Basic Principles of MRI

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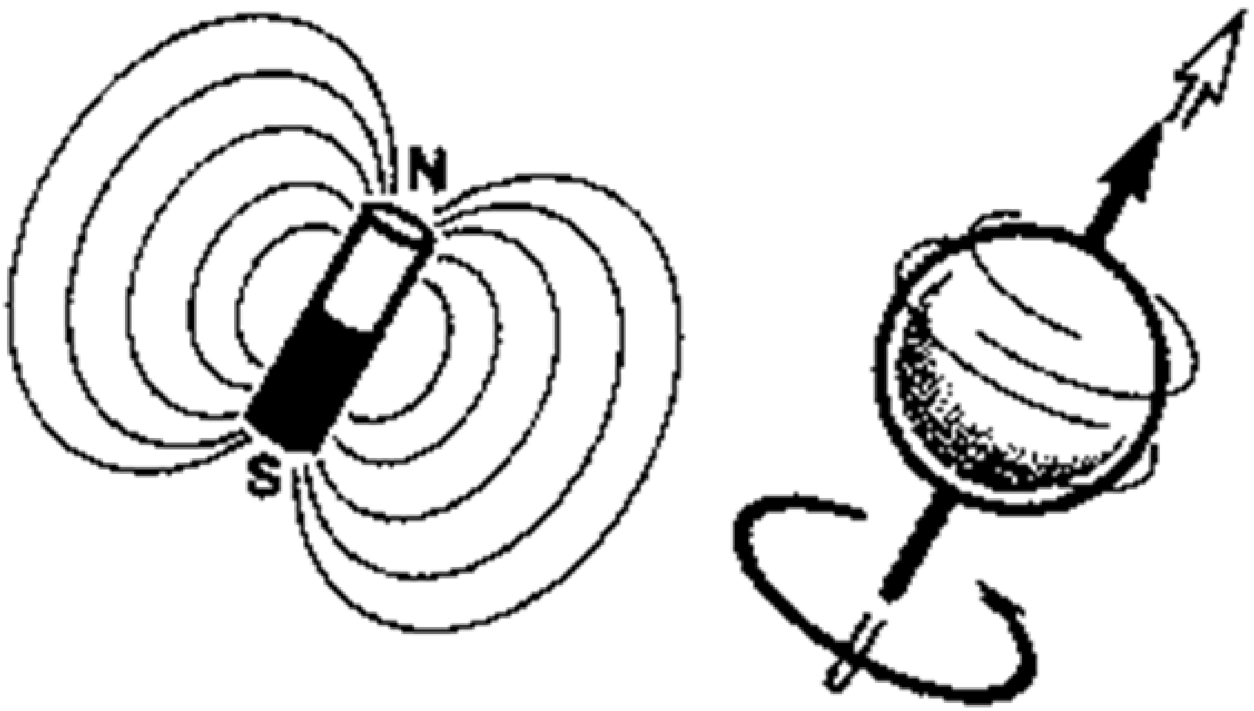
Basic ideas

- **Magnetic**: the signal source (magnetization)
- **Resonance**: signal excitation and detection
- **Imaging**: spatial encoding of signals

Nucleus of ^1H = single proton

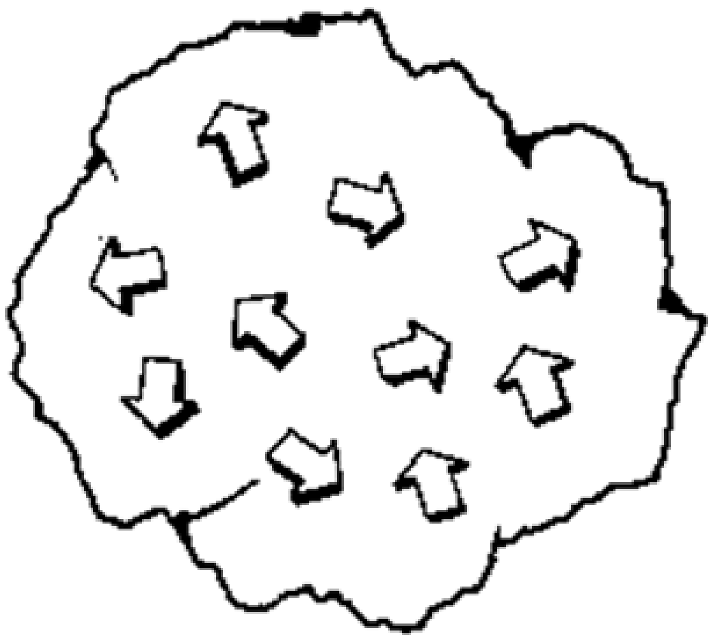


Magnetic field produced by the spin of a proton

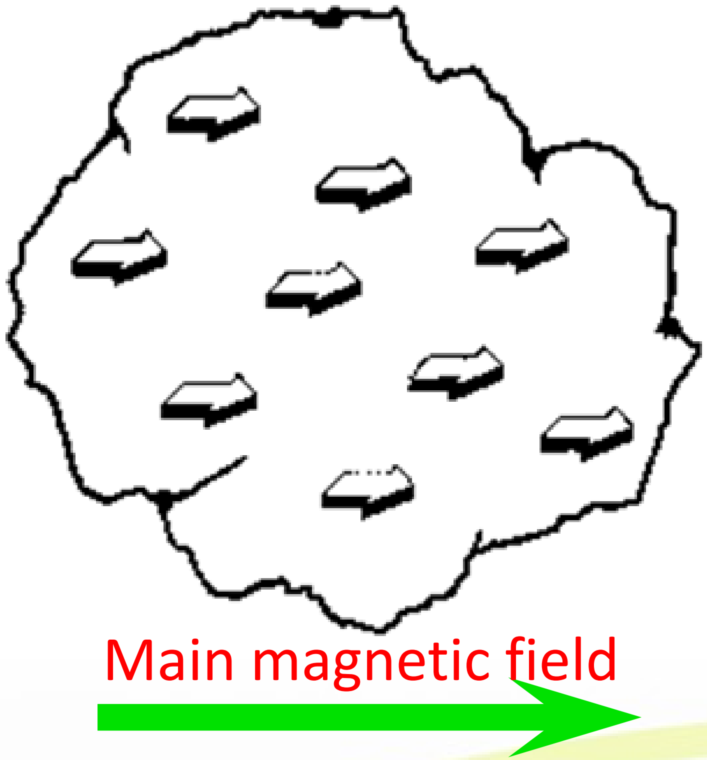
Hydrogens in human body

- Water (H_2O), fat, protein,…
- Every 18 g of water (1 mol.) contains 2 x 6 x 10^{23} hydrogens!
- Everyone could be Magneto!?

Application of an external magnetic field



Random distribution

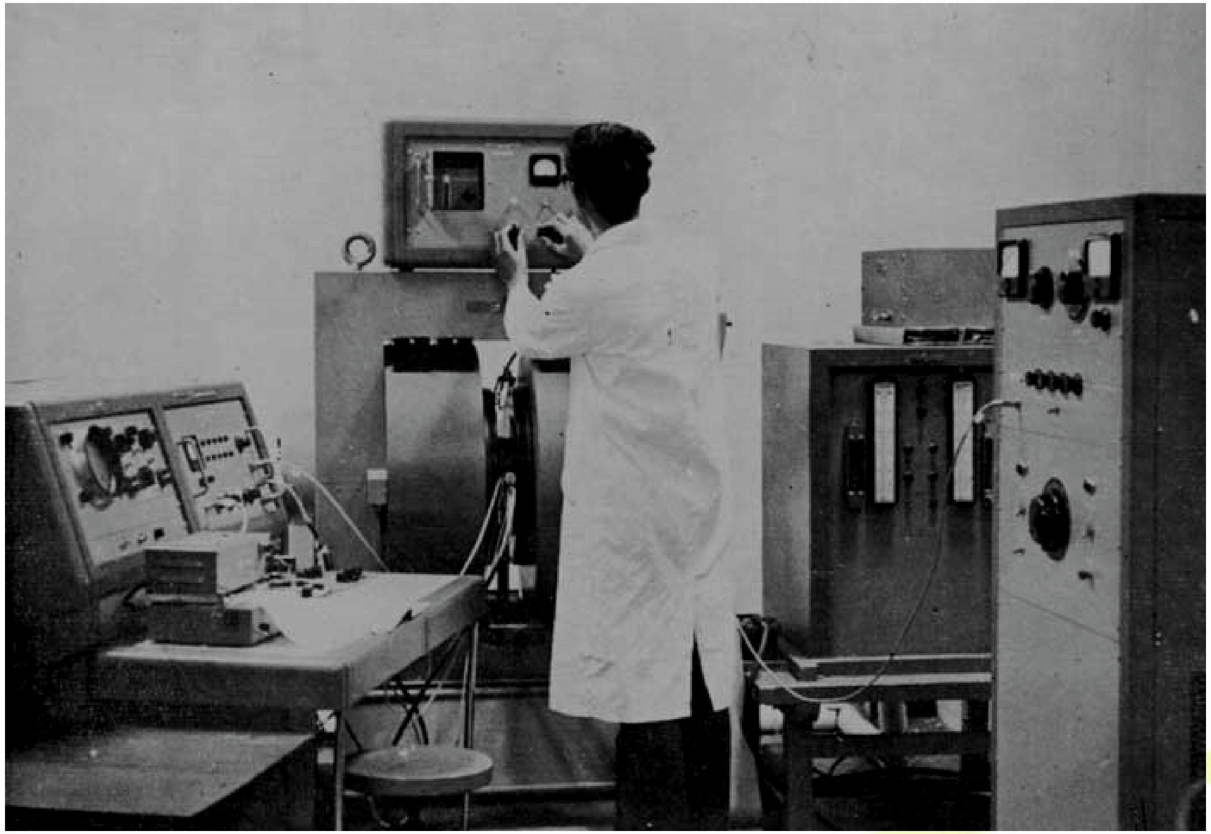


Regular distribution

To observe the nuclear magnetization…

- You definitely need an external magnetic field
- Felix Bloch and Edward Purcell
  - Awarded 1952 Noble Prize for “their development of new ways and methods for nuclear magnetic precision measurements”
- Basic tool of MRI: **magnet**

NMR experiments in early days



1964

Influence of the external magnetic field

- Without the main magnet field, protons are randomly distributed.
  - Human body has NO magnetization
- With the main magnet field, protons are regularly distributed.
  - Non-zero magnetization!

Now you are magnetic…

- Oops, will nails fly to me after I have an MRI scan?
- Will I be forced by Earth’s magnetic field?

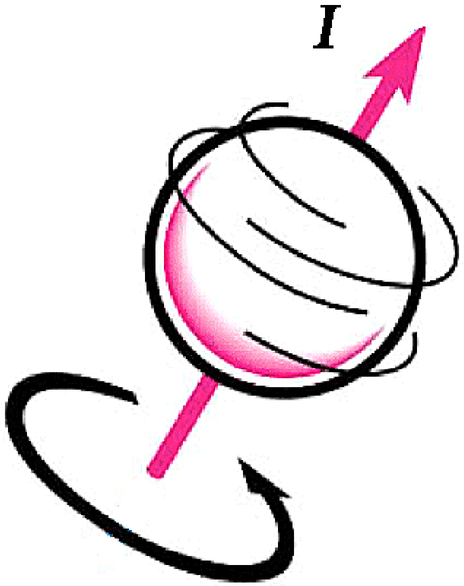
Don’t worry…

- The magnetization is temporary.
  – It’s gone right after leaving MRI.

- Besides, the magnetization is very weak.
  – In fact, not all H protons are aligned in parallel.

Spin of atomic nucleus generates…

- Magnetic moment
- Angular momentum

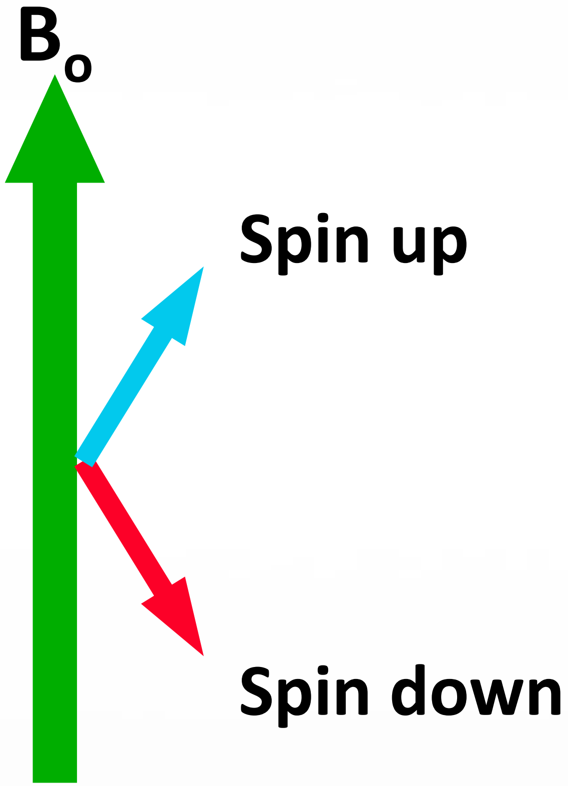


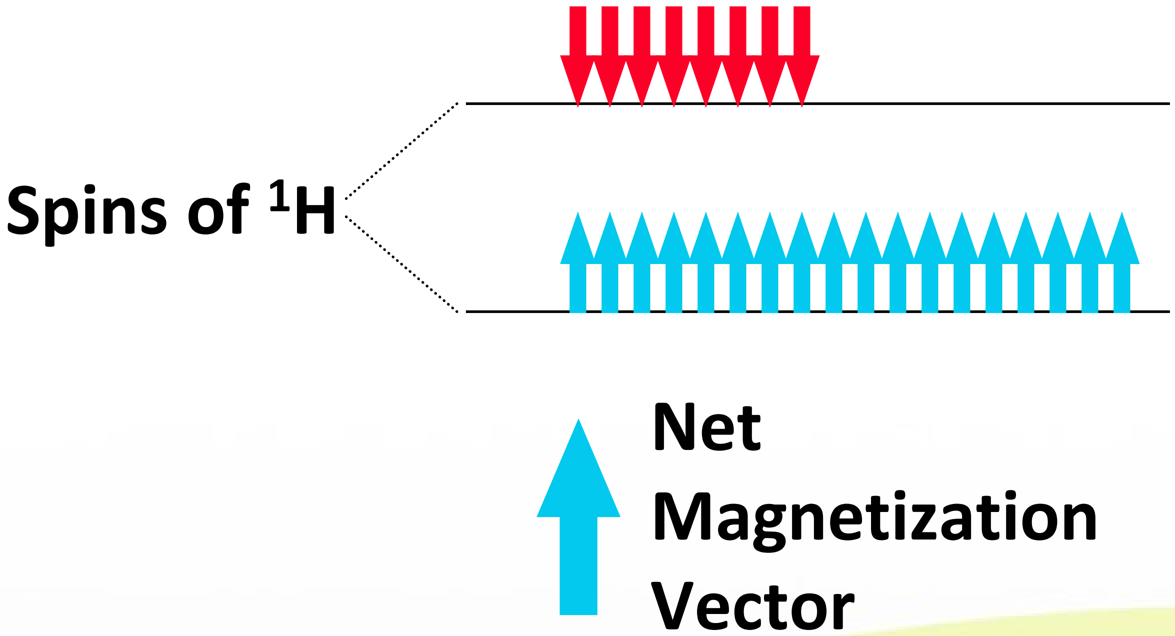
- Magnetogyric (or gyromagnetic) ratio (γ)

^{1}H: spin 1/2 system (S = 1/2)

- The magnitude of spin angular momentum is **quantized**.
  - According to quantum mechanics, spin quantum number (or simply, *spin*) can only be discrete integers or half integers. (e.g., 0, 1/2, 1, 3/2, …)
- The spin of ^{1}H nucleus (proton) is 1/2.
  - Magnetic quantum number = $\pm$ 1/2
  - Corresponding to 2 spin states (2S+1 states)

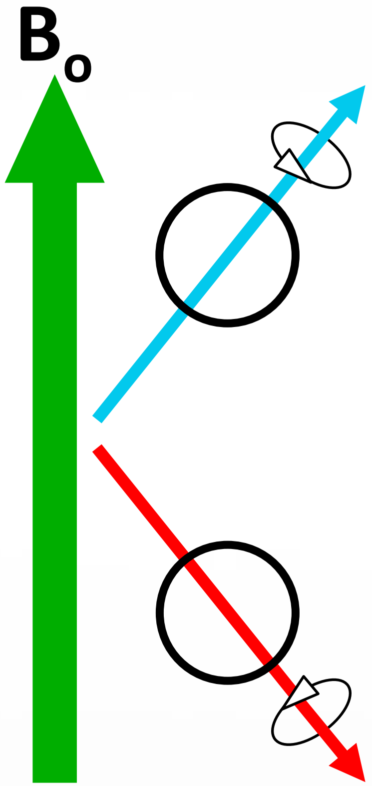
Two spin states of ^{1}H





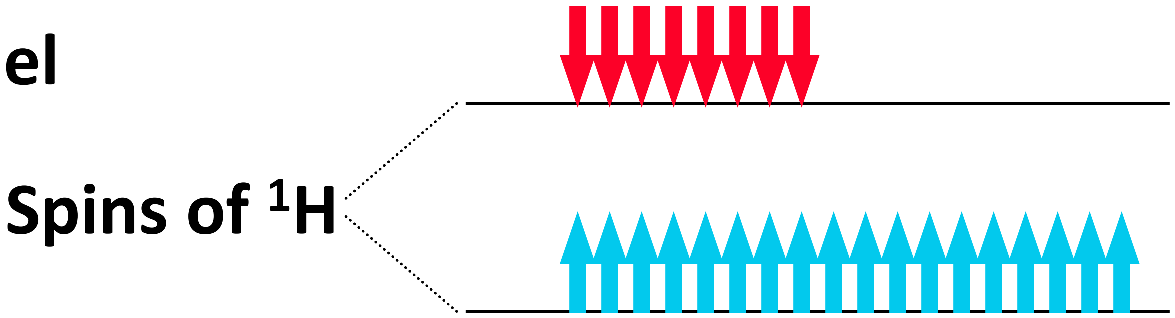
Net magnetization = sum of magnetic vectors ~ population difference

Population distribution



m = +1/2
Spin up/parallel
Low energy

m = -1/2
Spin down/anti-parallel
High energy

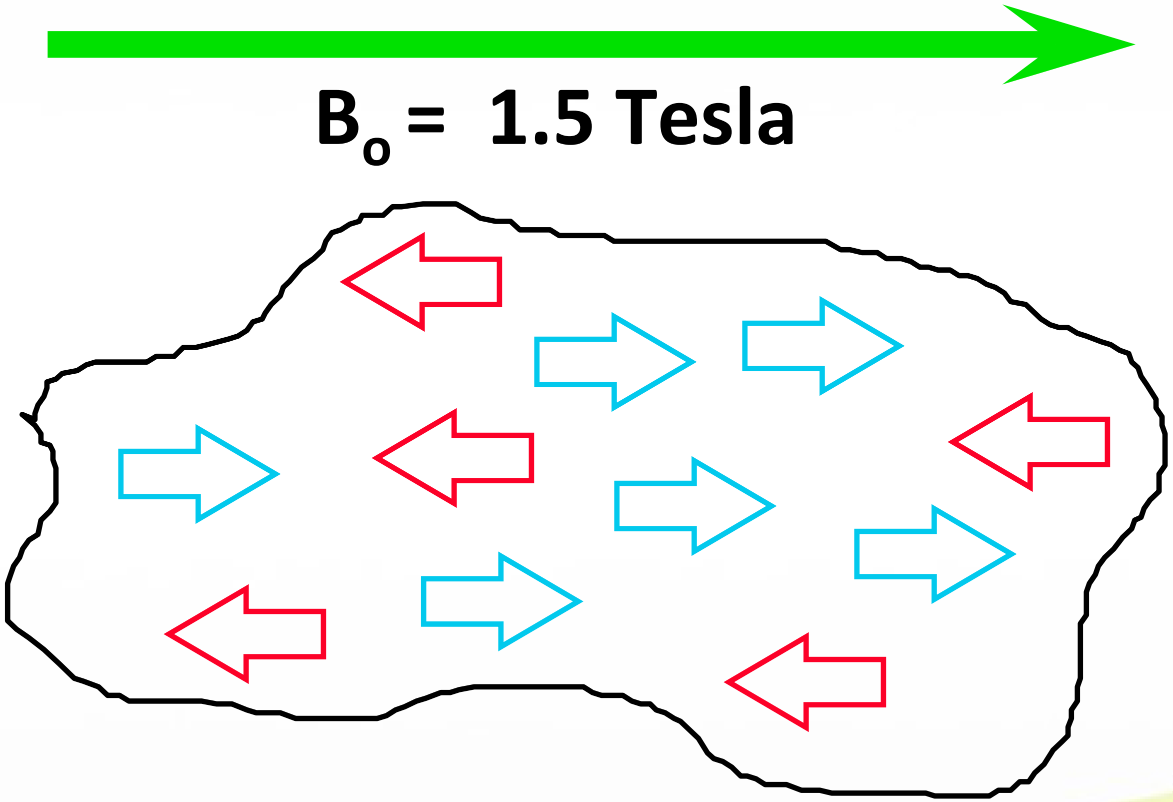


Boltzmann Equilibrium

$$\frac{N_{upper}}{N_{lower}} = e^{-\frac{\Delta E}{KT}}$$

$$\Delta E = \frac{\gamma \cdot h \cdot B_0}{2\pi}$$

(Simplicity) parallel and anti-parallel spins



The population difference is around 5 in every one million spins.

Common numbers in MRI

- Strength of external magnetic field = 1.5 Tesla
  - 15000 Gauss
  - 30000 times of Earth magnet (~0.5 G in Taiwan)
- The magnetic field of human body at surface ~ 0.05 Gauss
  - Only 1/10 of Earth magnet
  - Become smaller when moving away from the body

Weak magnetic field of human body

- Despite of the use of a strong external magnetic field, the induced human magnet is very weak.
- Not to mention when a smaller magnetic field of 0.3 Tesla (in 1980s) was applied, the MR signal was smaller.

Spinning of nucleus leads to…

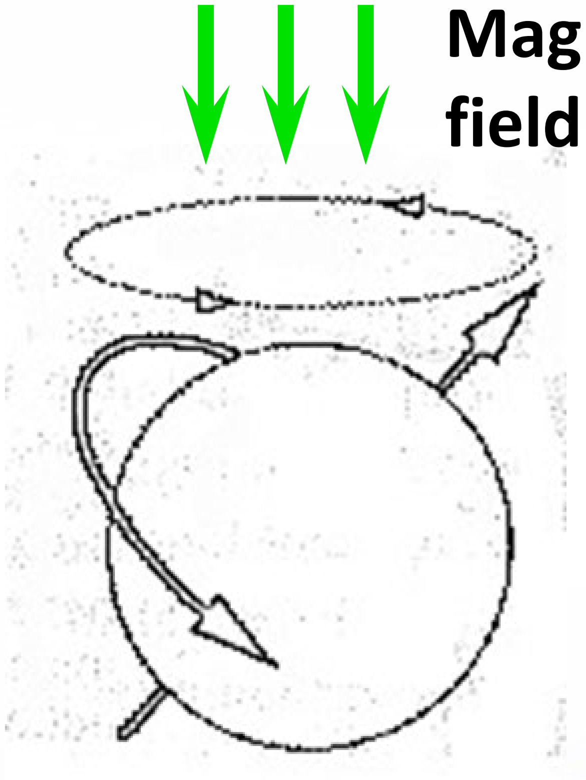
- Spinning of electrical charge: magnetic moment
  - Tend to align with the external magnetic field
- Spinning of mass: angular momentum
  - Tend to maintain its own motion (inertia)
- **Precession**: a circular motion of spin when an external magnetic field is applied

Precession of spins

Gravitational field

Spinning top

Magnetic field



Nucleus

Precession of spins

- Bloch equation

$$\overrightarrow{M} \times \overrightarrow{B} = \frac{d\vec{J}}{dt} = \frac{1}{\gamma}\frac{d\overrightarrow{M}}{dt}$$

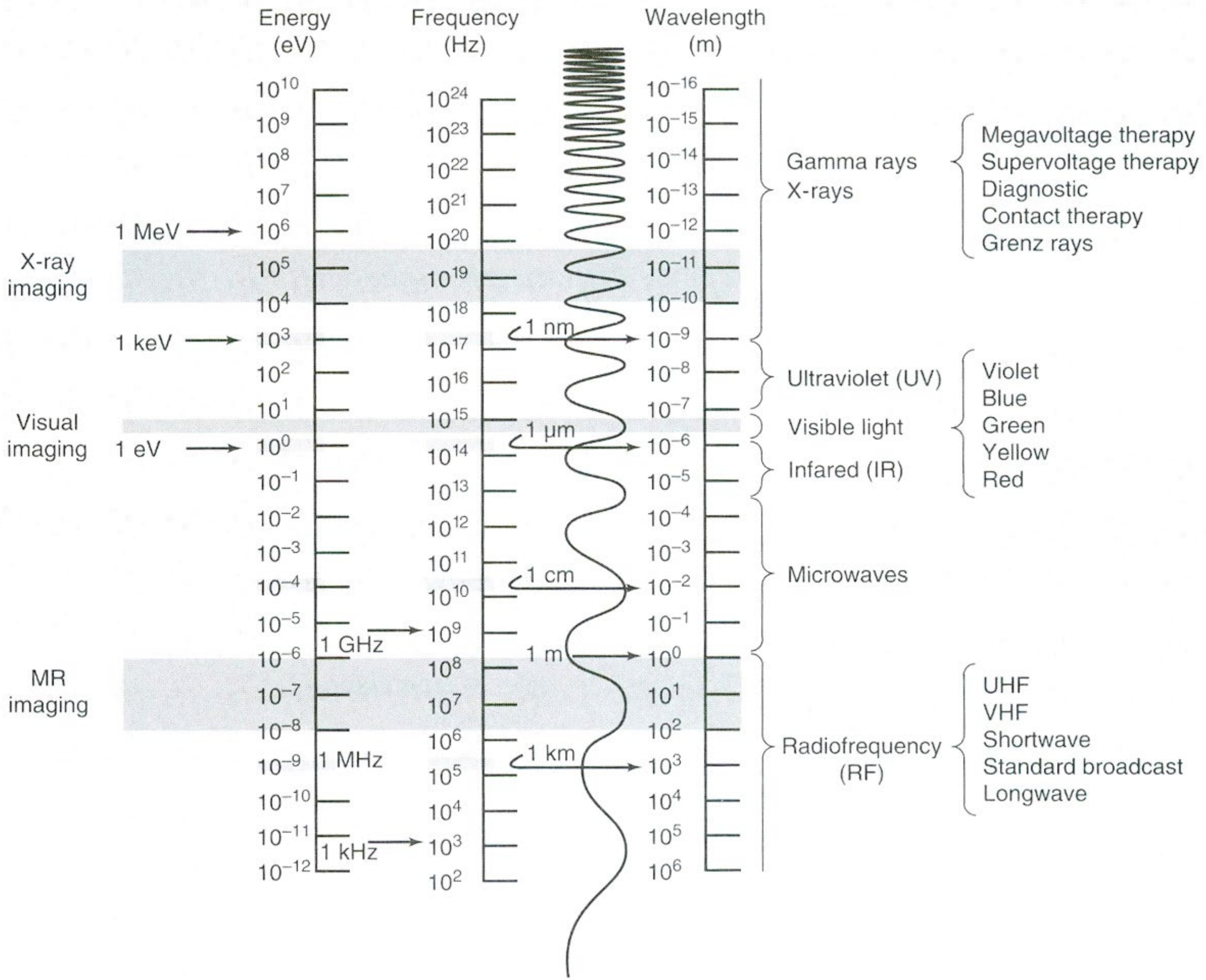
  - $\overrightarrow{M}$: bulk magnetization ($\sum_i \overrightarrow{\mu_i}$)
  - $\overrightarrow{B}$: external magnetic field
  - Describe the motion of $\overrightarrow{M}$ in NMR and MRI

Larmor equation

- The frequency (ω) of precession is obtain by

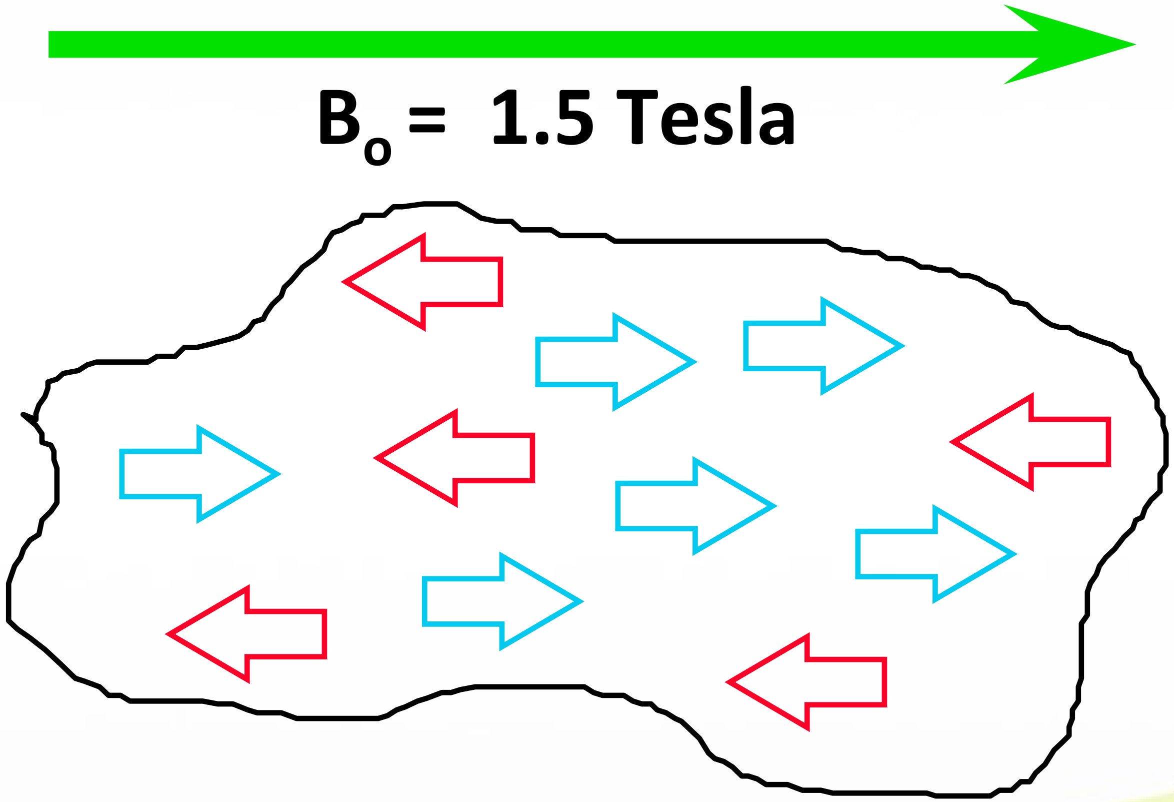
$$\vec{\omega} = -\gamma \vec{B}$$

  - Larmor frequency
  - 63.87 MHz @1.5 Tesla



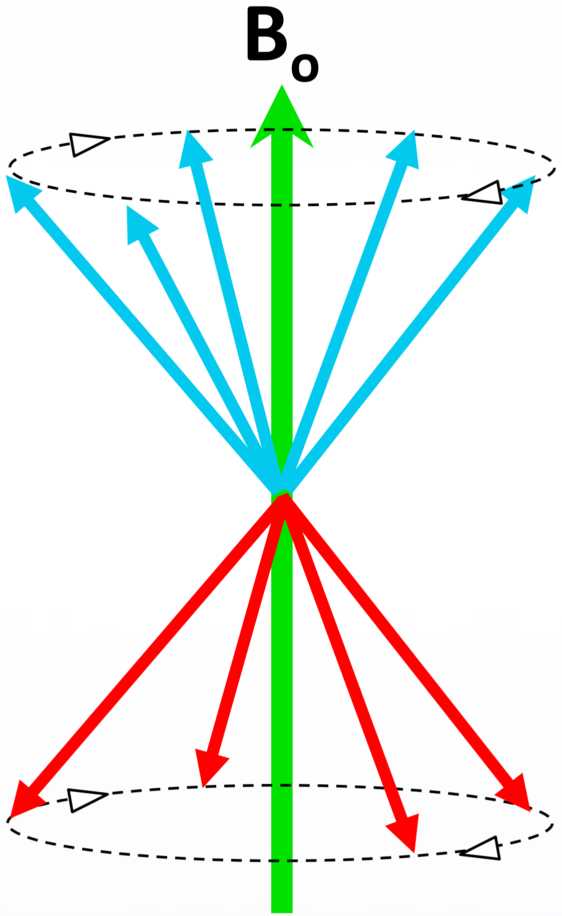
Energy (eV)
Frequency (Hz)
Wavelength (m)
X-ray imaging
Visual imaging
MR imaging
1 MeV
1 keV
1 eV
1 GHz
1 MHz
1 kHz
1 nm
1 μm
1 cm
1 m
1 km
Gamma rays
X-rays
Megavoltage therapy
Supervoltage therapy
Diagnostic
Contact therapy
Grenz rays
Ultraviolet (UV)
Visible light
Infared (IR)
Violet
Blue
Green
Yellow
Red
Microwaves
Radiofrequency (RF)
UHF
VHF
Shortwave
Standard broadcast
Longwave

A quick look back



(Simplicity) Parallel and anti-parallel spins

More accurate (but still too simplified…)



m = +1/2
Spin up
Low energy

m = -1/2
Spin down
High energy

$$\frac{N_{upper}}{N_{lower}} = e^{-\frac{\Delta E}{KT}}$$

$$\Delta E = \frac{\gamma \cdot h \cdot B_0}{2\pi} = \hbar \cdot \omega$$

The measured NMR signal is…

- The summation of nuclear magnetization of all spins
  - Bulk/Net magnetization ($\vec{M}$)
- The population difference of spins is almost proportional to the strength of magnetic field.
  - The higher magnetic field, the stronger MR signal.

Any other nucleus having MR signal?

- Any nucleus with a non-zero spin ($S \neq 0$)
  - Odd number of proton or neutron
  - For example, ^{13}C, ^{19}F, ^{31}P,...
- Signal intensity of these nuclei is much lower than that of ^{1}H because of their low concentrations in human body.

Properties of some nuclei

Isotope	Spin quantum number	γ (MHz/T)	Abundance (%)
^{1}H	**1/2**	**42.58**	**99**
^{12}C	0	--	98
^{13}C	1/2	10.7	1.1
^{16}O	0	--	99
^{17}O	5/2	5.8	0.1
^{19}F	1/2	40.0	100
^{23}Na	3/2	11.3	100
^{25}Mg	5/2	2.6	10
^{31}P	1/2	17.2	100
^{33}S	3/2	3.3	0.7
^{57}Fe	1/2	1.4	2.2

Nucleus? Proton? Spin? Are they the same?

- Nucleus of ^{1}H = Single proton
- Spin is an intrinsic quantum property of every nucleus that allows MR signal to exist.
- For routine MRI scan, nucleus, proton, and spin are roughly synonymous.
  - Not true for other nuclei, such as ^{19}F and ^{31}P.