Edinburgh Imaging
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Basics of MRI

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- **Magnetic Resonance physics**

➢Quick tour in particle physics

➢Magnetic Resonance

➢What’s happening in the magnet

- **Magnetic Resonance Imaging**

➢How do we make an image?

➢What is a contrast image?

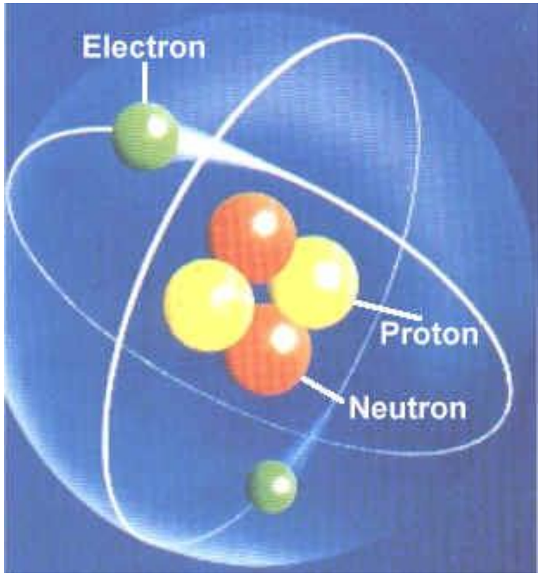
Magnetic Resonance physics

Quick tour in particle physics

What’s an atom?

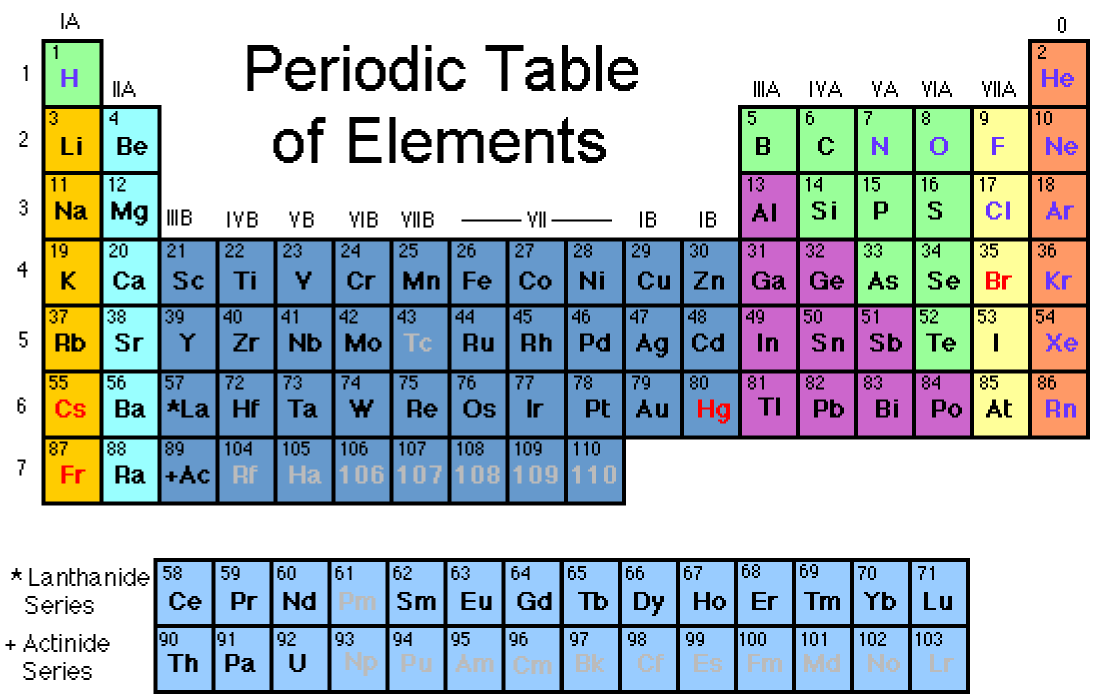
- It is a fundamental piece of matter. Everything in the universe, except energy, being made of matter, everything in the universe is made of atoms.
- An atom itself is made up of three tiny kinds of particles called subatomic particles: protons, neutrons, and electrons.

- The protons and the neutrons make up the centre of the atom called the nucleus and the electrons fly around above the nucleus in a small cloud. The electrons carry a negative charge and the protons carry a positive charge.



Some atomic properties

- An element is defined by it's number of protons – for instance hydrogen as 1 proton (isotopes are atoms with the same number of protons but different number of neutrons, e.g. deuterium 1 proton 1 neutron)

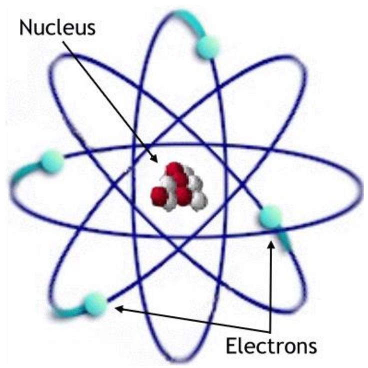


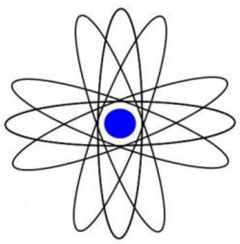
Some atomic properties

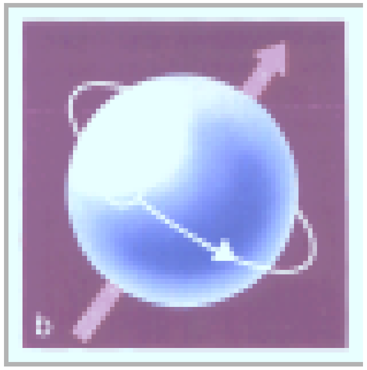
- Mass: the large majority of an atom's mass comes from the protons and neutrons, the total number of these particles in an atom is called the mass number
- Size: the dimensions are usually described in terms of the distances between two nuclei when the two atoms are joined in a chemical bond. The radius varies with the location of an atom on the atomic chart, the type of chemical bond, the number of neighbouring atoms and it’s spin (see after)
- Energy levels: When an electron is bound to an atom, it has a potential energy that is inversely proportional to its distance from the nucleus. This is measured by the amount of energy needed to unbind the electron from the atom. In the quantum mechanical model, a bound electron can only occupy a set of states centred on the nucleus, and each state corresponds to a specific energy level. Similarly, nuclei posses their own energy levels.

Some atomic properties

- Magnetic moment and spin (Wolfgang Pauli in 1924.): particles possess an intrinsic quantum mechanical property known as spin. We can think in terms of classical physic that atoms are like spinning tops. These tops can spin at only given frequencies and exert particular magnetic forces. The magnetic moment corresponds to the field produced by electric charges (proton/electron) which are spinning.







Magnetic Resonance physics

Magnetic Resonance

Nuclear Magnetic Resonance

- Isidor Rabi (1938, Phys Rev 53) showed that when an external magnetic field oscillates at the same frequency as some atomic nuclei, these ones absorb the energy from the field. This is called magnetic resonance.

- The frequency of the field has to match the spin frequency, and this match corresponds to the resonance frequency. (1944 Nobel Prize in physics)

Nuclear Magnetic Resonance

- NMR was discovered independently by Felix Block *(1946, Physiol Rev, 70)* and Edward Purcell *(1946, Physiol Rev, 69)*.

- They showed that atomic nuclei of bulk matter placed in a magnetic field absorb and re-emit radio waves, a phenomenon called nuclear induction or nuclear magnetic resonance. (1952 Nobel Prize in physics)

This phenomenon turned out to be very useful for studying physical, chemical, and biological properties of matter.

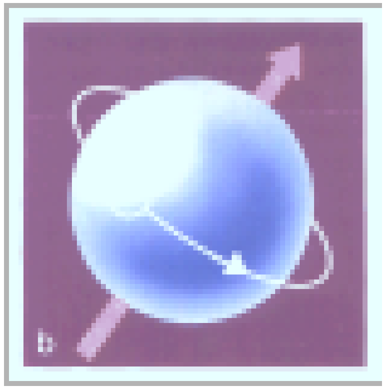
Magnetic Resonance physics

What’s happening in the magnet

NMR: magnetism

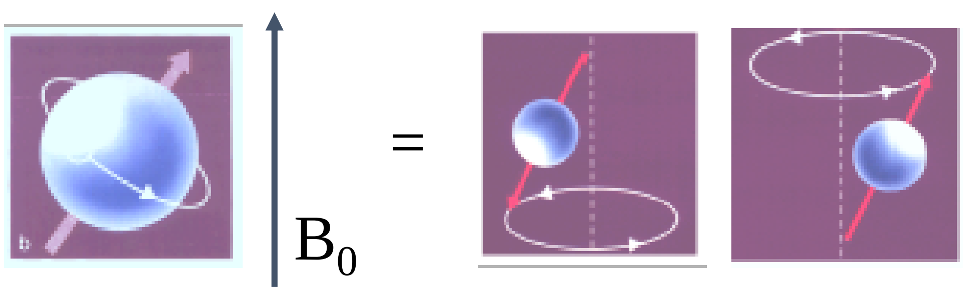
- We have seen that atomic nuclei (protons + neutrons) have spins and magnetic moments
- Outside a magnetic field, spins of different nuclei are randomly oriented whereas inside a magnetic field, spins of nuclei tend to be aligned with the magnetic field

  - *Magnetic field strengths are measured*
  - *in units of Gauss (G) and Tesla (T).*
  - *Earth's magnetic field = 0.5G*
  - *1T= 10 000G*
  - *Scanner 3T = 60,000 times Earth's MF*



NMR: magnetism

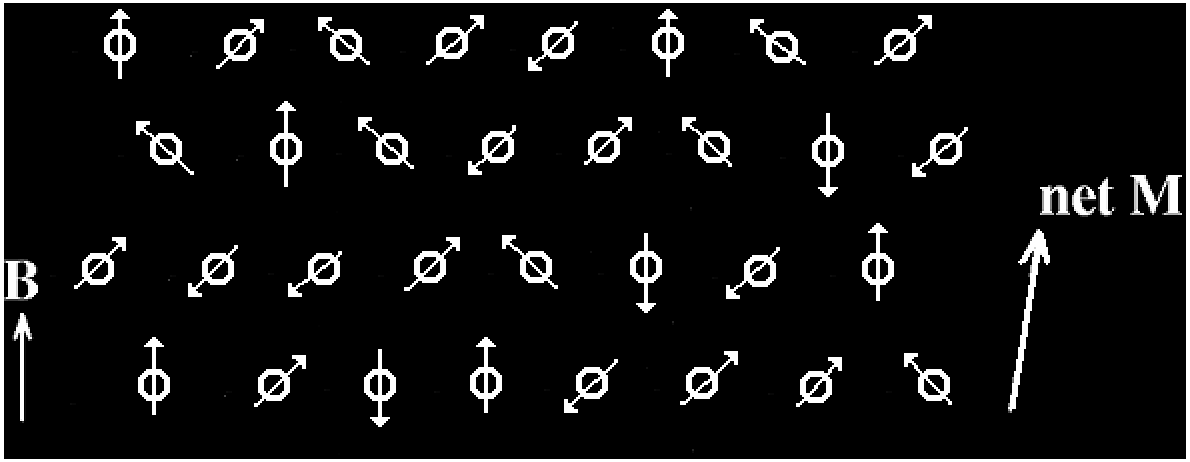
- For a magnetic field B_0, the alignment of spins corresponds to low and high energetic states of the nuclei (spins are said aligned or counter-aligned). Because the parallel alignment of atoms' spin with B0 is energetically more favourable, it exists a net (macroscopic) magnetization M_0 for all the nuclei.

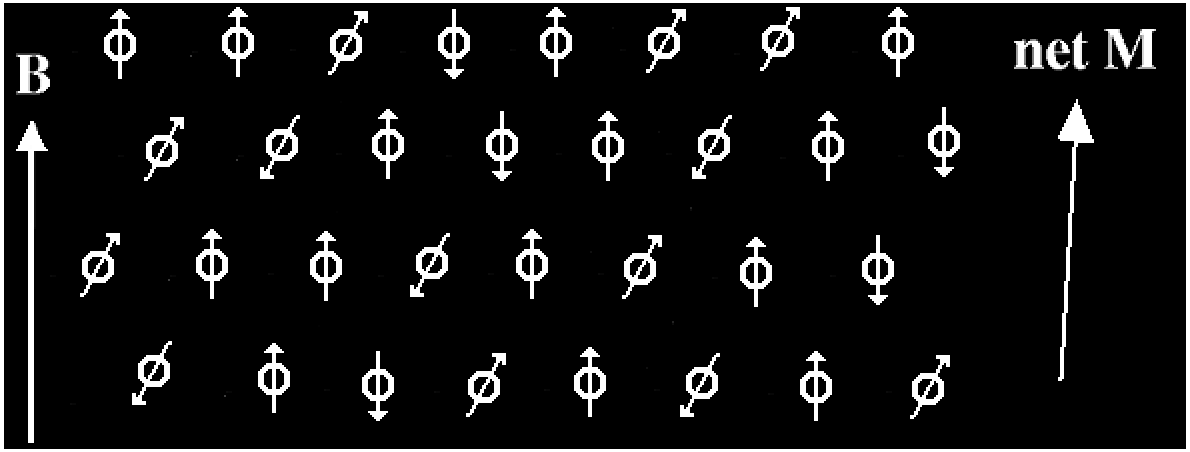


At 1.5T, for every one-million nuclei, there is about one extra spin aligned with the B_0 field!

NMR: magnetism

Small B_0 produces small M_0 and large B_0 produces large M_0

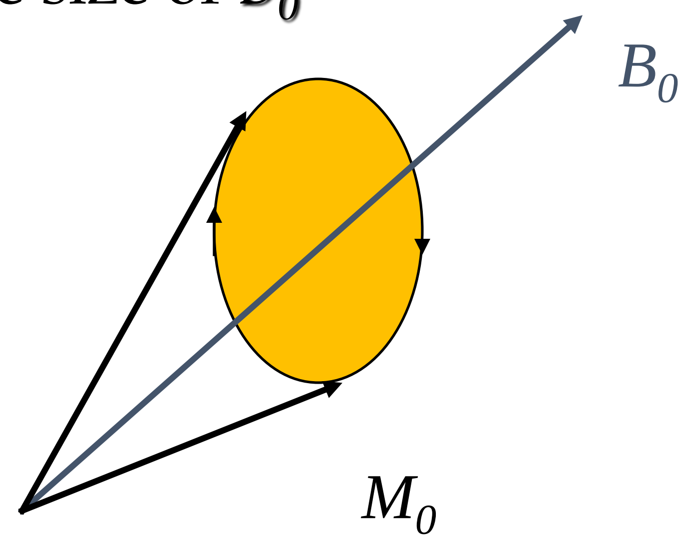




NMR: magnetism

- In addition to the alignment of spins and the orientation of the magnetic moment, there also exists a rotation of M_0 around B_0, this is the precession

M_0 rotates (precesses) at a frequency ω, proportional to the size of B_0



$$\omega = \gamma . B_0$$

γ is the gyro-magnetic ratio which varies according to the type of nucleus (Larmor Frequency)

Summary 1

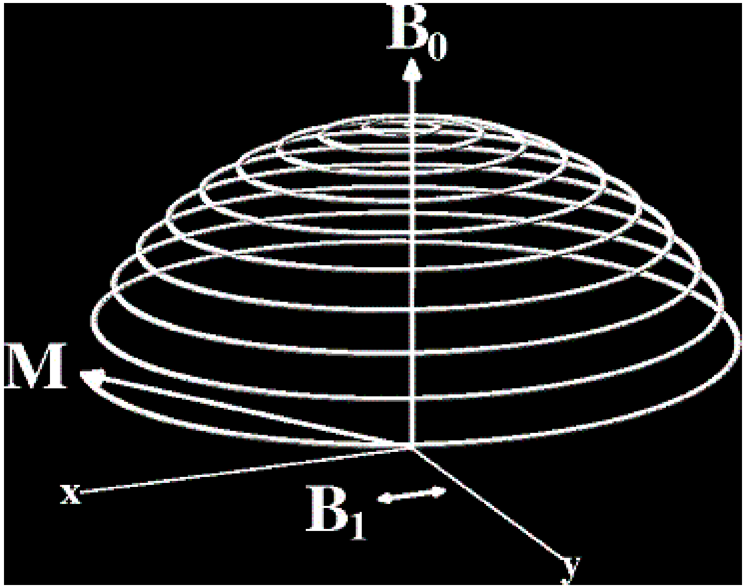
- People like the rest of the universe are made of atoms
- Atoms are themselves composed of protons, neutrons and electrons – atoms have an intrinsic property called spin ; in addition protons and electrons possess electric charges so that atoms spinning produces a small magnetic field
- If we apply an external magnetic field then i) spins get aligned to the field ii) because the parallel alignment of atoms’ spin is energetically more favourable, it exists a net macroscopic magnetization and iii) this macroscopic magnetization vector precesses at a frequency which is proportional to the strength of the field and depends on the type of elements.

NMR: RF excitation

- Remember that if we apply a magnetic field that oscillates at the same frequency than atoms they absorb and re-emit radio waves.
- In a scanner, we have a constant magnetic field B0 such as each atom has it's spin oriented with the field and precessing at a given frequency ω.
- We then apply magnetic pulses at the frequency ω so that i) atoms will absorb the energy of the field and thus jump into a higher energy level (thus we have a change in the spin alignment and decrease of M0) and ii) the precessions of the different atoms become in phase

NMR: RF excitation

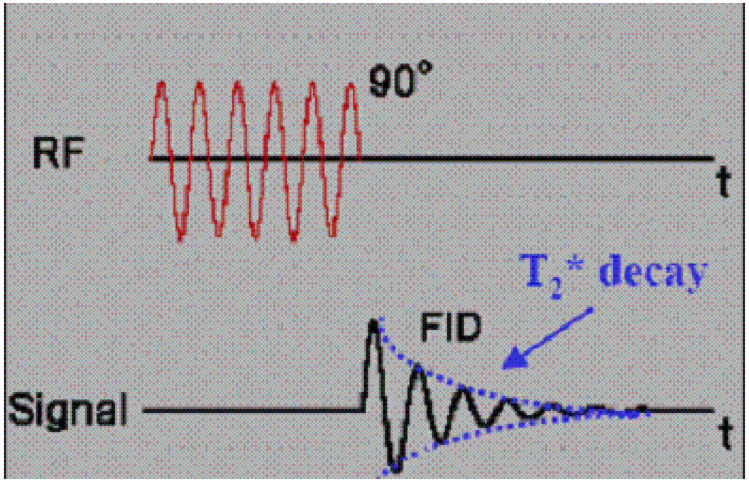
- On a macroscopic level, RF exposure causes the net magnetization M to spiral away from the direction of the B_0 field.



The RF pulse changes the number of nuclei at high and low energy states (*Mz* decreases) and puts spins in phase (*Mxy* increases).

NMR: RF excitation

- After applying a RF pulse, *Mxy* is like a little magnet that rotates. It generates an oscillating voltage induced by magnetic field changes and is detected by a coil of wires placed around the subject, this is called magnetic *induction.* This voltage is the *RF signal* whose measurements form the raw data for MRI



Free induction decay

Summary 1

- People like the rest of the universe are made of atoms
- Atoms are themselves composed of protons, neutrons and electrons – atoms have an intrinsic property called spin ; in addition protons and electrons possess electric charges so that atoms spinning produces a small magnetic field
- If we apply an external magnetic field then i) spins get aligned to the field ii) because the parallel alignment of atoms' spin is energetically more favourable, it exists a net macroscopic magnetization and iii) this macroscopic magnetization vector precesses at a frequency which is proportional to the strength of the field and depends on the type of elements.

Summary 2

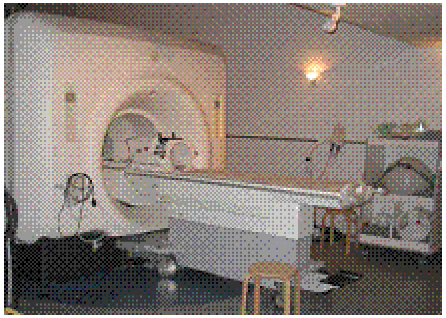
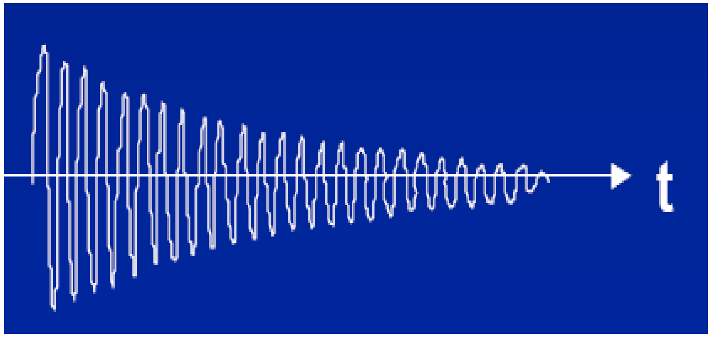
- By applying a RF pulse at the frequency of which the net magnetization oscillates, we make the nuclei to change their energy level, i.e. we change the spin alignment = decrease of the signal in the direction of B0 (the static magnetic field).
- This also make each atoms to oscillate in phase = increase of the signal in the direction of B1 (the RF pulse).
- The signal measured in the scanner is then the oscillation of the net magnetization vector in the direction of the pulse which create voltage variations in the coil of wires.

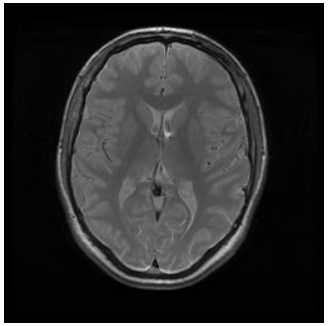
Magnetic Resonance Imaging

How do we make an image?

How to make an image?

- We can only detect one dimensional signal, i.e. the total RF signal from the entire 3D volume inside the "RF coil" (the detecting antenna) .. How do we make an image from that?



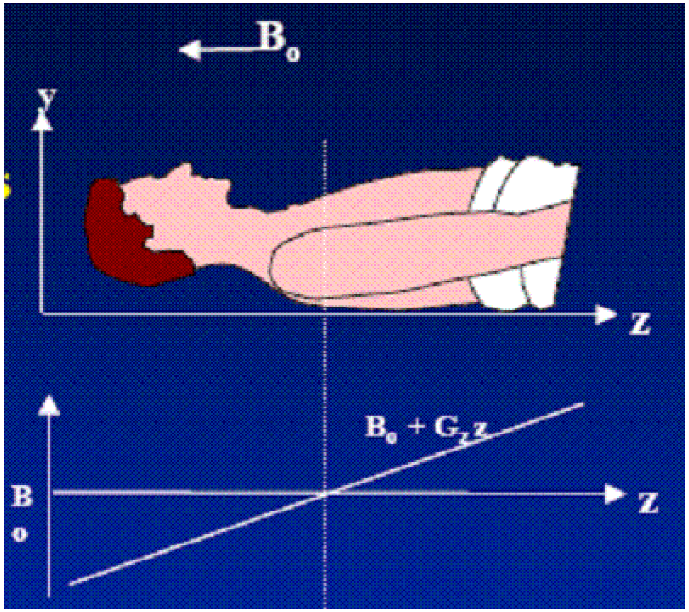
- 1st NMR experiment in 1945, 1st MRI Image in 1972
- 2003 Physiology or Medicine Nobel prize: Lauterbur and Mansfield

How to make an image?

1. Put the subject into the magnet, within B0 = alignment (parallel or anti-parallel) of protons' spins
2. Excite some protons (H+) in one slice of the brain (RF pulse) = change in the alignment of a fraction of the protons' spins and creation of Mxy, i.e. smthg that can be measured
3. Receive the signal from the precessing protons' spins = transform frequencies and phases into an image (and this is what all is about here!!) … how since we have only 1 signal from the whole slice?
4. Repeat for another slice

How to make an image?

- We have seen that the resonance frequency ω of atoms at a given location depends on the value of the magnetic field applied at this location

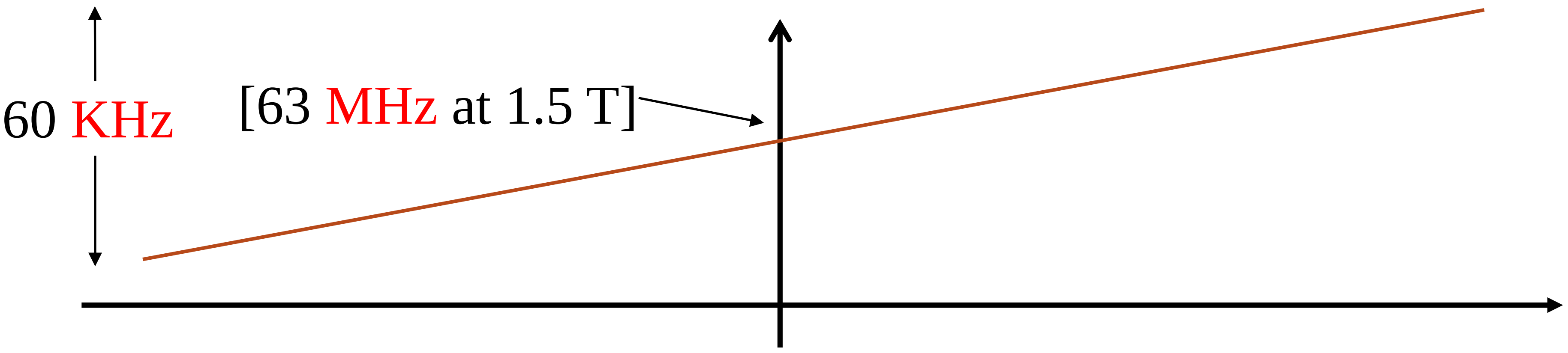


We can thus apply an additional (very small) magnetic field changing over space to tune the frequency of protons

$$\omega = \gamma . \boldsymbol{B_0} + \boldsymbol{G_z}$$

How to make an image?

- Example of gradient field:
- The gradient field changes linearly its intensity across the subject space. Consequently, the precession frequency of protons varies across the space (= *frequency and phase encoding – apply 2 gradients*).



$$\omega = \gamma . \boldsymbol{B_0} + \boldsymbol{G_z}$$

How to make an image?

- The signal we receive in a coil is thus the sum of all the transverse magnetizations (Mxy) for a given field B0, RF pulse B1, type of nuclei γ …
  $S(t) = \iiint Mxy\ (x,y,z)e^{-t/t2}e^{-i\omega 0t}e^{-i\gamma\int(Gx(t)x+Gy(t)y+Gz(t)z)dt}\ dx\ dy\ dz$

- The equation is simplified because we limit the reconstruction slice per slice, we are not interested in the amplitude per se (we look at the decay), etc .. + gradient are integrated in time = the equation describe the signal as a <u>set of phases and frequencies</u> – a 2D inverse Fourier transform (mathematic stuff to go from frequencies to time/space) will create an image of the slice.

Magnetic Resonance Imaging

What is a contrast image?

Contrast images

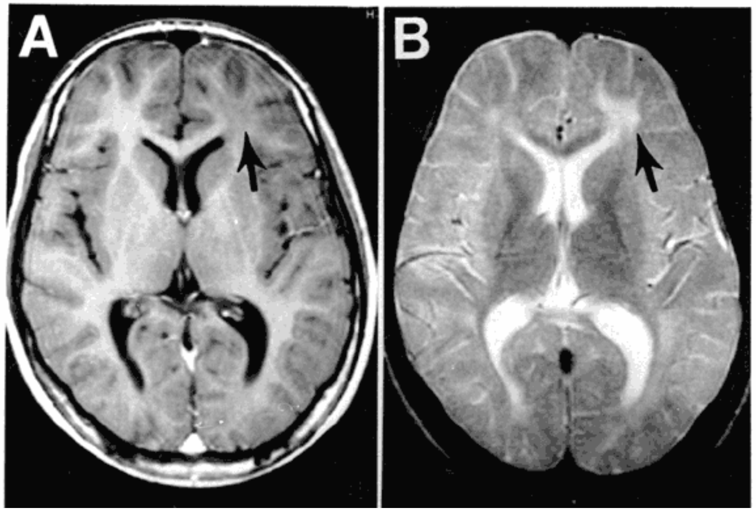
- Depending on the pulse sequence used by the scanner, images can be created that differentiate low vs. high proton density, grey vs. white matter, or fluid vs. tissue.
- Contrast weighted images are images that measure differences, i.e. that contrast, properties related to different tissue types.
- T1-weighted images reflect differences in the T1 property of the tissues , T2-weighted images …
- Functional MRI or BOLD contrast images reflect differences in amount of oxygenation (blood) of the same tissue(s) in different experimental conditions

T1/T2/T2* contrast images

- After the RF pulse, atoms jumped into higher energy state – but they do not stay forever like this .. They return to their initial energy level.
- T1 relaxation is the return of excited nuclei from the high energy state to the low energy state (*Mz* aligned with B_0).
- T2 relaxation is the loss of the transverse magnetization *Mxy* occuring 'in parallel' because spins of nuclei interact and thus get out-of phase.
- In pure water, the T2 and T1 times are approximately the same, 2-3 seconds. In biological materials (higher density than water = more interaction between spins), the T2 time is considerably shorter than the T1 time. For CSF, T1=1.9 sec and T2=0.25 sec. For white matter in the brain, T1=0.5 sec and T2=0.07 sec (70 msec).

T1/T2/T2* contrast images

- T2* relaxation is the overall decay of the observable RF signal over a **macroscopic** region (millimeter size). It is related to the phase difference of the magnetizations between microscopic regions due to field inhomogeneity. Macroscopically, it is characterized by a loss of transverse magnetization at a rate greater than T2.



Summary 3

1. Because the parallel alignment of atoms' spin with B0 is energetically more favourable than the antiparallel state, there is a net excess of spins aligned with B0 creating a net magnetization
2. The spins precess according to the Larmor frequency which depends on the gyromagnetic ratio of each type of atoms
3. When a RF pulse (B1) rotating synchronously with the processing spins is applied, the net magnetization rotates away from its equilibrium position (moves from aligned with B0 (z-axis) to perpendicular to B0 (xy-plane)) – this occurs for an RF equal to the Larmor frequency (magnetic resonance)

Summary 3

4. B1 equalizes the populations of spins in the two energy states (decrease of the magnetization along the z-axis) and also introduces phase coherences among spins.
5. Additional gradient fields are used to encode spatial information by gradually changing the frequency and phase in space.
6. The transverse magnetization (xy plane) decreases as magnetic
7. moments move out of phase as a result of their mutual interaction. This is referred as relaxation. The different kind of relation processes (T1, T2, T2*) reflect different interactions of the spins with the environment or with other spins – the relaxation rates differ depending on the properties of the tissue which is the basis of image contrast.