UNIT 3 MAGNETIC RESONANCE IMAGING

Magnetic resonance is a phenomenon involving the interaction of magnetic fields with the intrinsic magnetic properties of atomic nuclei or electrons. This concept forms the basis for techniques such as nuclear magnetic resonance (NMR) and electron spin resonance (ESR), with applications in physics, chemistry, biology, and medicine.

3.1FUNDAMENTALS OF MAGNETIC RESONANCE

Magnetic Properties of Particles

- **Spin:** Many atomic nuclei and electrons have intrinsic angular momentum called spin, which generates a magnetic moment.
- **Magnetic Moments:** Particles with spin act like tiny magnets, aligning with or against an external magnetic field.

Zeeman Effect

When a particle with a magnetic moment is placed in a magnetic field, its energy levels split into discrete states based on the orientation of its magnetic moment relative to the field.

Resonance Condition

- Magnetic resonance occurs when a system absorbs electromagnetic radiation at a frequency corresponding to the energy difference

where is Planck's constant.

Precession and Larmor Frequency

- In an external magnetic field, the magnetic moment of the particle precesses around the field at a characteristic angular frequency, called the **Larmor frequency** .

Relaxation Processes

After excitation, the system returns to equilibrium via two relaxation mechanisms:

- **T1 (Longitudinal Relaxation):** Recovery of the net magnetization along the magnetic field direction.
- **T2 (Transverse Relaxation):** Decay of magnetization perpendicular to the magnetic field, due to interactions among spins.

Magnetic Resonance Techniques

- **Nuclear Magnetic Resonance (NMR):** Focuses on nuclei with nonzero spin, widely used for molecular structure determination and imaging (e.g., MRI).
- **Electron Spin Resonance (ESR):** Deals with unpaired electrons, useful in studying free radicals and paramagnetic centers.

Applications

- **Medicine:** Magnetic resonance imaging (MRI) for non-invasive imaging.
- **Chemistry:** NMR spectroscopy for identifying molecular structures.
- **Physics and Materials Science:** ESR for studying electronic properties of materials.

3.1.1 Properties of electromagnetic waves

Electromagnetic waves are a form of energy that travels through space at the speed of light, consisting of oscillating electric and magnetic fields. Below are the key properties of electromagnetic waves:

Transverse Nature

Electromagnetic waves are transverse waves, meaning the oscillating electric field and magnetic field are perpendicular to each other and to the direction of wave propagation.

Self-Propagation

The changing electric field produces a magnetic field, and the changing magnetic field generates an electric field. This mutual induction allows the wave to propagate through space without requiring a medium.

Speed

In a vacuum, electromagnetic waves travel at the speed of light . The speed of electromagnetic waves in a medium depends on the medium's permittivity and permeability .

Energy Transport

Electromagnetic waves carry energy and momentum, which they can transfer to matter upon interaction.

Wavelength and Frequency

- **Wavelength** : The distance between successive peaks or troughs of the wave.
- **Frequency** : The number of oscillations per second.

Spectrum

Electromagnetic waves exist in a wide range of wavelengths and frequencies, forming the electromagnetic spectrum. This includes (in order of increasing wavelength)

- Gamma rays
- X-rays

- Ultraviolet (UV) light
- Visible light
- Infrared (IR) radiation
- Microwaves
- Radio waves

No Medium Required

Unlike sound waves, electromagnetic waves do not need a medium and can propagate through the vacuum of space.

Obeys Maxwell's Equations

Electromagnetic waves are solutions to Maxwell's equations, which describe the behavior of electric and magnetic fields.

Wave-Particle Duality

Electromagnetic waves exhibit both wave-like (diffraction, interference) and particle-like (photoelectric effect, Compton scattering) behavior, with photons being the quantum particles associated with the waves.

Perpendicular Energy Transport

The energy and momentum of electromagnetic waves are transported in the direction of wave propagation. The energy flux is described by the **Poynting vector** .

Amplitude

- The amplitude of an electromagnetic wave refers to the maximum strength of the oscillating **electric field** or **magnetic field** .
- It determines the **intensity** or energy carried by the wave. Intensity is proportional to the square of the amplitude:

Phase

- The phase describes the position of a point in the wave cycle at a given time and location.
- **Phase difference** determines how two waves interact (constructive or destructive interference).

Orientation (Polarization)

- The **orientation** of an electromagnetic wave refers to the direction of the oscillating **electric field vector** .

- Types of polarization:
  - **Linear**: The electric field oscillates in a single plane.
  - **Circular**: The electric field rotates in a circular path, maintaining constant amplitude.
  - **Elliptical**: A generalized form of polarization, combining linear and circular.
- Polarization is an important property in optics and communication systems.

Waves in Matter

Electromagnetic waves interact with matter in various ways depending on the material properties:

- **Reflection**: When waves bounce off a surface (e.g., mirrors).
- **Refraction**: When waves pass through a medium and change direction due to a change in speed (e.g., light bending in water).
- **Absorption**: When matter absorbs wave energy, converting it to heat or other forms.
- **Transmission**: When waves pass through a material with minimal loss.
- **Dispersion**: Different wavelengths travel at different speeds in a medium, causing splitting (e.g., prisms splitting light into a spectrum).
- **Attenuation**: Reduction in amplitude as waves propagate through a medium due to absorption and scattering.

3.1.2 Interaction of Nuclei with static magnetic field and radio frequency wave

The interaction of nuclei with a **static magnetic field (B_0)** and a **radio frequency (RF) wave** is the fundamental principle behind **Nuclear Magnetic Resonance (NMR)** and **Magnetic Resonance Imaging (MRI)**. This interaction involves several key concepts:

Static Magnetic Field (B_0)

- When a nucleus with a non-zero magnetic moment is placed in an external magnetic field , the magnetic moments align either parallel (low energy) or anti-parallel (high energy) to the field.
- This creates two distinct energy states for the nucleus, resulting in a phenomenon called **Zeeman splitting**.
- The energy difference between these states depends on the magnetic field strength and the gyromagnetic ratio of the nucleus.

Precession of Nuclear Spins

- The nuclear magnetic moments do not align perfectly . Instead, they precess around the direction of at a specific angular frequency, called the **Larmor frequency**:

This precession is the fundamental frequency at which the nucleus interacts with an RF field.

Radio Frequency (RF) Wave

- When a radio frequency wave with energy matching the Larmor frequency is applied, it induces transitions between the two energy states of the nuclei.
- This phenomenon, known as **resonance**, causes the nuclear spins to absorb energy and flip from the lower-energy state to the higher-energy state.

Rotating Frame and Flip Angles

- The RF wave is often applied perpendicularly , producing an oscillating magnetic field . In the rotating frame of reference (moving with the Larmor frequency), the field can be visualized as tipping the magnetization vector away from its equilibrium alignment along .
- The extent of tipping depends on the duration and strength of the RF pulse, defined by the **flip angle**.

Relaxation and Signal Detection

- After the RF pulse ends, the nuclei return to their equilibrium state in processes called:
  - **T_1 relaxation (longitudinal relaxation):** Realignment of magnetization with .
  - **T_2 relaxation (transverse relaxation):** Dephasing of spins in the transverse plane due to local magnetic field variations.
- As the nuclei relax, they emit RF signals that can be detected using a coil. These signals are the basis of NMR spectroscopy and MRI imaging.

Applications

- **NMR Spectroscopy:** Used to determine molecular structure and dynamics.
- **MRI:** Exploits differences in relaxation properties of tissues for imaging in medicine.

3.1.3 Rotation in MRI

In the context of MRI, rotation refers to the movement of the net magnetization vector within a plane due to the application of a **radiofrequency (RF) pulse**.

- **Net magnetization vector**: In a magnetic field (B_0), nuclear spins align either parallel or anti-parallel, creating a net magnetization along the field direction.
- **RF pulse**: When an RF pulse at the Larmor frequency is applied, the net magnetization vector tips away from its alignment with B_0 and rotates into the transverse plane (x-y plane).
- **Flip angle**: The degree of this rotation depends on the duration and strength of the RF pulse.

Precession in MRI

Precession refers to the **wobbling motion** of nuclear spins around the axis of the applied magnetic field (B_0).

- **Larmor frequency**: Spins precess at a frequency proportional to the magnetic field strength. This is described by the Larmor equation.
- **Precessional motion**: The individual magnetic moments of the nuclei trace out circular paths in the transverse plane. This behavior underpins the generation of the MRI signal.

Connection Between Rotation and Precession

- When an RF pulse rotates the net magnetization vector into the transverse plane, the spins begin to **precess** coherently around the B_0 field.
- This coherent precession generates a time-varying magnetic field that induces a signal in the receiver coil.

Additional Concepts Related to Precession

- **Free induction decay (FID)**: As the spins lose coherence due to relaxation processes, the precessing magnetization decays, leading to a reduction in the signal.
- **T_1 and T_2 relaxation**: T_1 is the recovery of longitudinal magnetization, while T_2 is the loss of transverse magnetization due to spin-spin interactions.