Lecture one

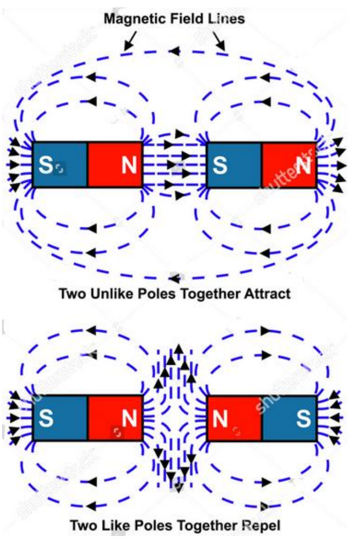
MRI Design: Magnetism and electromagnetism

Magnetic susceptibility

The **magnetic susceptibility** of a substance is the ability of external magnetic fields to affect the nuclei of a particular atom, and is related to the electron configurations of that atom. The nucleus of an atom, which is surrounded by paired electrons, is more protected from, and unaffected by, the external magnetic field than the nucleus of an atom with unpaired electrons. There are three types of magnetic susceptibility: **paramagnetism**, **diamagnetism,** and **ferromagnetism**.

Magnets

Magnets are **bipolar** as they have two poles, north and south. The magnetic field exerted by them produces magnetic field lines or lines of force running from the magnetic south to the north poles of the magnet (Figure 1.3). They are called **magnetic lines of flux.** The number of lines per unit area is called the **magnetic flux density**. The strength of the magnetic field, expressed by the notation **(B)** – or, in the case of more than one field, the primary field **(B_0)** and the secondary field **(B_1)** – is measured in one of three units: **gauss (G)**, **kilogauss (kG)** and **tesla (T)**. If two magnets are brought close together, there are forces of attraction and repulsion between them depending on the orientation of their poles relative to each other. Like poles repel and opposite poles attract.



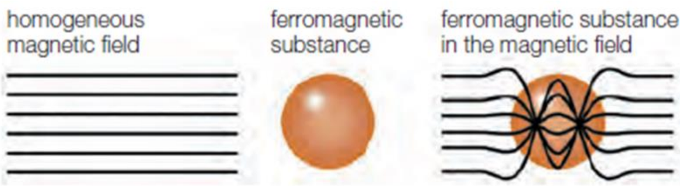


Figure 1.3 Ferromagnetic properties.

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Electromagnetism

A magnetic field is generated by a moving charge (electrical current). The direction of the magnetic field can either be clockwise or counter-clockwise with respect to the direction of flow of the current. **Ampere's law** or **Fleming's right-hand rule** determines the magnitude and direction of the magnetic field due to a current (Figure 1.4).

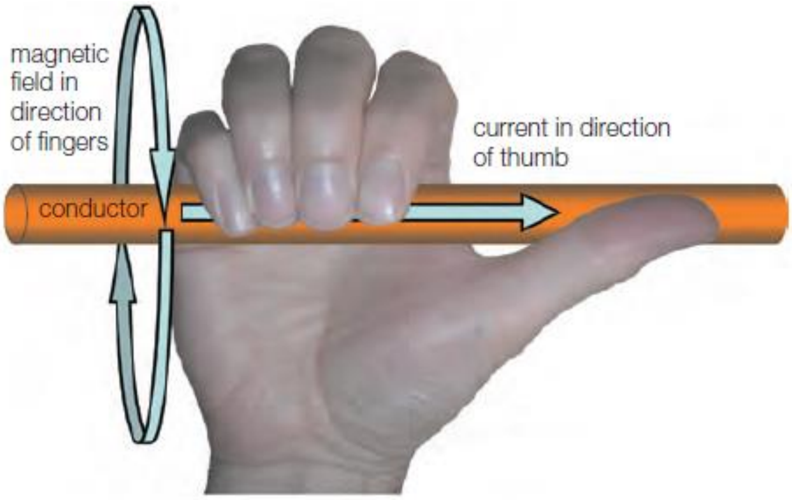

Figure 1.4 The right-hand thumb rule.

Just as moving electrical charge generates magnetic fields, changing magnetic fields generate electric currents. When a magnet is moved in and out of a closed circuit, an oscillating current is produced, which ceases the moment the magnet stops moving. Such a current is called an **induced electric current** (Figure 1.5).

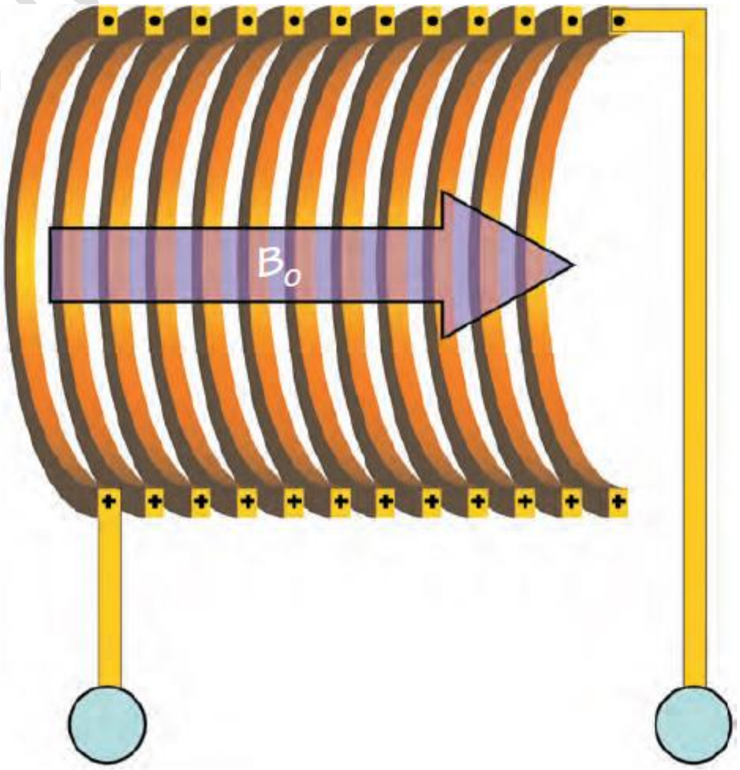

Figure 1.5 A simple electromagnet.

According to **Faraday's law of induction,** the change of magnetic flux through a closed circuit induces an **electromotive force (emf)** in the circuit. The emf is defined as the energy available from a unit of charge travelling once around a loop of wire. The emf drives a current in the circuit and is the result of a changing magnetic field inducing an electric field. The laws of electromagnetic induction (Faraday) state that the induced emf:

- is proportional to the rate of change of magnetic field and the area of the circuit;
- is proportional to the number of turns in a coil of wire;
- is in a direction so that it opposes the change in magnetic field which causes it (**Lenz's law**).

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MRI Design: Atomic structure

Atoms make up all matter in the universe and also therefore in the human body. Most of the human body (96%) is made up of just four elements: hydrogen, oxygen, carbon and nitrogen. Hydrogen is the most common element in the universe and in humans. The atom consists of the following particles:

Protons: in the nucleus, are positively charged

Neutrons: in the nucleus, have no charge

Electrons: orbit the nucleus, are negatively charged (Figure 2.1).

The following terms are used to characterize an atom:

· **Atomic number:** number of protons in the nucleus and determines the type of element the atoms make up.

· **Mass number:** sum of the neutrons and protons in the nucleus.

Atoms of the same element having a different mass number are called **isotopes**. In a stable atom the number of negatively charged electrons equals the number of positively charged protons. Atoms with a deficit or excess number of electrons are called **ions** and the process of removing electrons from the atom is called **ionization.**

Motion within the atom

There are three types of motion of particles in the atom:

- Negatively charged electrons spinning on their own axis.
- Negatively charged electrons orbiting the nucleus.
- Particles within the nucleus spinning on their own axes (Figure 2.1).

Each type of motion produces a magnetic field. In MRI we are concerned with the motion of particles within the nucleus and the nucleus itself.

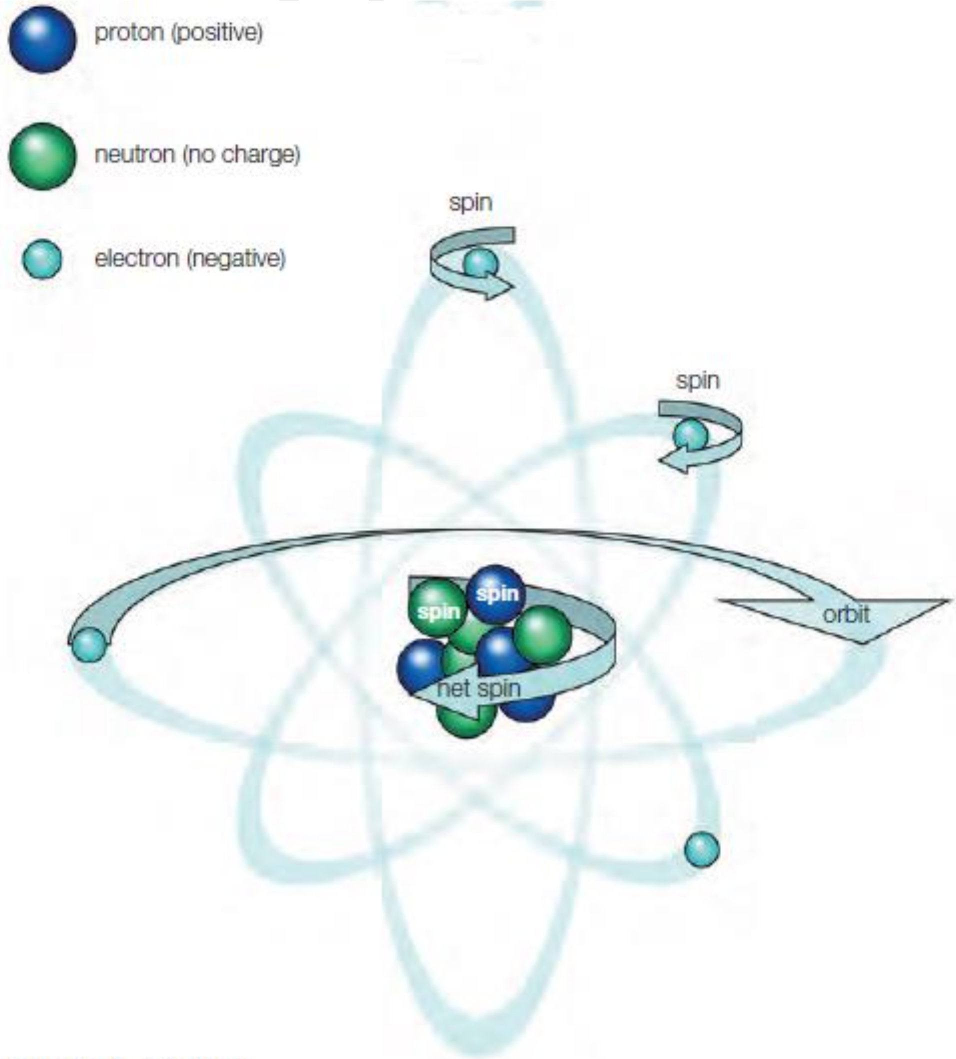

Figure 2.1 The atom.

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MR active nuclei

Protons and neutrons spin about their own axis within the nucleus. The direction of spin is random, so that some particles spin clockwise and others anticlockwise.

- When a nucleus has an *even mass number*, the spins cancel each other out so the nucleus has *no net spin*.
- When a nucleus has an *odd mass number*, the spins do not cancel each other out and the *nucleus spins*.

As protons have charge, a nucleus with an odd mass number has a net charge as well as a net spin. Due to the laws of electromagnetic induction, a moving unbalanced charge induces a magnetic field around itself. The direction and size of the magnetic field are denoted by a magnetic moment (Figure 2.2). The total magnetic moment of the nucleus is the vector sum of all the magnetic moments of protons in the nucleus. The length of the arrow represents the magnitude of the magnetic moment. The direction of the arrow denotes the direction of alignment of the magnetic moment.

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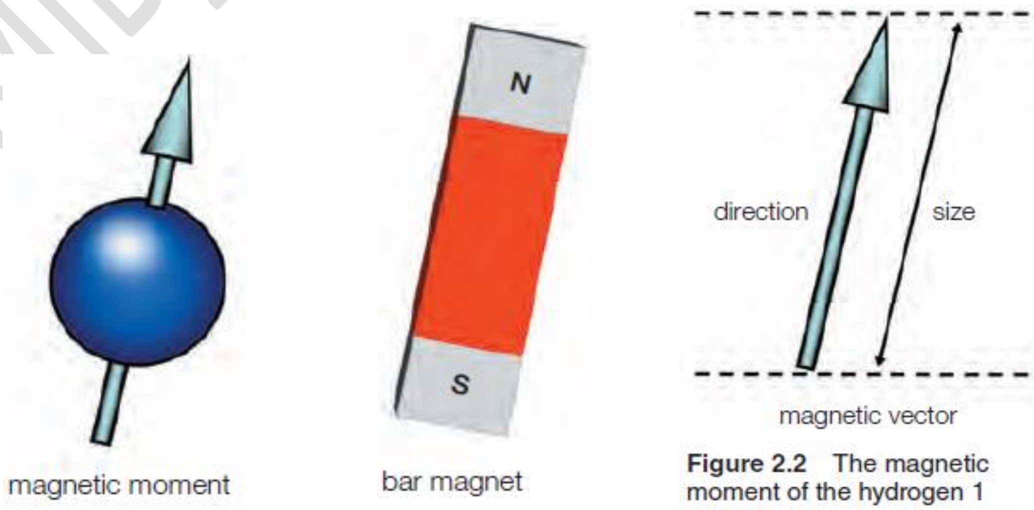

Figure 2.2 The magnetic moment of the hydrogen 1 nucleus.

Nuclei with an odd number of protons are said to be **MR active**. They act like tiny bar magnets. There are many types of elements that are MR active. They all have an odd mass number. The common MR active nuclei, together with their mass numbers and spin characteristics are shown in Table 2.1.

Table 2.1 Constants of selected MR active nuclei.

Element	Protons	Neutrons	Nuclear spin	% Natural abundance
^{1}H (protium)	1	0	1/2	99.985
^{13}C (carbon)	6	7	1/2	1.10
^{15}N (nitrogen)	7	8	1/2	0.366
^{17}O (oxygen)	8	9	5/2	0.038

*The isotope of hydrogen called **protium** is the MR active nucleus used in MRI*, as it has a mass and atomic number of 1. The nucleus of this isotope consists of a single proton and has no neutrons. It is used for MR imaging because:

- it is abundant in the human body (e.g. in fat and water);
- the solitary proton gives it a relatively large magnetic moment because there are no neutrons present in this type of nucleus.

Neutrons tend to decrease the relative size of the nuclear magnetic field, so if they are not present, the magnetic field is maximized (Table 2.1). In the rest of this course MR active nuclei, and specifically protium, are referred to as *spins*.

Key points.

- Hydrogen is the most abundant element in the human body.
- The nuclei that are available for MRI are those that exhibit a net spin (because their mass number is an odd number).
- As all nuclei contain at least one positively charged proton, those that also spin have a magnetic field induced around them.
- An arrow called a magnetic moment denotes the magnetic field of a nucleus.

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MRI DESIGN: Alignment

In a normal environment the magnetic moments of MR active nuclei (spins) point in a random direction, and produce no overall magnetic effect. When spins are placed in an external magnetic field, their magnetic moments line up with the magnetic field flux lines. This is called **alignment**. Alignment is described using two theories.

The classical theory

This uses the direction of the magnetic moments to illustrate alignment.

- **Parallel alignment**: alignment of magnetic moments in the *same* direction as the main field.
- **Anti-parallel alignment**: alignment of magnetic moments in the *opposite* direction to the main field (Figure 3.1).

At room temperature there are always more spins with their magnetic moments aligned parallel than anti-parallel. The net magnetism of the patient (termed the **net magnetization vector**; **NMV**) is therefore aligned parallel to the main field.

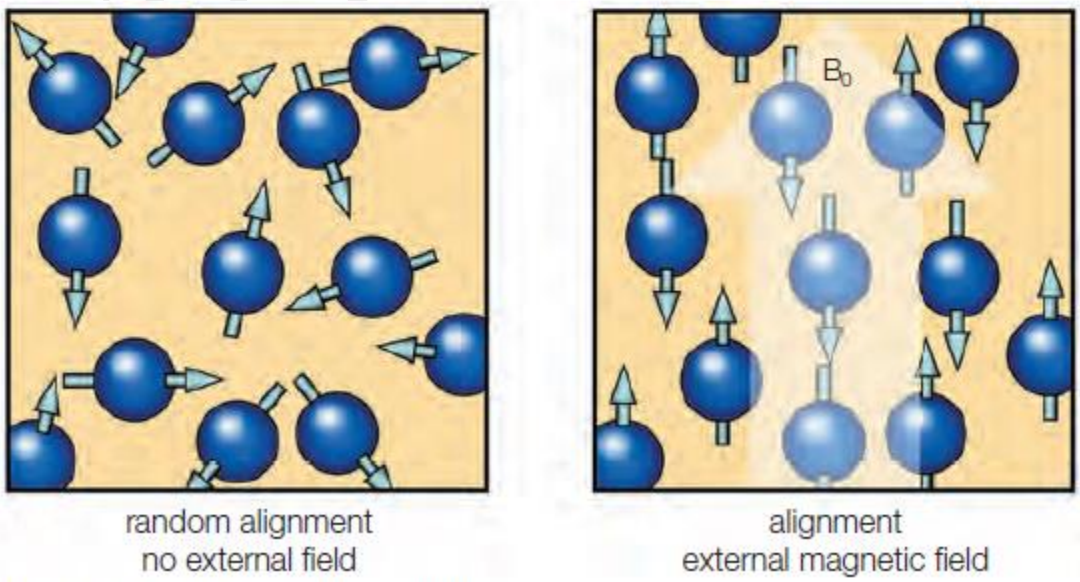

Figure 3.1 Alignment: classical theory.

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The quantum theory

This uses the energy level of the spins to illustrate alignment. According to the quantum theory, protons of hydrogen nuclei interact with the external magnetic field of the scanner and cause a discrete number of energy states. For hydrogen nuclei there are only two possible energy states.

- **Spin-up** nuclei have low energy and do not have enough energy to oppose the main field. These are nuclei that align their magnetic moments parallel to the main field in the classical description.
- **Spin-down** nuclei have high energy and have enough energy to oppose the main field. These are nuclei that align their magnetic moments anti-parallel to the main field in the classical description.

The difference in energy between these two states is proportional to the strength of the external magnetic field (B_0). The magnetic moments of the spins actually align at an angle to B_0 due to the force of repulsion between B_0 and the magnetic moments.

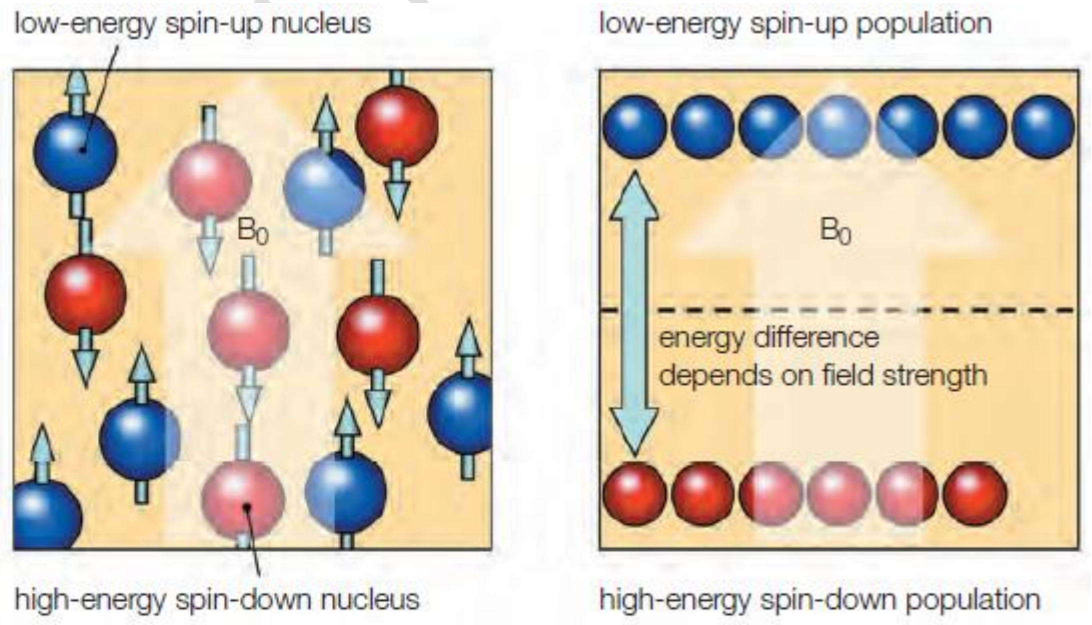

Figure 3.2 Alignment: quantum theory.

What do the quantum and classical theories tell us?

- Hydrogen only has two energy states: high or low. Therefore, the magnetic moments of hydrogen spins only align in the parallel or anti-parallel directions. The magnetic moments of hydrogen spins cannot orientate themselves in any other direction.
- The patient's temperature is an important factor that determines whether a spin is in the high or low energy population. In clinical imaging, thermal effects are discounted, as we assume the patient's temperature is the same inside and outside the magnetic field (thermal equilibrium).
- The magnetic moments of hydrogen spins are constantly changing their orientation because they are constantly moving between high and low energy states. The spins gain and lose energy and their magnetic moments therefore constantly alter their alignment relative to B_0.
- In thermal equilibrium, at any moment there are a greater proportion of spins with their magnetic moments aligned with the field than against it. Th is excess aligned with B_0 produces a net magnetic effect called the NMV that aligns with the main magnetic field (Figure 3.3).

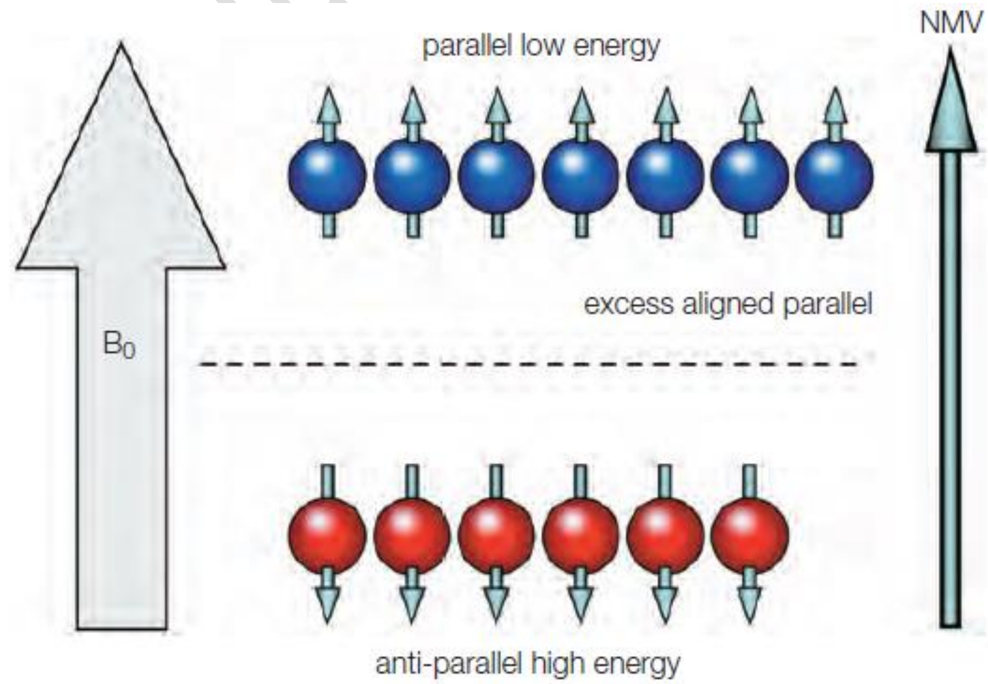

Figure 3.3 The net magnetization vector (NMV).

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- As the magnitude of the external magnetic field increases, more magnetic moments line up in the parallel direction, because the amount of energy the spins must possess to align their magnetic moments in opposition to the stronger field and line up in the anti-parallel direction is increased. As the field strength increases, the low-energy population increases and the high energy population decreases. As a result, the NMV increases.

Key points.

- When placed in an external magnetic field, the magnetic moments of hydrogen either align in a spin-up, low-energy or spin-down, high-energy orientation.
- At thermal equilibrium, there are more spin-up, low-energy than spin-down, high-energy spins, so the net magnetization of the patient (NMV) is orientated in the same direction as B_0.
- The difference in energy between these populations is determined by the strength of B_0.
- As B_0 increases the energy difference between the two populations also increases, as the number of spin-up, low-energy spins increases relative to the number of spin-down, high-energy spins.
- The signal to noise ratio (SNR) increases at higher values of B_0.

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MRI DESIGN: Precession

Every MR active nucleus is spinning on its own axis. The magnetic field exerts a torque on the magnetic moments of all MR active nuclei, causing a secondary spin (Figure 4.1). This spin is called **precession** and causes the magnetic moments of all MR active nuclei (spin up and spin down) to describe a circular path around B_0 (Figure 4.2). The speed at which the magnetic moments spin about the external magnetic field is called the **precessional frequency**.

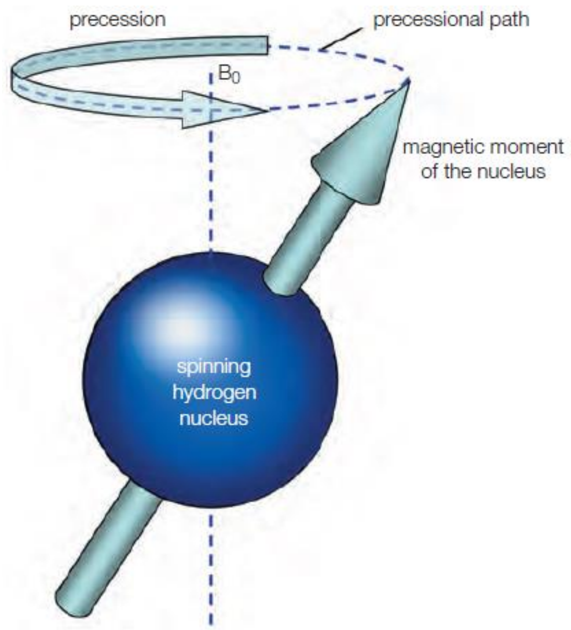

Figure 4.1 Precession.

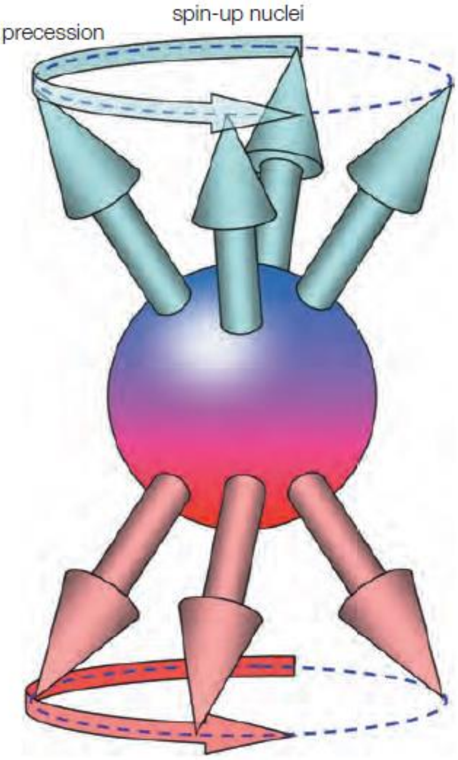

Figure 4.2 Precession of the spin-up and spin-down populations.

Precessional (Larmor) frequency

The **Larmor equation** is used to calculate the frequency or speed of precession for the magnetic moments of a specific nucleus in a specific magnetic field strength. The Larmor equation is simply stated as follows:

$$\omega_0 = \gamma B_0$$

- The precessional frequency is denoted by ω_0 and expressed in megahertz (MHz).
- The strength of the external field is expressed in tesla (T) and denoted by the symbol B_0 (Table 4.1).
- The **gyromagnetic ratio** is the precessional frequency of the magnetic moments of a specific nucleus at 1T and has units of MHz/T. It is denoted by γ. As it is a constant of proportionality, the precessional frequency or Larmor frequency is proportional to the strength of the external field and can be calculated for any type of MR active nucleus and field strength (Table 4.2).

Table 4.1 Common equations of precession.

Equations			
$\omega_0 = \gamma B_0/2\pi$ *simplified to* $\omega_0 = \gamma B_0$	ω_0 is the precessional of Larmor frequency (MHz) γ is the gyromagnetic ratio (MHz/T) B_0 is the strength of the external magnetic field (T)	This is the Larmor equation. The 2π function enables the conversion of ω_0 from angular to cyclical frequency. As γ is a constant, for a given MR active nucleus ω_0 is proportional to B_0.	
^{15}N (nitrogen)	1/2	4.3173	6.4759
^{17}O (oxygen)	5/2	5.7743	8.6614

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The precessional frequencies of the magnetic moments of hydrogen spins (gyromagnetic ratio 42.57 MHz/T) commonly found in clinical MRI are:

- 21.285 MHz at 0.5 T
- 42.57 MHz at 1 T
- 63.86 MHz at 1.5 T (Table 4.2)

Table 4.2 Spin characteristics of selected MR active nuclei.

Element	Nuclear spin	Gyromagnetic ratio (MHz/T)	Larmor frequency at 1.5T (MHz)
^{1}H (protium)	1/2	42.5774	63.8646
^{13}C (carbon)	1/2	10.7084	16.0621
^{15}N (nitrogen)	1/2	4.3173	6.4759
^{17}O (oxygen)	5/2	5.7743	8.6614

The precessional frequency corresponds to the range of frequencies in the electromagnetic spectrum of **radiowaves** (Figure 4.3). Therefore, the magnetic moments of hydrogen spins precess at a relatively low radio frequency (RF) compared to other types of electromagnetic radiation. This is why from the perspective of the energies used, MRI is thought to be safe. RF energy is not sufficiently energetic to ionization.

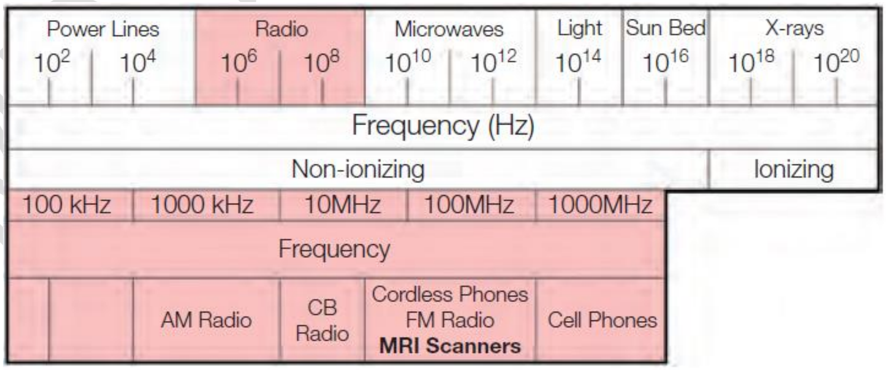

Figure 4.3 The electromagnetic spectrum.

Precessional phase

Phase refers to the position of the magnetic moments of spins on their precessional path at any moment in time. Its units are radians. A magnetic moment travels through 360 radians during one rotation. In this context, frequency is the rate of change phase of magnetic moments; that is, it is a measure of how quickly the phase position of a magnetic moment changes over time.

In MRI, we are particularly interested in the relative phase position of all the magnetic moments of hydrogen spins in the tissue we are imaging.

- **Out of phase** or **incoherent** means that the magnetic moments of hydrogen spins are at different places on the precessional path at a moment in time.
- **In phase** or **coherent** means that the magnetic moments of hydrogen spins are at the same place on the precessional path at a moment in time (Figure 4.4).

At rest (when the patient is simply placed inside the magnetic field and exposed to B_0), the magnetic moments of the hydrogen spins are out of phase with each other and therefore the NMV does not precess. The key points of this chapter are summarized in Table 4.3.

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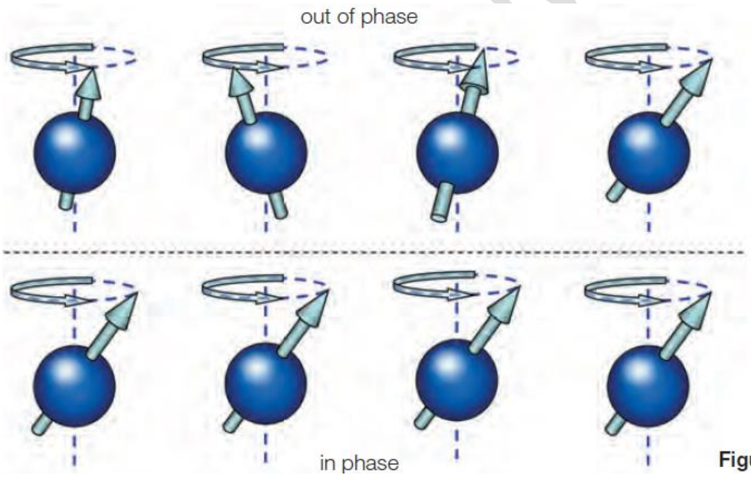

Figure 4.4 Coherent and incoherent phase positions

KEY POINTS

✓ The magnetic moments of all the spins precess around B_0 at the Larmor frequency that is proportional to B_0 for a given MR active nucleus. Frequency therefore refers to how fast the magnetic moments of spins are precessing and is measured in MHz in MRI.

✓ For field strengths used in clinical imaging, the Larmor frequency of hydrogen is in the radiofrequency band of the electromagnetic spectrum.

✓ At rest the magnetic moments of the spins are out of phase with each other.

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