

From MRI physic to fMRI BOLD:

An introduction to the bases of functional magnetic resonance imaging

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Overview

- **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?

- **Blood Oxygen Level Dependant contrast**

- Where is the signal coming from?
- Why is this functional imaging?

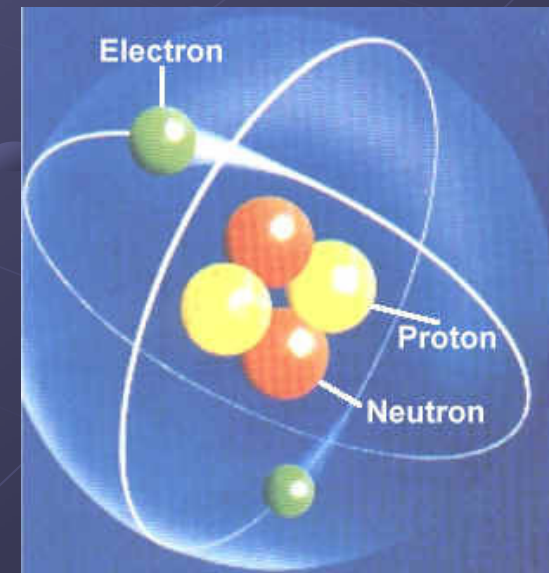


Magnetic Resonance physics

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 its 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)

Periodic Table of Elements															
1	2											3	4	5	6
H	He											B	C	N	O
3	4											7	8	9	10
Li	Be											11	12	13	14
Na	Mg	Al	Si	P	S	Cl	Ar								
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84
Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po
87	88	89	104	105	106	107	108	109	110						
Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110						

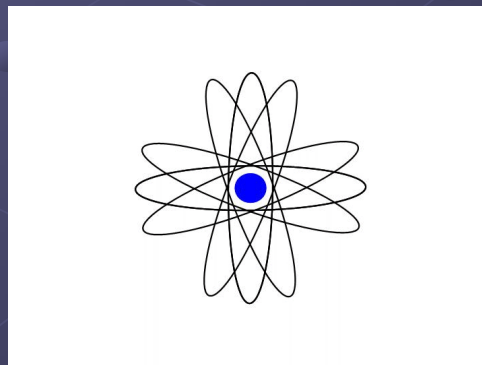
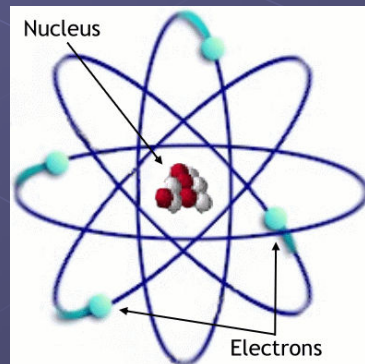
* Lanthanide Series	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
+ Actinide Series	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

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 its 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 possess 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

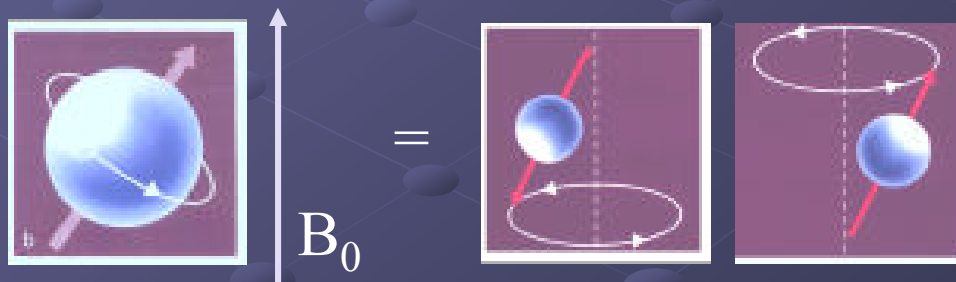
NMR: magnetism

- 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

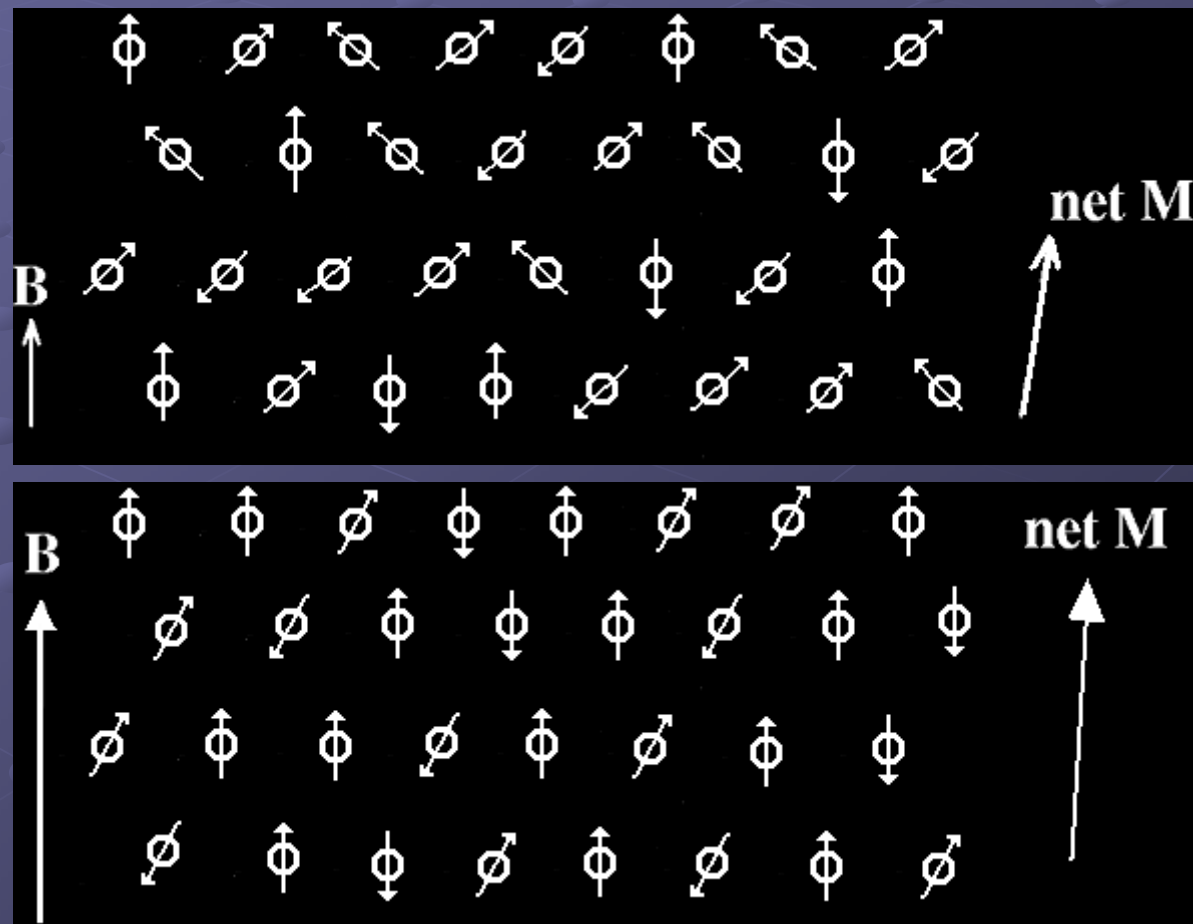
- ◆ For a magnetic field B_0 , the alignment of spins corresponds to low and high energetic states of the nuclei (spins are said aligned or counter-aligned). Because the parallel alignment of atoms' spin with B_0 is energetically more favourable, it exists a net (macroscopic) magnetization M_0 for all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

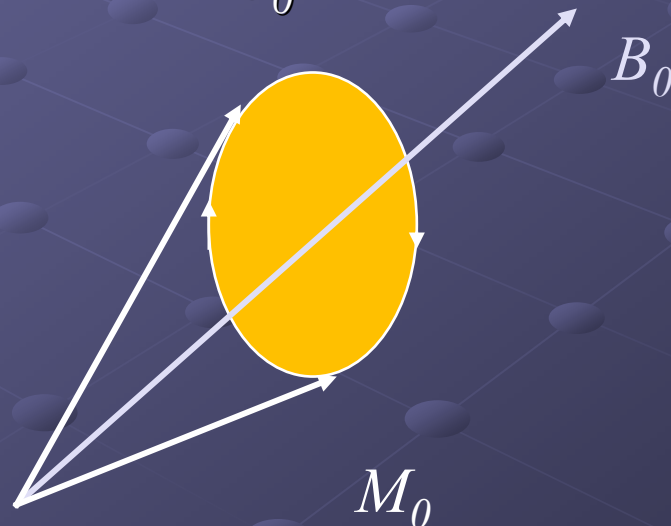


NMR: magnetism

- 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

[Video ☺](#)



$$\omega = \gamma \cdot B_0$$

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

Summary 1

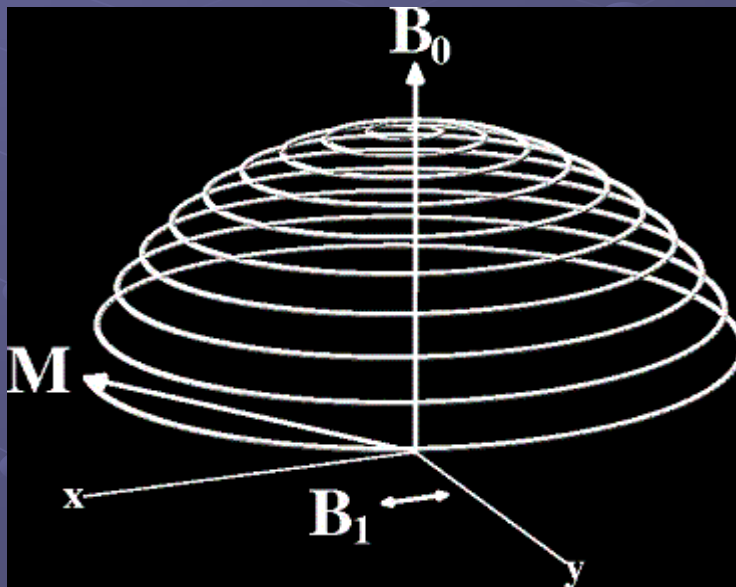
- People like the rest of the universe are made of atoms
- Atoms are themselves composed of protons, neutrons and electrons – atoms have an intrinsic property called spin ; in addition protons and electrons possess electric charges so that atoms spinning produces a small magnetic field
- If we apply 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 B_0 such as each atom has its 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 M_0) 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.

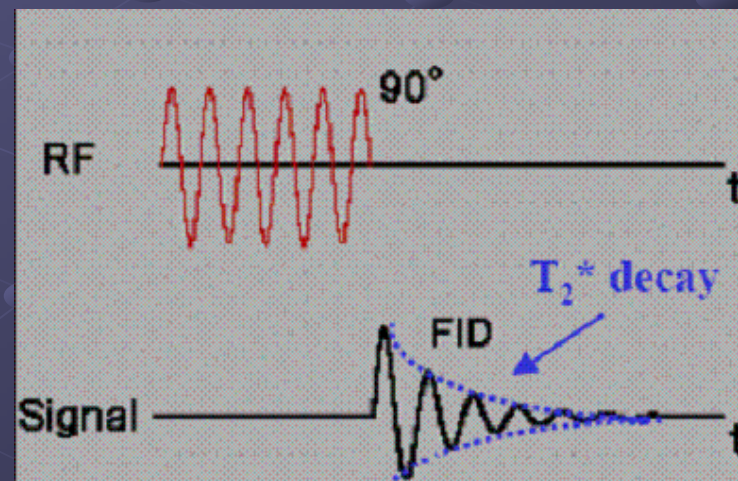


The RF pulse changes the number of nuclei at high and low energy states (M_z decreases) and puts spins in phase (M_{xy} increases).

[Video ☺](#)

NMR: RF excitation

- After applying a RF pulse, M_{xy} 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

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Summary 2

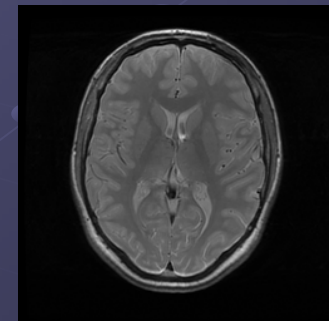
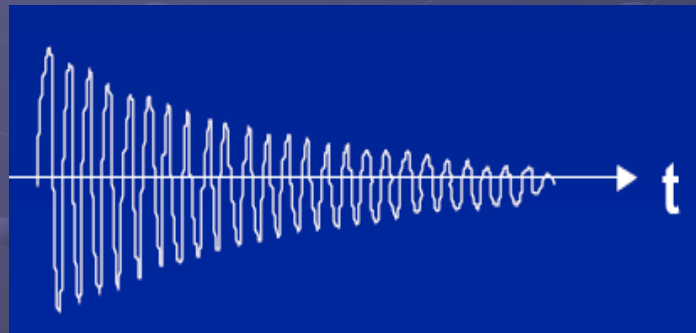
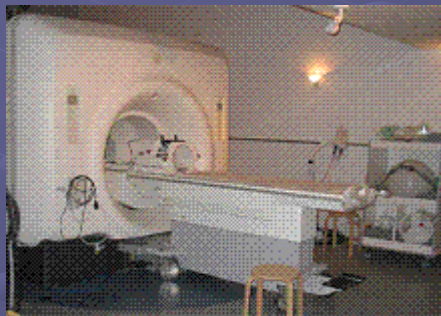
- By applying a RF pulse at the frequency of which the net magnetization oscillates, we make the nuclei to change their energy level, i.e. we change the spin alignment = decrease of the signal in the direction of B_0 (the static magnetic field).
- This also make each atoms to oscillate in phase = increase of the signal in the direction of B_1 (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