CHAPTER

6

NUCLEAR MAGNETIC RESONANCE

1. Nuclear Spin States

Many atomic nuclei have a property called spin, the nuclei behave as if they were spinning. In fact, any atomic nucleus that possesses either *odd* mass, *odd* atomic number, or both has a quantized spin angular momentum and a magnetic moment. The more common nuclei that possess spin include ${}^1_1H$, ${}^2_1H$, ${}^{13}_6C$, ${}^{14}_7N$, ${}^{17}_8O$, and ${}^{19}_9F$. For each nucleus, the number I is a physical constant, and there are 2I + 1 allowed spin states with integral differences ranging from +I to –I. The individual spin states fit into the sequence.

$$+I, (I-1), ..., (-I+1), -I$$

Mass No.	Atomic No.	Nuclear spin
odd	even or odd	1/2, 3/2, 5/2, $\cdots$
even	even	0
even	odd	1, 2, 3, 4

SPIN QUANTUM NUMBERS OF SOME COMMON NUCLEI										
Element	${}^1_1H$	${}^2_1H$	${}^{12}_6C$	${}^{13}_6C$	${}^{14}_7N$	${}^{16}_8O$	${}^{17}_8O$	${}^{19}_9F$	${}^{31}_{15}P$	${}^{35}_{17}Cl$
Nuclear spin quantum number	$\frac{1}{2}$	1	0	$\frac{1}{2}$	1	0	$\frac{5}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{3}{2}$
Number of spin states	2	3	0	2	3	0	6	2	2	4

2. Nuclear Magnetic Moments

Spin states are not of equivalent energy in an applied magnetic field because the nucleus is a charged particle, and any moving charge generates a magnetic field of its own. Thus, the nucleus has a magnetic moment μ generated by its charge and spin. A hydrogen nucleus may have a clockwise $\left(+\frac{1}{2}\right)$ or counterclockwise $\left(-\frac{1}{2}\right)$ spin, and the nuclear magnetic moments (μ) in the two cases are pointed in opposite directions. In an applied magnetic field, all protons have their magnetic moments either aligned with the field or opposed to it.

Hydrogen nuclei can adopt only one or the other of these orientations with respect to the applied field. The spin state $+\frac{1}{2}$ is of lower energy since it is aligned with the field, while the spin state $-\frac{1}{2}$ is of higher energy since it is opposed to the applied field.

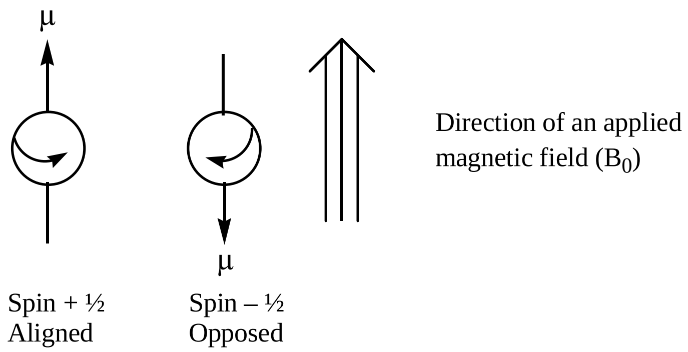

Figure: The two allowed spin states for a proton

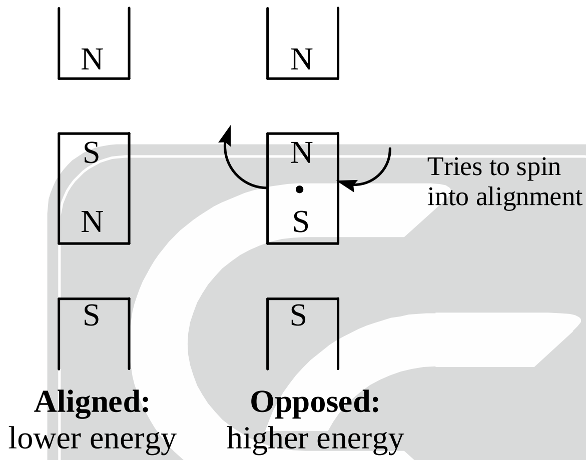

Figure : Aligned and opposed arrangements of bar magnets

3. Absorption of Energy

The nuclear magnetic resonance phenomenon occurs when nuclei aligned with an applied field are induced to absorb energy and change their spin orientation with respect to the applied field.

The energy absorption is a quantized process, and the energy absorbed must equal the energy difference between the two states involved.

$$E_{\text{absorbed}} = \left(E_{-\frac{1}{2}\,state} - E_{+\frac{1}{2}\,\text{state}}\right) = h\nu$$

In practice, this energy difference is a function of the strength of the applied magnetic field B_0, as illustrated in figure.

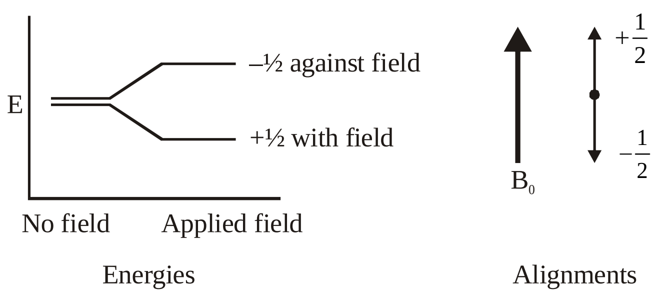

Figure : The spin states of a proton in the absence and in the presence of an applied magnetic field.

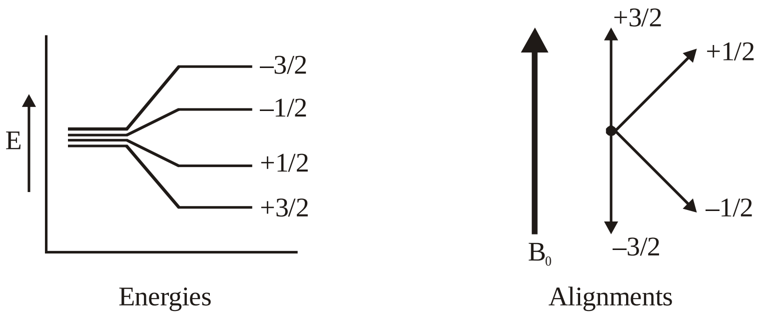

Figure : The spin states of a chlorine atom both in the presence and in the absence of an applied magnetic field.

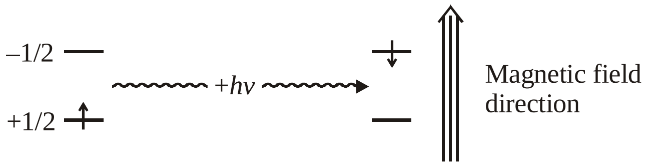

Figure : The NMR absorption process for a proton.

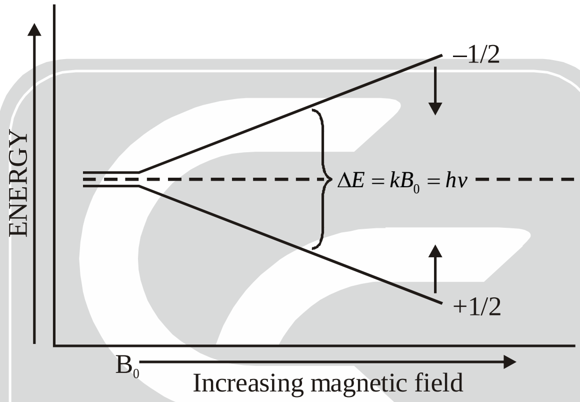

Figure : The spin-state energy separation as a function of the strength of the applied magnetic field B_0.

The stronger the applied magnetic field, the greater the energy difference between the possible spin states:

$$\Delta E = f\left(B_0\right)$$

The magnitude of the energy-level separation also depends on the particular nucleus involved. Each nucleus (hydrogen, chlorine, and so on) has a different ratio of magnetic moment of angular momentum since each has different charge and mass. This ratio, called the magnetogyric ratio γ , is a constant for each nucleus and determines the energy dependence on the magnetic field:

$$\Delta E = f\left(\gamma B_0\right) = h\nu$$

Since the angular momentum of the nucleus is quantized in units of $\frac{h}{2\pi}$, the final equation takes the form

$$\Delta E = \gamma\left(\frac{h}{2\pi}\right)B_0 = h\nu$$

Solving for the frequency of the absorbed energy,

$$\nu = \left(\frac{\gamma}{2\pi}\right)B_0$$