Radiospectroscopy methods

Radiowaves are on the “low end” of the photon energy scale, much less than 1eV.

Schay G.

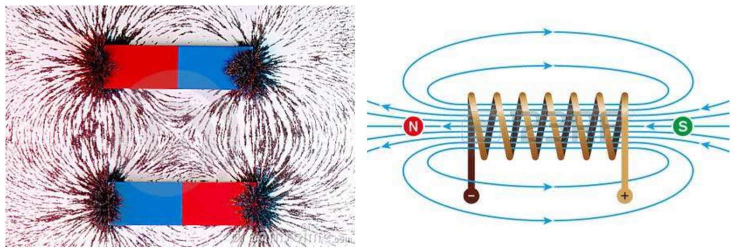
NMR : Nuclear magneic resonance
ESR : electron spin resonance
Microwave spectroscopy

NMR (MRI) and ESR are both based on magnetism.

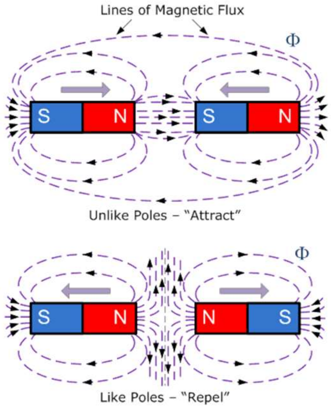
We review magnetism first

Magnetic poles

n.B: magnetic monopoles do not exist, just dipoles. A moving (accelerating) charge creates a magnetic field



Magnetic field (or flux) lines of a magnet



N.B: magnetic Flux (Φ) is the magnetic field added up over a given area.

Magnetic moment (μ)

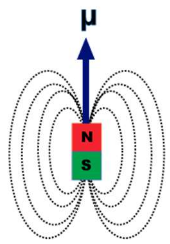
It is related to the torque experienced in a magnetic field:

$$\tau = \mu \, x \, B$$

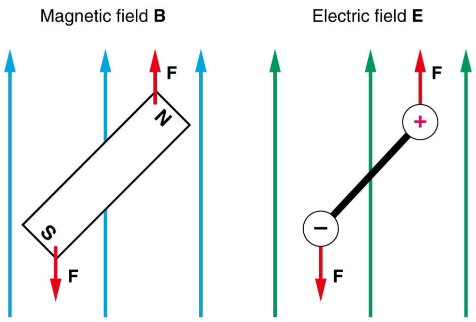
Here every quantity is a vector, x is the vector product.
Unit: Nm/T = J/T

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

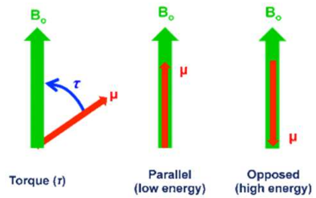
H: magnetizing force
B: magnetic field (developed in the material)
M: magnetization (of the material)



Torque acting on the magnetic dipole in a given field is very similar to the case of an electric dipole.



Energy of a dipole in an external field

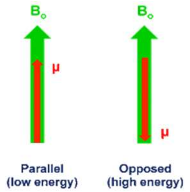


If the magnetic moment is not parallel to the B field, then a torque τ will act on it. This may produce mechanical work, so the concept of potential energy applies.

$E_{pot} = -\mu \cdot \mathbf{B}$
Since this is a scalar product, extrema are in the parallel or antiparallel orientations

The energy difference $\Delta E = E_{high} - E_{low}$ depends on the magnetic field strength!

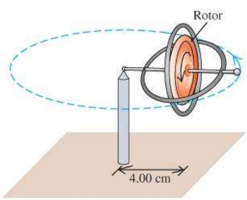
$\Delta E = 2 \cdot \mu \cdot B_0$

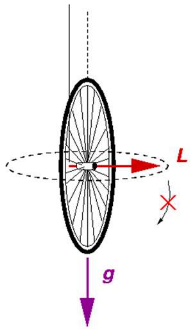


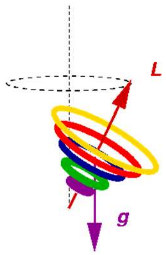
Nuclear and electron spin

A spin is an ancient toy, but also an interesting object of physics

A change in the angular momentum will caused by the force acting on the rotating object.

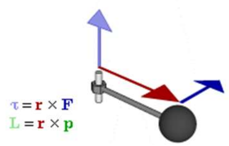






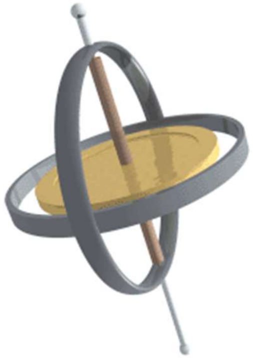
THE LAW OF CONSERVATION OF ANGULAR MOMENTUM STATES THAT:
"When the net external torque (τ) acting on a system about a given axis is zero , the total angular momentum (L) of the system about that axis remains constant."

$$\frac{\Delta L}{\Delta t} = \tau$$

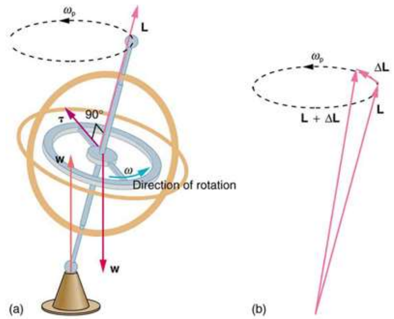


Beware, these are all vectors!

Gyroscpe and precession



Gyroscope
A torque (τ) is created on the rotating object by the gravity force and the holding force of the stand (w).
Since this torque is perpendicular to the angular momentum, therefore ΔL is perpendicular to L itself causing **precession**:
the magnitude of the angular momentum will not change, just its direction.

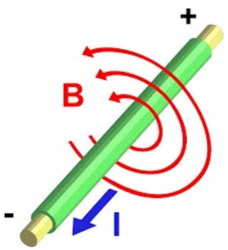


ω_p is the Larmor frequency, which is the angular frequency of precession.

$$\omega_p = \frac{x \cdot mg}{I \cdot \omega}$$

Where x is the axle length,
mg = w is the gravity force (responsible for the τ torque)
and I is the inertia of the rotating disc.

Electromagnetism



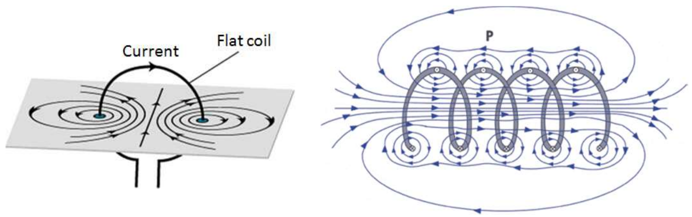
A wire with current flowing will create a magnetic field.

$$\sum_{loop} \boldsymbol{B} \cdot \Delta \boldsymbol{l} = \mu_0 I$$

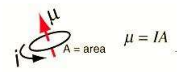
Ampère's law

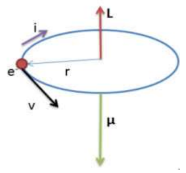
$\mu_0 = 4\pi \cdot 10^{-7}$ N/A^2 is the magnetic permeability of free space

Electromagnets work by winding up the wire into multiple turns.
It functions like an ordinary magnetic dipole



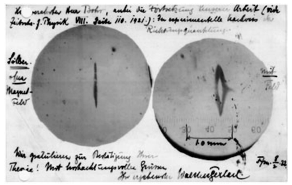
A current loop also has a magnetic moment

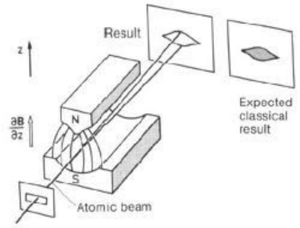




Even a single electron orbiting a centre has a magnetic moment

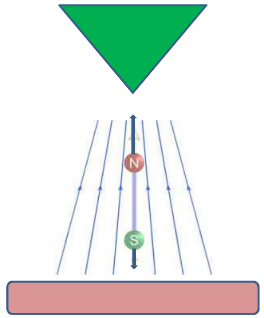
Spin of electrons or protons





The Stern-Gerlach experiment:
In an inhomogeneous magnetic field an ion beam can split into two.

Explanation: in an nonuniform field net force is acting on a magnetic dipole



TWO paths -> TWO dipole orientations

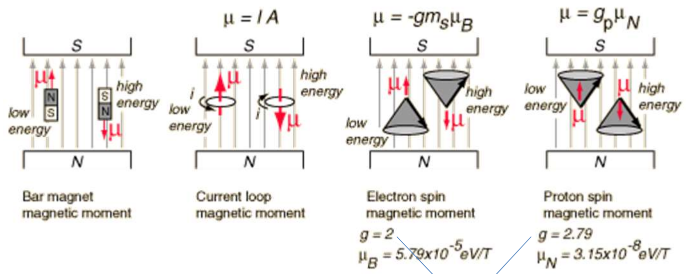
(random dipoles would give a smear)

Intrinsic magnetic moment of electron / proton
The orientation is quantized.

The intrinsic magnetic moments comes from the SPIN of the particle. (behaves like a spin)

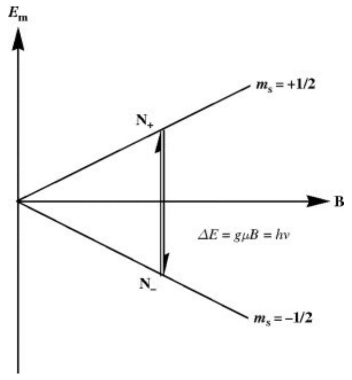
$$\mu = \hbar \cdot \gamma \cdot s \qquad \hbar = \frac{h}{2\pi}$$

Gyromagnetic factor



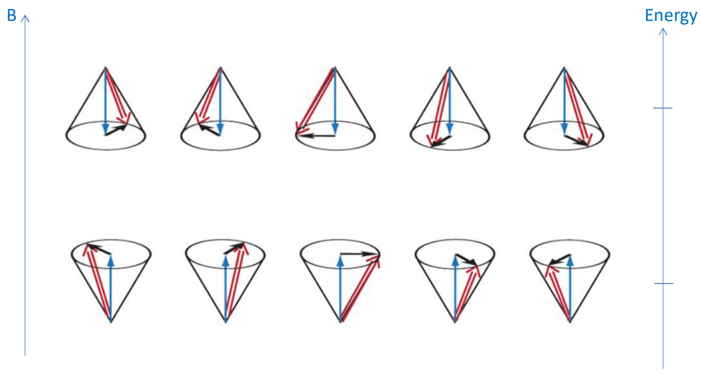
$$\gamma = g \cdot \frac{q}{2m}$$ ← charge

Zeeman-splitting: energy depends on magnetic field strength.



Spin = +/- ½

precession in an external field



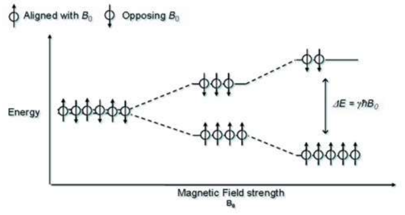
EXTENSION MATERIAL

Proton (and electron) spins with spin quantum number **m_s = ½**
follow the usual **two-level system** distribution

$$\Delta E = 2\mu B_0 = \gamma \cdot \hbar \cdot B_0$$

$$\mu = \hbar \cdot \gamma \cdot \left(\pm\frac{1}{2}\right)$$

$$\gamma = g \cdot \frac{q}{2m}$$



$$\Delta E = 2 \cdot \left(\hbar \cdot g \cdot \frac{q}{2m} \cdot \frac{1}{2}\right) \cdot B_0 = g \cdot \frac{q \cdot h}{4\pi \cdot m} \cdot B_0 = g \cdot \mu_N \cdot B_0 = g_P \cdot \mu_N \cdot H$$

μ_N: Bohr magneton, here q=*e*, m=m_{proton}

An example:

$$\Delta E = g_P \cdot \mu_N \cdot H$$

If H = 3T then:

- Find the energy difference
- The photon energy in eV
- The frequency of the photon
- The ratio of excited/ground state protons
- From 5000000 protons, what is the difference between N_{exc} and N_{gr}?

g_P = 5.59 ; $\mu_N = 5.05 \cdot 10^{-27}\ \frac{J}{T}$

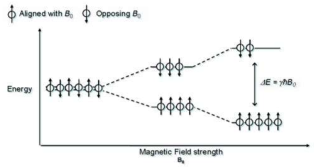
$$\Delta E = 5.59 \cdot 5.05 \cdot 10^{-27}\frac{J}{T} \cdot 3T = 8.469 \cdot 10^{-26}\,J = 5.29 \cdot 10^{-7}\ eV$$

n.B. : kT at 25°C is $1.38 \cdot 10^{-23}$ J/K · (273+25)K = $4.11 \cdot 10^{-21}$ J
This means $\Delta E/kT = 2.06 \cdot 10^{-5}$ = 0.0000206
The energy difference for parallel and antiparallel orientation is much smaller than the thermal energy at room temperature.

$$f=\frac{\Delta E}{h} = \frac{8.46\quad{}^{-26}J}{6.63 \cdot 10^{-34}Js} = 1.27 \cdot 10^{8}\,\frac{1}{s} = 127MHz$$

The photons are actually radio frequency electromagnetic waves, just like FM music radio!

$$\frac{N_{excited}}{N_{ground\ state}} = e^{-\frac{\Delta E}{kT}} = e^{-2.06\cdot10^{-5}} =$$
$$= 0.9999794002$$



There are almost the same number of protons in both states even under a very strong ~T magnetic field. (The field of the Earth is in the 20-70 μT range)

$$N_{ground} - N_{excited} = 102$$

In NMR we can measure the magnetic field of the protons.

Since the opposite oriented spins practically cancel each other, we only have to deal with this small difference, the rest (the vast majority!) of the protons can be neglected.

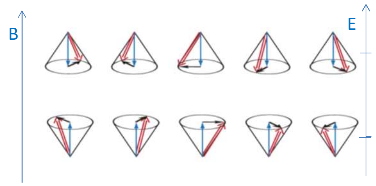
The excess spins are parallel oriented to the magnetic field. If there is an RF irradiation (eg. 127 MHz) then the spins will be excited to the antiparallel state.

One RF photon can excite one spin. Depending on the intensity (photons/s) and duration of the irradiation, some or all of the spins can get to the excited state.

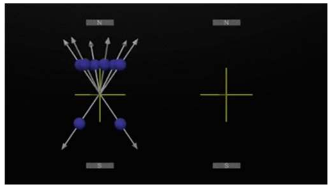
From the excited state the exponential decay will follow.

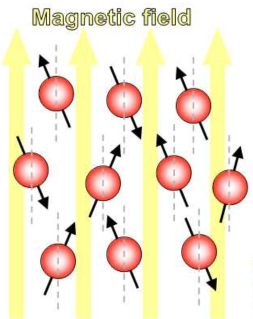
But spins are precessing:
$\omega_p = 2\pi f_{Larmor}$
$h \cdot f_{Larmor} = \Delta E$

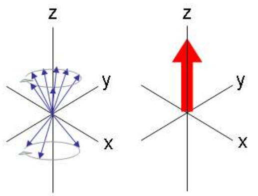
The precession has a frequency and a phase



Both will depend on the magnetic field strength

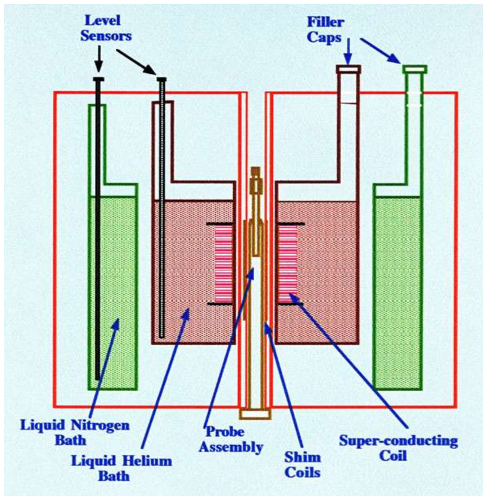






Overall magnetisation of nuclei = Sum of vectors from individual nuclei

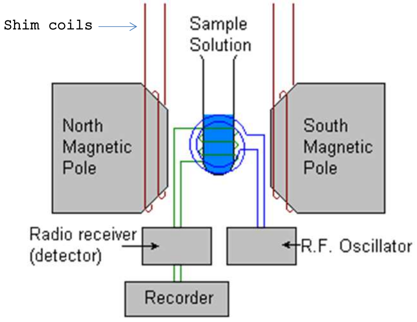
NMR spectrometer setup



The high filed magnet is superconductive coil, it needs to be cooled with liquid He.

The field inhomogenities are compensated with the *shim-coils*

Schematic of an NMR spectrometer



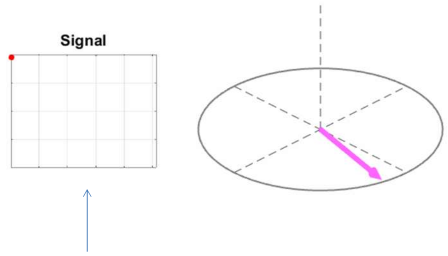
The conventional method: We measure the RF absorption spectrum of the sample. (with cw RF irradiation, varying frequency)

Drawback: absorption methods have a low sensitivity.

Emission methods have a high sensitivity-> FT-NMR
We excite with an **RF pulse**, and measure the resulting emission.

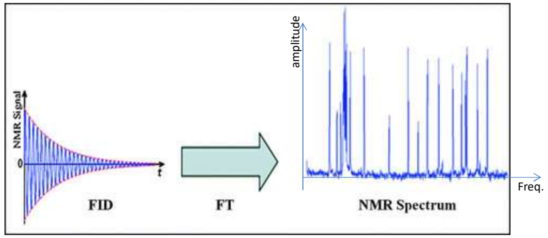
After a pulsed excitation we can measure the relaxation signal

We can measure the electro-magnetic field produced by the precessing spins (with a simple wire coil. Similar coils can send the RF pulses)



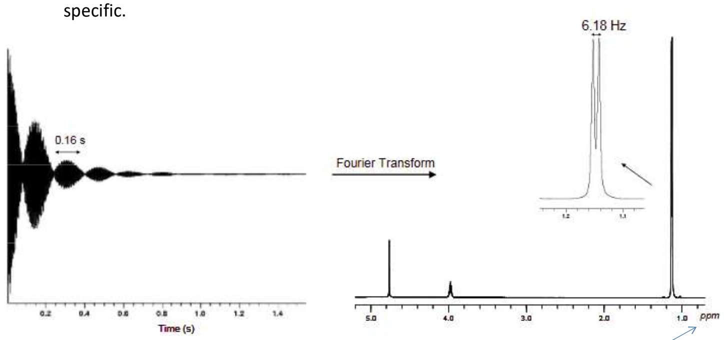
The relaxation signal is the Free Induction Decay (FID) signal.

Fourier-transformation of the FID signal will produce the NMR spectrum.



The frequency scale is often shown as $\Delta f/f_0$ as the "chemical shift" in ppm ($1/10^6$)
f_0 is the Larmor frequency of a given substance's proton signal.

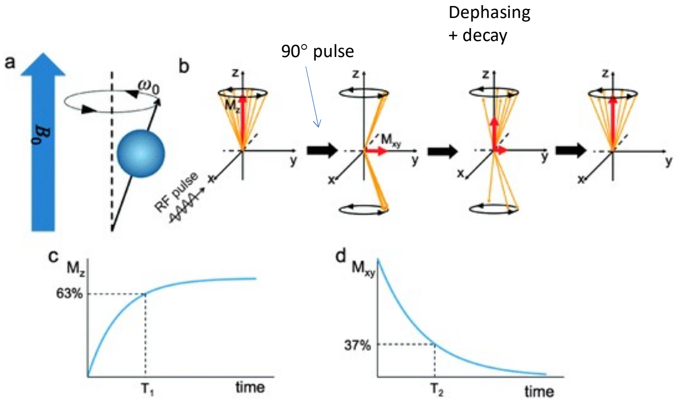
The frequencies are very sensitive to the presence of other atoms/electrons.
Therefore the spectrum is different for every molecule.
The reason: electrons shield the magnetic field, so $H=H_0(1-\sigma)$.
The local field H will depend on the electrons, which is molecule and chemistry specific.

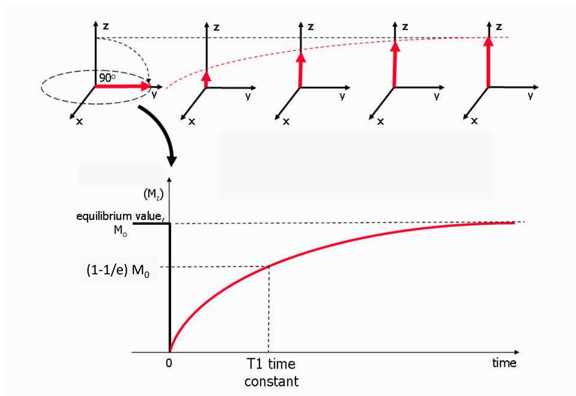


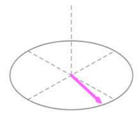
$$\delta = \frac{f - f_0}{f_0} \cdot 10^6\ (ppm)$$

90° pulse: the duration+intensity is "enough" to excite ½ of the excess spins

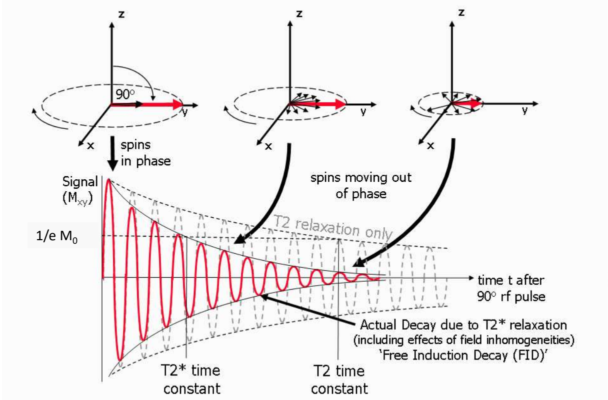
After the 90° pulse the z-magnetization is 0, and the xy is max.

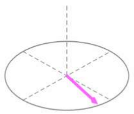






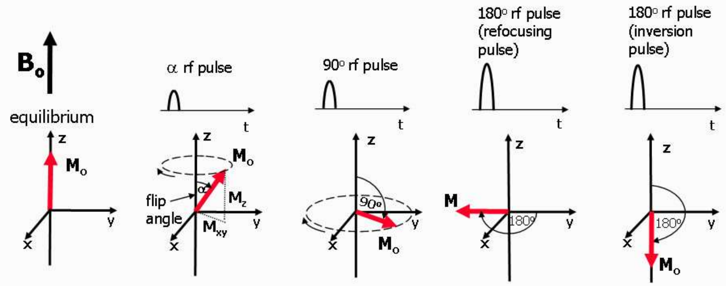
The excited spins return to the ground state following an exponential decay.
The decay rate is sensitive to the local magnetic field, which is influenced by the surrounding material (the "lattice") : **spin-lattice realxation: T1**





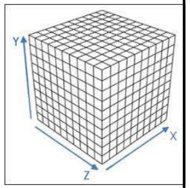
In the xy plane ALL spins can contribute. They are synchronized by the RF pulse, but then due to local inhomogeneities (T2->T2*) and random fluctuations (caused by nearby spin's fields) of local H a dephasing will start. (**spin-spin relaxation: T2**)

Other pulse types:

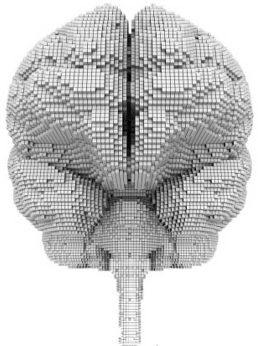


Spin-echo methods and MRI (Magnetic Resonance Imaging)

For 3D imaging one needs to select a **voxel** of the reconstruction volume
This can be done in general by varying the larmor frequency of the spins.



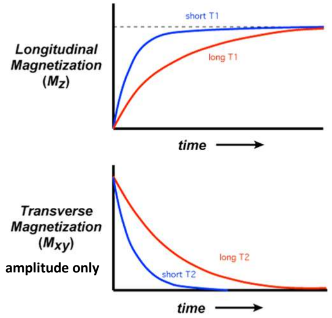
Reconstruction volume



3 types of contrast:
- Nº of spins / voxel volume (^{1}H conc., Proton Density)
- T1 (spin-lattice) differences
- T2 (or T2*) (spin-spin) differences

The brain made-up from voxels: small boxes.

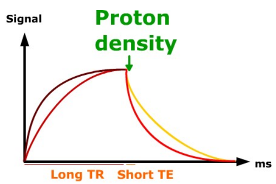
Contrast factors

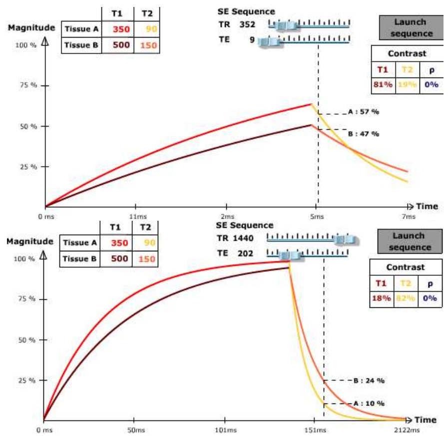


Tissue	T1 (msec)	T2 (msec)
Water/CSF	4000	2000
Gray matter	900	90
Muscle	900	50
Liver	500	40
Fat	250	70
Tendon	400	5
Proteins	250	0.1- 1.0
Ice	5000	0.001

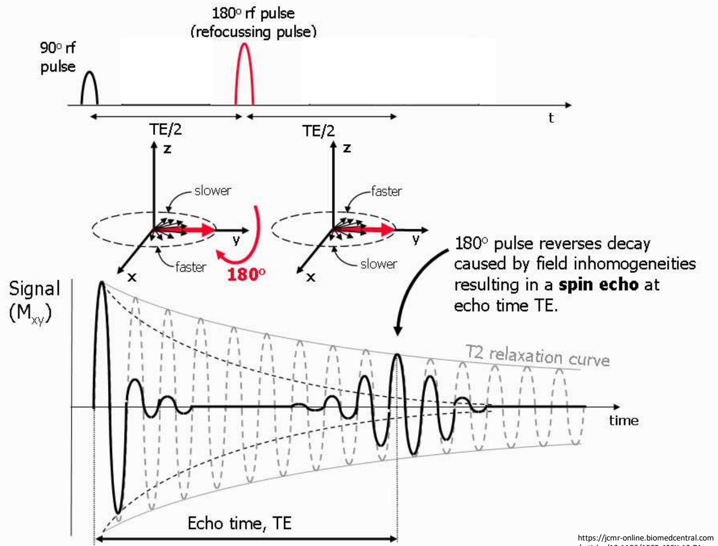
EXTENSION MATERIAL

long TR + short TE : PD weighted
short TR + short TE : T1 weighted
long TR + long TE : T2 weighted



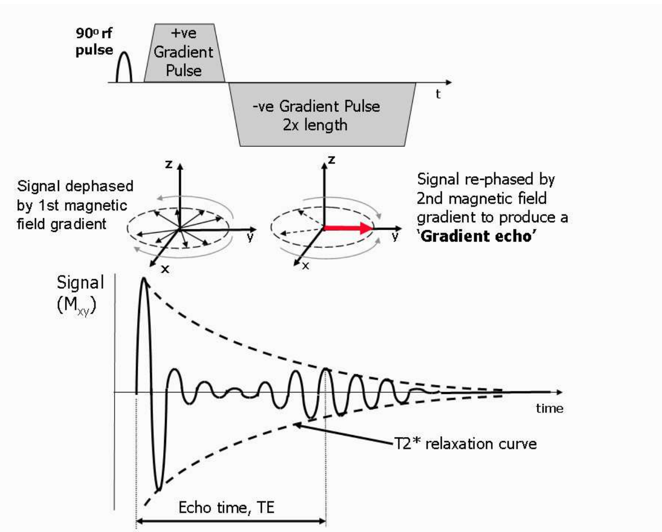


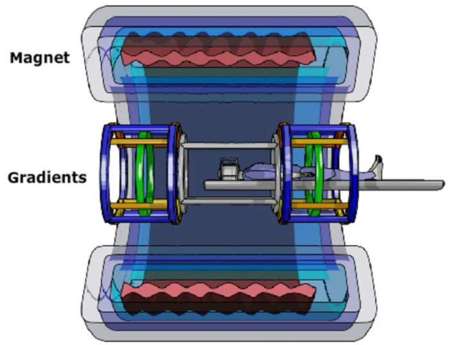
EXTENSION MATERIAL



https://jcmr-online.biomedcentral.com/articles/10.1186/1532-429X-12-71

EXTENSION MATERIAL





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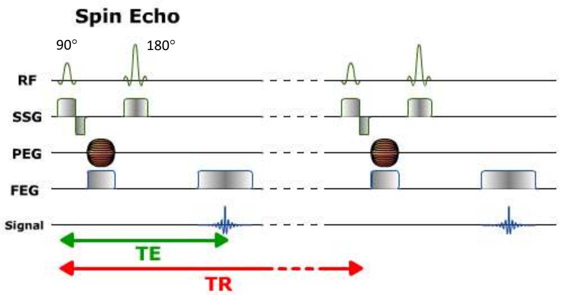
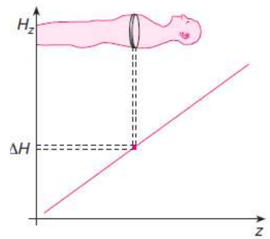
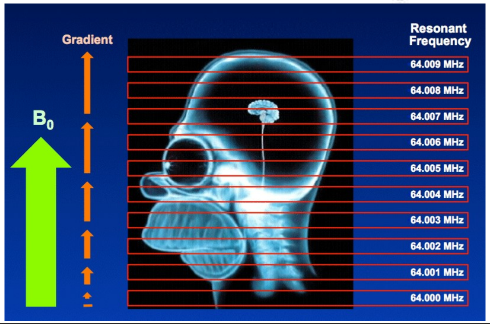


SSG: slice selection gradient
PEG: phase encoding gradient
FEG: Frequency encoding gradient

SSG: Slice selection.

By applying a gradient in the magnetic field the Larmor frequency of protons change in every layer.

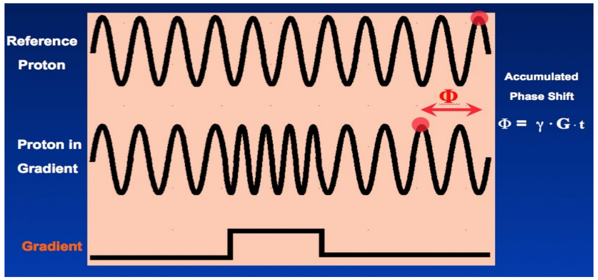




EXTENSION MATERIAL

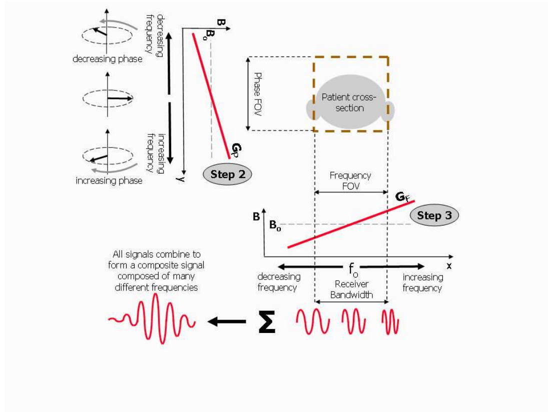
Phase gradient: during the gradient is on, the frequency changes, which causes a phase shift of the affected protons.

At the end of the gradient pulse, we will have a mixed proton population with many different phases. This will produce a mixed signal.



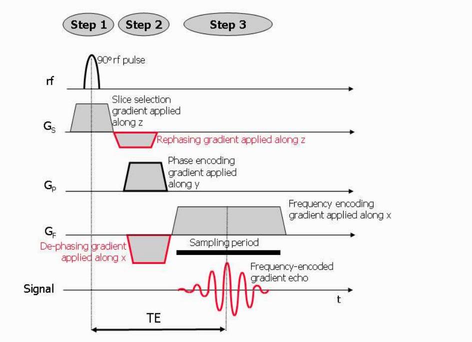
EXTENSION MATERIAL

The frequency coding is applied during data collection.
The received signal will have a mixture of different frequency spin-echo signals.
A Fourier-transform can decompose the signal.



1: slice select
2: phase select: this has to be repeated multiple times with different gradients!
3: frequency select

1+2+3 = x,y,z directions:
3D imaging is possible.

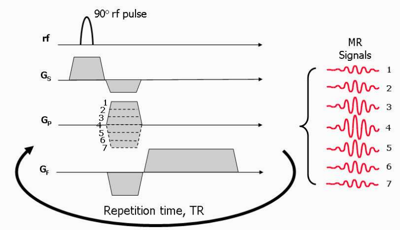


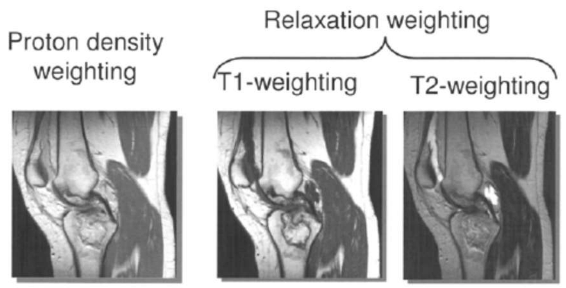
EXTENSION MATERIAL

The acquisition has to be repeated many times to decompose the signal correctly (due to the phase gradient)

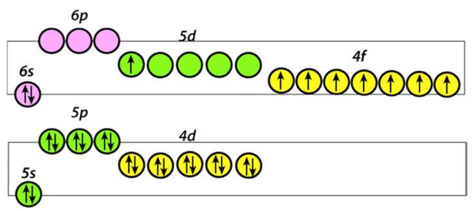
This can be speed up by using multiple gradient echo signals from the same 90 pulse.
(echo planar imaging)

-brain

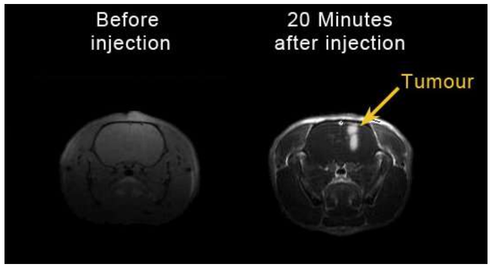




Gd: Gadolinium, has a lot of unpaired electrons, these have a large net magnetic moment. This can induce relaxation of nearby nuclei. (a paramagnetic effect)
This shortens T1 relaxation times of nearby protons



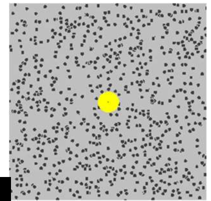
Gd-contrast: tracer molecules give flexibility

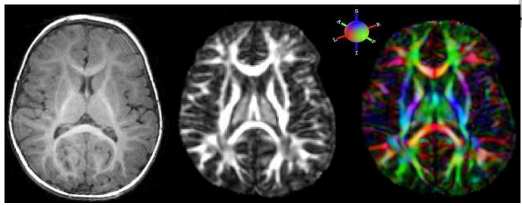


EXTENSION MATERIAL

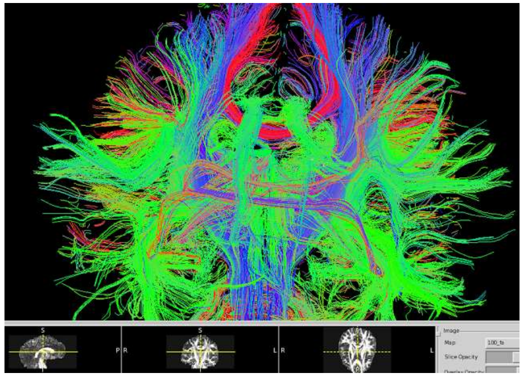
Diffusion tensor imaging: diffusion during the signal recording modifies the signal, this can be combined with contrast agents.

If the diffusion is not free, than the different gradients will show different sensitivity to diffusion-> direction and magnitude can be recovered





EXTENSION MATERIAL



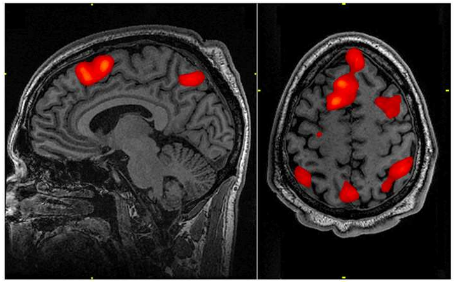
Tracking fibers in the white matter by constrained diffusion

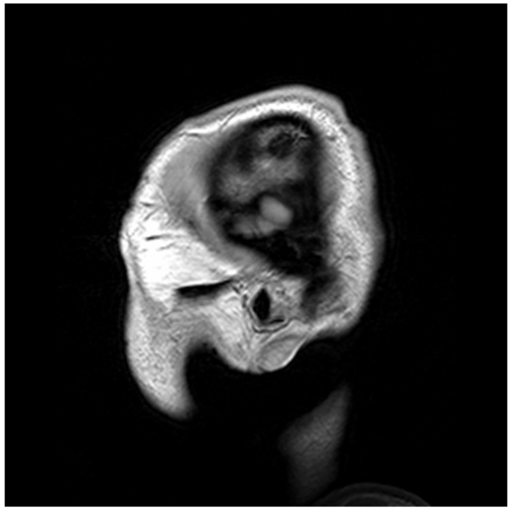
EXTENSION MATERIAL

fMRI: functional MRI.

A special brain-imaging method: brain activity ⇔ blood flow.

BOLD: Blood Oxygen Level Dependent.
Deoxyhemoglobin is paramagentic, Oxyhemoglobin is diamagnetic
T2* is sensitive to paramagnetism.

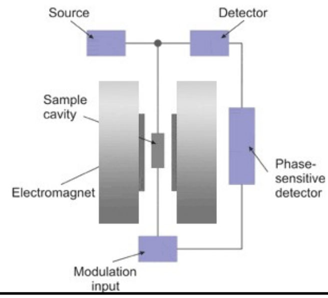


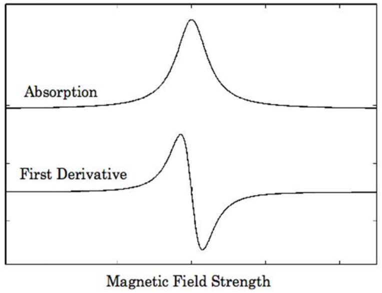


EPR/ESR: Electron spin resonance

Electrons have spins, and spin+orbital magnetic moments.
The magnetic moment is larger -> GHz frequency photons are required.

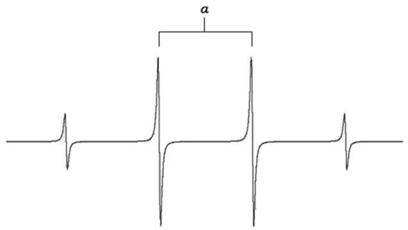
Due to technical difficulties most EPR machines are not FT, but cw.
Moreover, often the GHz frequency source is fixed-frequency, and the magnetic field is varied.





EXTENSION MATERIAL

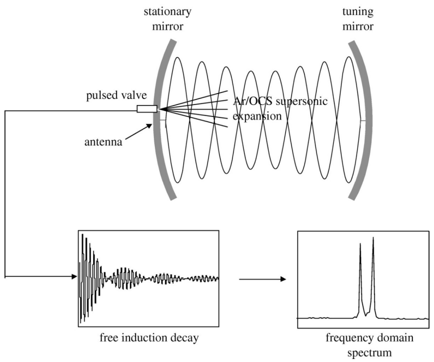
Splitting of the spectrum occurs due to hyperfine interaction:
The electron spin interacts with the spin of it's own nucleus, or even of a neighbouring nucleus (super hyperfine splitting)



Chemistry and environment sensitive!

EXTENSION MATERIAL

Microwave spectroscopy: rotational excitation.



EXTENSION MATERIAL