note:** Note down the fitted relaxation times of water and oil. These parameters are highly useful for the correct performance of the other experiments.

## Procedure (6/7)

PHYWE

### C: Measurement of the relaxation time $T_2$

- Place the 10 mm oil sample into the sample chamber of the MR unit. In the experiments area (lessons), select the lesson T2 measurement. The parameters area shows the setting options Number of echoes and Echo time. Vary the number of generated echoes by way of the slider Number of echoes and the time interval between two consecutive echoes by way of the slider Echo time.
- Adjust all of the sliders so that you can see an adequate exponential curve on the screen. This curve is part of the  $T_2$  relaxation curve of oil.

Parameters	
Number of echos	45
Echotime	3ms

T2 measurement - parameters

## Procedure (7/7)

PHYWE

- TIP: A number of approximately 250 echoes and an echo time of approximately 2 ms provide already a rather good exponential curve. Note: Longer echo times lead to an artificial and unwanted dephasing due to the special measurement sequence. As a result, the relaxation time  $T_2$  changes towards considerably smaller values. This is why the echo time should be as short as possible.
- Fit the recorded signal course with the aid of an exponential curve  $ae^{-x/T_2} + c$ . To do so, right-click the graph and select "Evaluation/Absolute". Then, select the  $T_2$  FIT and click "Data fitting". The fitted parameters can be read directly in the diagram. Replace the 10 mm oil sample with the 10 mm water sample and repeat points 1 and 2. Increase the number of echoes and, if necessary, also the echo time. Compare the fitted parameters  $a$ ,  $c$ , and  $T_2$  of oil and water.

**Note:** Note down the fitted  $T_2$  relaxation times of water and oil. These parameters are highly useful for the correct performance of the other experiments.

## Evaluation (1/17)

PHYWE

### A: Estimation of the relaxation time $T_1$

1. Study the effects of the repetition time between two  $90^\circ$  HF pulses on the recorded signal.
  - Figures a-c show the measurement signal after the second  $90^\circ$  HF pulse of the 10 mm water sample for three different repetition times  $T_R = \tau_{\Delta 90}$ . The repetition time indicates the exact interval between the two pulses. The signal is extremely weak in the case of very short repetition times, which means that water must have a  $T_1$  relaxation time that is considerably longer than 1 s.
  - It can be seen that after the second  $90^\circ$  HF pulse the signal is lowest for the shortest repetition time (a) and that it increases when the repetition time increases (b, c). This is directly due to the comparably long relaxation time of water.

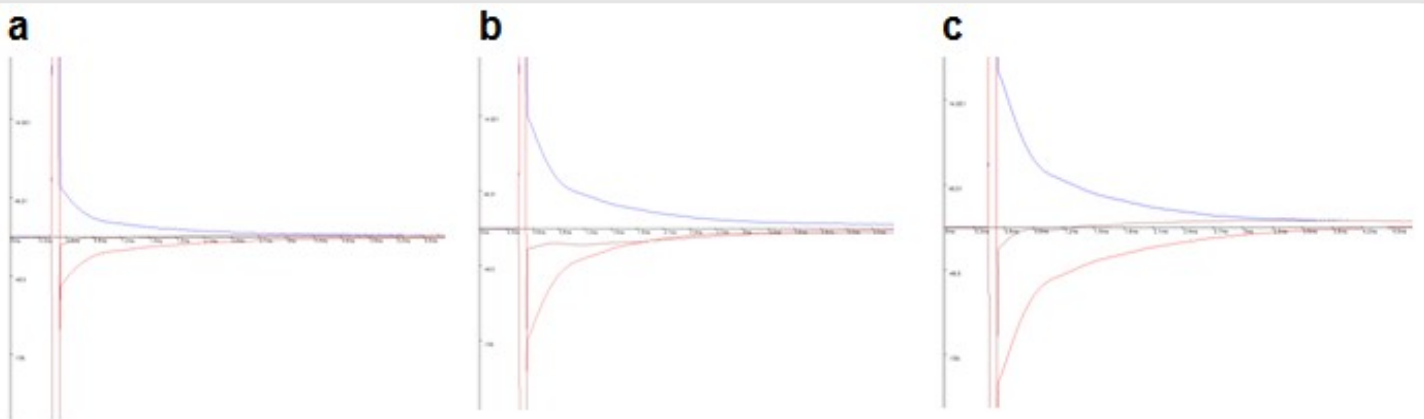
## Evaluation (2/17)

PHYWE

- If the second HF pulse is applied before the state of equilibrium is reached, i.e. before the magnetisation vector is again nearly parallel to the external static magnetic field  $\vec{B}_0$ , the second HF pulse does not lead to a complete deflection of all of the nuclear spins into the plane that is perpendicular to  $\vec{B}_0$ .
- As a result, the value of the transverse magnetisation vector  $\vec{M}_Q(t)$  is smaller and the signal is weaker. This means that the measured signal is directly proportional to the value of the relaxed longitudinal magnetisation  $\vec{M}_L(t)$ .

## Evaluation (3/17)

PHYWE



Measurement signal after the second of two  $90^\circ$  HF pulses of the 10 mm water sample for three different repetition times  $T_R = \tau_{\Delta 90}$ . (a)  $T_R = 1\text{ s}$  (b)  $T_R = 5\text{ s}$  (c)  $T_R = 16\text{ s}$

## Evaluation (4/17)

PHYWE

2. Reduce the repetition time until the recorded signal amplitude corresponds approximately to half of the maximum amplitude and use the approximate spin-lattice half-life to calculate the approximate relaxation time of water.

If the repetition time is set to approximately 15 seconds, a good estimate of the maximum amplitude after the second  $90^\circ$  pulse can be obtained. This means that longer repetition times hardly evoke any changes of the signal amplitude after the second  $90^\circ$  pulse. After a reduction of the repetition time to approximately 2 seconds, the measured signal amplitude corresponds approximately to half of the maximum amplitude. The repetition time thus adjusted is the spin-lattice half-life  $TR_{1/2}$  of water.

Then, use the equation (6):

$$T_1 \approx 2.9s.$$

This is the estimated  $T_1$  relaxation time of water.

## Evaluation (5/17)

PHYWE

3. Compare the estimated relaxation times of water and oil and comment on your results.

Figs. a-c show the measurement signal after the second  $90^\circ$  HF pulse of the 10 mm oil sample for the same three repetition times  $T_R = \tau_{\Delta 90}$  as the figures in task 1. There are hardly any differences in terms of the signal amplitude after the second  $90^\circ$  pulse. This means that oil reaches the state of equilibrium already after a comparably short relaxation time, i.e. that the magnetisation vector is again nearly parallel to the external static magnetic field  $\vec{B}_0$  much more quickly than in the case of water. The second pulse then leads to a deflection of nearly all of the nuclear spins into the plane perpendicular to  $\vec{B}_0$  for all three repetition times.

As a result, the absolute value of the transverse magnetisation vector and, thereby, the recorded signal is nearly identical after the second  $90^\circ$  pulse for all three repetition times.

## Evaluation (6/17)

PHYWE

Similar to task 2, the relaxation time of oil can be estimated. However, in the case of oil, the repetition time must be set to a much smaller value. After approximately 0.08 seconds, the measured signal amplitude corresponds to half of the maximum amplitude. This repetition time thus adjusted is the spin-lattice half-life  $TR_{1/2}$  of oil.

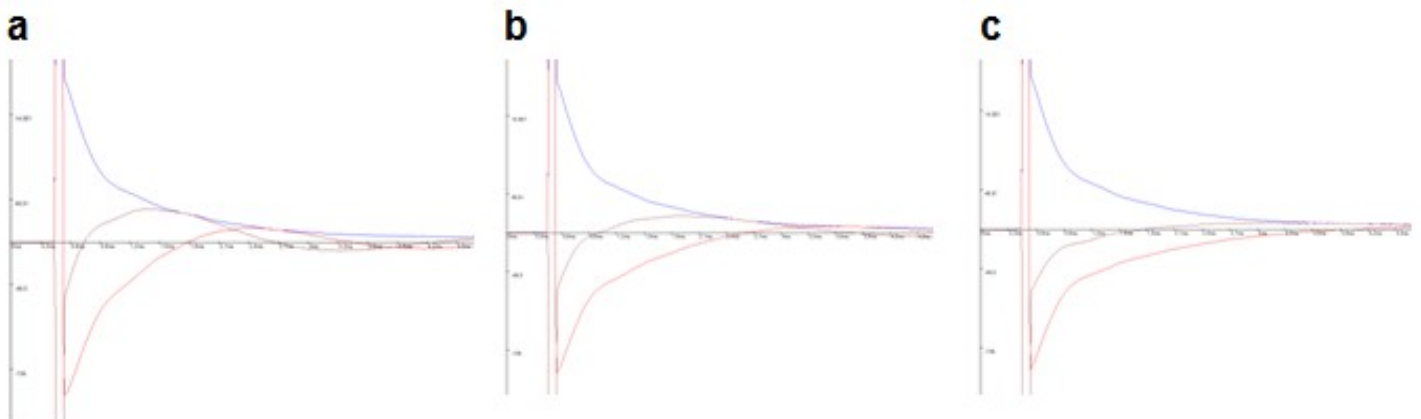
Then, use the equation (6):

$$T_1 \approx 0.115s.$$

This is the estimated  $T_1$  relaxation time of oil

## Evaluation (7/17)

PHYWE



Measurement signal after the second of two  $90^\circ$  HF pulses of the 10 mm oil sample for three different repetition times  $T_R = \tau_{\Delta 90}$ . (a)  $T_R = 1s$  (b)  $T_R = 5s$  (c)  $T_R = 16s$

## Evaluation (8/17)

PHYWE

### B: Measurement of the relaxation time $T_1$

1. Record the exponential  $T_1$  relaxation curve of oil. Study the influence of the repetition time, time step, and number of points on this relaxation curve.

In this experiment part, the repetition time is the time between the individual measurements that are formed by the two  $90^\circ$  HF pulses. This shows that for an adequate  $T_1$  relaxation curve, the repetition time must be selected so that the spin ensemble is again nearly in the state of equilibrium for the new measurement, i.e. that the magnetisation vector points again in the direction of the external static magnetic field  $\vec{B}_0$  (see part A). If the selected repetition time is not sufficiently long, the first FID signal of a measurement will already be weaker, since the magnetisation vector will not be completely deflected into the plane perpendicular to  $\vec{B}_0$ .

## Evaluation (9/17)

PHYWE

As a consequence, the signal after the second HF pulse within the individual measurement will also be distorted and will no longer provide the exact value of the  $T_1$  relaxation curve at the moment of the second signal. Of course, the measuring time is longer in the case of longer repetition times. Still, the repetition time should be set at least to three times the estimated  $T_1$  value of the substance that is examined since, at this point of time, approximately 95% of the original longitudinal magnetisation has already been rebuilt.

The interval between the two  $90^\circ$  pulses in consecutive measurements is varied by way of the time step. From one measurement to the next, the interval between the two  $90^\circ$  pulses is increased exactly by this time step. The detailed scanning of the  $T_1$  relaxation curve requires a small time step. Still, at the end of the measurement, the relaxation curve should have been scanned up to the relaxation time  $T_1$  so that a good exponential FIT is possible. This means that the more a scan should be detailed, the more measurements (number of points) must be generated.

If these two parameters are selected inappropriately, the exponential FIT will lead to incorrect results.

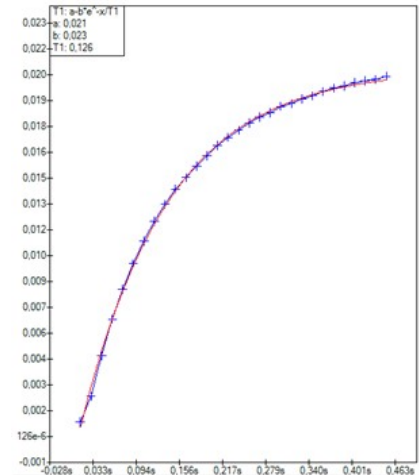
## Evaluation (10/17)

PHYWE

2. Record an ideal  $T_1$  relaxation curve and fit the signal course with the FIT routine that is implemented in the software. Read the relaxation time  $T_1$  of oil and print the graph.

The repetition time was set to 0.5 seconds, the number of data points to 30, and the time step to 15 ms. The FIT algorithm fits the exponential function  $a - b \cdot e^{-x/T_1}$  to the data points. The parameters thereby found are  $a = 0.021$ ,  $b = 0.023$  and  $T_1 = 0.126$  s. Please note:  $a$  and  $b$  should always be approximately identical. This is due to the 90° HF excitation ( $c = 1$ , see equation (2)).

$T_1 = 126$  ms is the relaxation time of oil.



Exponential FIT to the  $T_1$  relaxation curve of oil

## Evaluation (11/17)

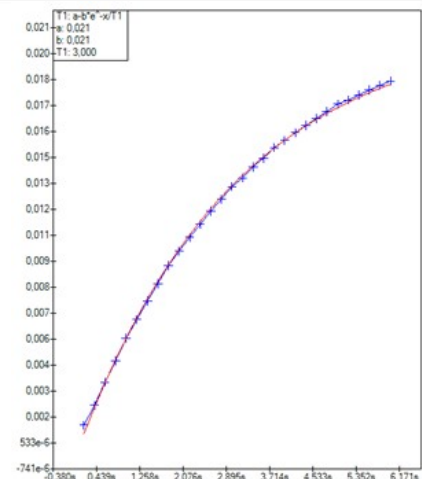
PHYWE

3. Repeat these measurements for water. Read the relaxation time  $T_1$  of water on the corresponding FIT curve and print the graph.

The repetition time was set to 10 seconds, the number of data points to 30, and the time step to 200 ms. The FIT algorithm fits the exponential function  $a - b \cdot e^{-x/T_1}$  to the data points.

The parameters thereby found are  $a = 0.021$ ,  $b = 0.021$ , and  $T_1 = 3$  s.

$T_1 = 3$  ms is the relaxation time of water.



Exponential FIT to the  $T_1$  relaxation curve of water

## Evaluation (12/17)

PHYWE

### C: Measurement of the relaxation time $T_2$

1. Study the effect of the echo time and number of echoes on the exponential  $T_2$  , relaxation curve of oil.

The aim of this part is to determine the relaxation time  $T_2$  , of substances by way of a multi-echo sequence.

Every spin echo is a detection signal for the remaining proportion of the transverse magnetisation  $\overrightarrow{M_Q(t)}$  in the relaxation process. It is separated from the next spin echo by the echo time  $T_E = \tau_{\Delta 180}$

This clearly shows that a fine scan of the  $T_2$  , relaxation curve requires a large number of echoes and a short echo time. Again, the scan should be performed approximately up to the  $T_2$  , relaxation time of the substance under examination in order to enable a good exponential FIT. This means that the more a scan should be detailed, the more echoes must be generated.

## Evaluation (13/17)

PHYWE

Note: Longer echo times lead to an artificial and unwanted dephasing due to the special measurement sequence.

As a result, the relaxation time  $T_2$  , changes towards considerably smaller values. If the echo time  $T_E$  , is selected inappropriately, the exponential FIT will lead to incorrect results.  $T_2$  , can be found based on an estimation method as per equation (7).

Note: Unlike in the case of the measurement of the relaxation time  $T_1$  ,  $T_2$  , can already be determined by way of a single measurement consisting of a multi-echo sequence.

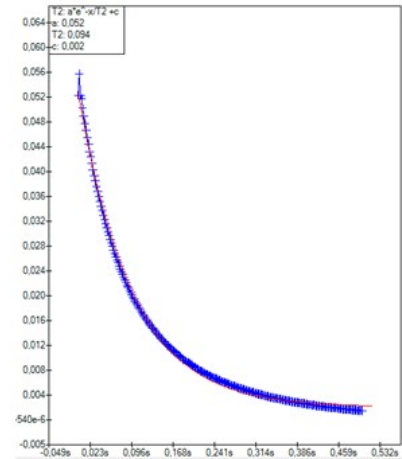
## Evaluation (14/17)

PHYWE

2. Record an ideal  $T_2$ , relaxation curve and fit the signal course with the FIT routine that is implemented in the software. Read the relaxation time  $T_2$ , of oil and print the graph.

In this case, the echo time was set to 2 ms and the number of echoes to 250. The FIT algorithm fits the exponential function  $c + a \cdot e^{-x/T_2}$  to the data points. The parameters thereby found are  $a = 0.052$ ,  $c = 0.002$ , and  $T_2 = 0.094$  s.

$T_2 = 94$  ms is the relaxation time of oil.



Exponential FIT to the  $T_2$  relaxation curve of oil

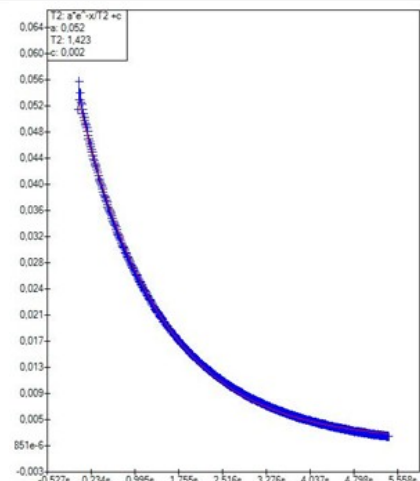
## Evaluation (15/17)

PHYWE

3. Repeat these measurements for water. Read the relaxation time  $T_2$  of water on the corresponding FIT curve and print the graph.

In this case, the echo time was set to 12 ms and the number of echoes to 450. The FIT algorithm fits the exponential function  $c + a \cdot e^{-x/T_2}$  to the data points. The parameters thereby found are  $a = 0.052$ ,  $c = 0.002$ , and  $T_2 = 1.423$  s.

$T_2 = 1.423$  s is the relaxation time of water.



Exponential FIT to the  $T_2$  relaxation curve of oil

## Evaluation (16/17)

PHYWE

Which of the following statements are true regarding  $T_1$  relaxation time?

- ☐ It depends on the size and structure of the molecules as well as on their mobility and viscosity
- ☐ It is caused by spin-lattice interaction
- ☐  $T_1$  relaxation time is relatively long in liquid medium
- ☐  $T_1$  relaxation time is relatively long in solid medium

☒ Check

## Evaluation (17/17)

PHYWE

True or False?

Due to spin-spin interaction, relaxation time  $T_2$  is generally smaller than relaxation time  $T_1$  in both solid and liquid substances.

☐ True☐ False☒ Check

## Question (1/3)

PHYWE

**A: Estimation of the relaxation time**

1. What is described by the relaxation times  $T_1$  and  $T_2$ ?
2. Why is the relaxation time  $T_1$  longer than the relaxation time  $T_2$ ?
3. When has the original longitudinal magnetisation  $M_L(t)$  rebuilt by approximately 95% following the application of a  $90^\circ$  HF pulse? Use the formula  $M_L(t) = M_{L0}(1 - ce^{-t/T_1})$  with  $c = 1$ .
4. Derive the general correlation  $c = 1 - \cos\phi$ , with  $\phi$  as the angle of deflection of the magnetisation vector out of its original precession around the static magnetic field  $\vec{B}_0$ .
5. Why is it possible to determine the relaxation time  $T_1$ , by way of a second  $90^\circ$  HF pulse after a primary  $90^\circ$  HF excitation?

## Question (2/3)

PHYWE

**B: Measurement of the relaxation time  $T_1$** 

1. Why is it possible to conclude the excitation angle of the magnetisation vector from an exponential FIT.  $a - be^{-x/T_1}$  of the  $T_1$  relaxation curve (see the questions in A)?
2. What is the precise effect of the spin-lattice interaction? Why is the relaxation time of fat (oil) shorter than the relaxation time  $T_1$  of cerebrospinal fluid (water)?
3. How can different  $T_1$  relaxation times of different substances be used for MR imaging? How must the repetition time be selected in order to obtain a high  $T_1$  contrast between different substances? Why are short repetition times associated with a very low signal strength?

## Question (3/3)

PHYWE

**C: Measurement of the relaxation time  $T_2$** 

1. What is the precise effect of the spin-spin interaction? Why is the relaxation time  $T_2$  of fat (oil) shorter than the relaxation time  $T_2$  of cerebrospinal fluid (water)?
2. How can different  $T_2$  relaxation times of different substances be used for MR imaging? How must the repetition time and echo time be selected in order to obtain a high  $T_2$  contrast between different substances?

Slide

Score/Total

Slide 56: Relaxation time

0/3

Slide 57: Spin-spin interaction

0/1

Total Score

 0/4

Show solutions



Retry