3. Principle

Nuclei with an odd number of protons and/or neutrons undertake nuclear spin with the nuclear magnetic moment μ proportional to the nuclear spin quantum number I, as:

$$\mu = g\mu_N I \quad (1)$$

where g is a dimensionless factor called g-factor (g=5.5856947 for Hydrogen nucleus), μ_N is a constant ($\mu_N = qh/2m_p \times C$) called Bohr nuclear magnetic moment, in which q is the charge of an electron, m_p is the mass of an electron, C is the speed of light, and h is the Planck's constant.

When a nuclear spin system is in a constant DC magnetic field B_0, the energy levels of the nucleus are split due to Zeeman effect. For a simple system such as a Hydrogen nucleus (I=1/2), the original energy level is split into upper and lower two energy levels, E_2 and E_1, as shown in Figure 1, whose energy difference is proportional to the product of g and B_0, as:

$$E_2 - E_1 = \Delta E = g\mu_N B_0 \quad (2)$$

If a sweeping magnetic field of $B_I\cos(wt)$ with an angular frequency (w) in the range of 10^6 to 10^9 Hz, is applied perpendicularly to a constant magnetic field B_0, two opposite processes, stimulated transition and spontaneous emission, would occur between the two energy levels if the RF quantum energy equals the energy difference between the two energy levels, as

$$\Delta E = g\mu_N B_0 = wh \quad (3)$$

These two processes have an equal probability, which is proportional to the square of B_I. As the nuclear spin system absorbs the energy from the RF magnetic field to create resonance absorption, it is in a non-equilibrium state. Equation (3) is referred to as the condition for nuclear magnetic resonance, which can be rewritten as

$$w_0 = B_0\gamma \quad (4)$$

where γ is called the gyromagnetic ratio. If the sweeping magnetic field is removed, the nuclear spin system will undertake a relaxation process through the interactions of lattice to spin and spin to spin to restore back to an equilibrium state.

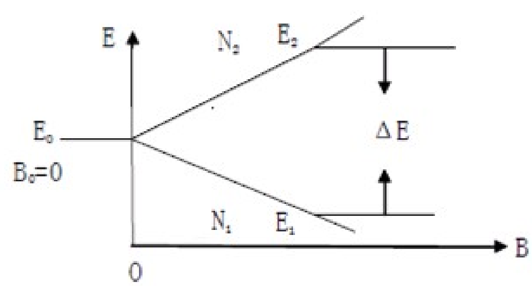

Figure 1 Zeeman splitting of energy level in magnetic field

4. Apparatus Structure

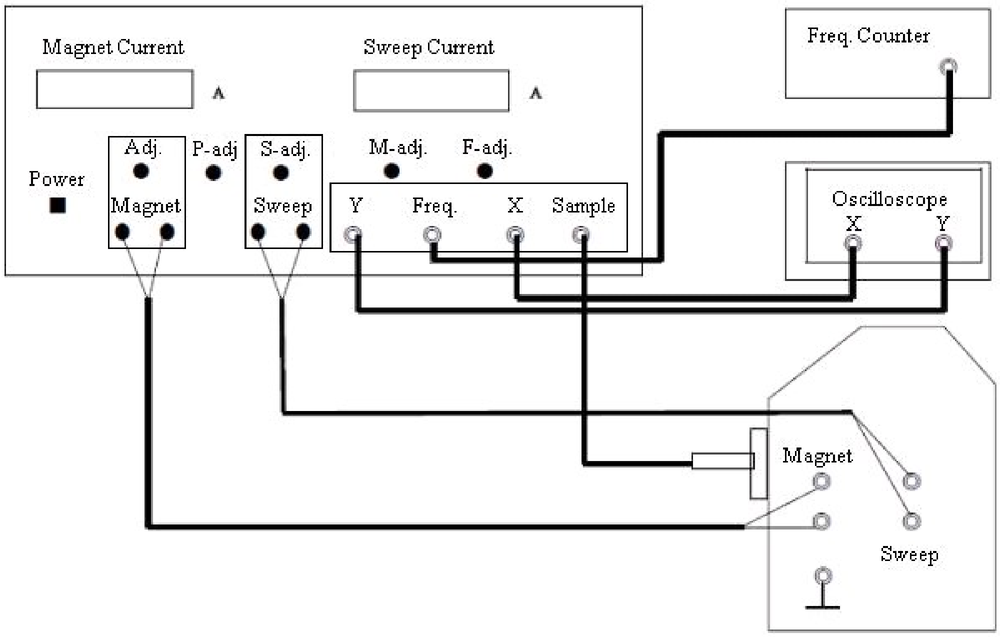

Figure 2 Schematic of NMR system

This NMR apparatus consists of a controller unit, an electromagnet, and a sample probe, together with a frequency counter (optional) and an oscilloscope (optional). A schematic of the NMR system is shown in Figure 2.

1) Controller unit

A RF magnetic field (B_1) is provided by the NMR apparatus through a sample probe which also detects the magnetic field strength. A block diagram of the NMR electronic unit is shown in Figure 3.

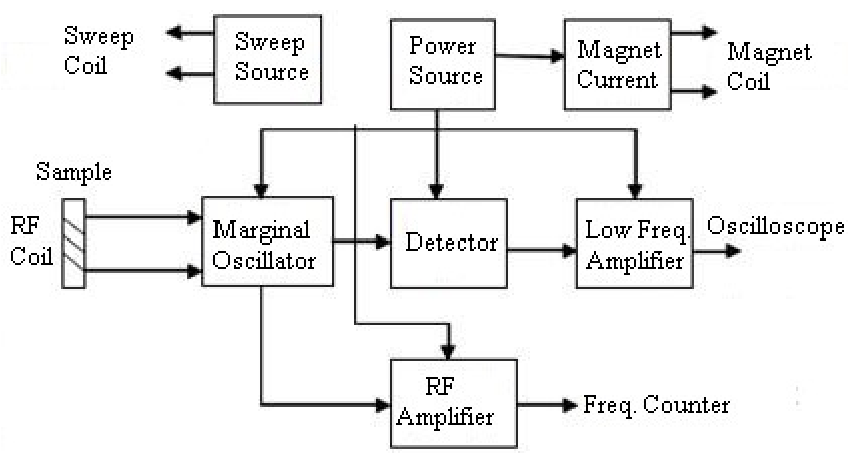

Figure 3 Block diagram of the electronic unit

In Figure 3, the marginal oscillator generates RF oscillations whose frequency is determined by the RF coil and a parallel capacitor. A marginal oscillator is normally tuned to work in the critical state to prevent from NMR signal saturation while offering higher detection sensitivity. In the absence of NMR, the oscillator generates equal-amplitude oscillations detected as a DC signal, which appears as a straight line on the oscilloscope through the low frequency amplifier. In the presence of NMR, since the sample absorbs the RF energy, oscillation amplitude of the oscillator reduces. Thus, the envelope of the RF signal is amplitude-modulated by the resonant absorption signal. After demodulation and amplification, the butterfly-alike resonant absorption signal can be detected and displayed, which reflects the change in oscillation amplitude.

2) Electromagnet and sweep coil

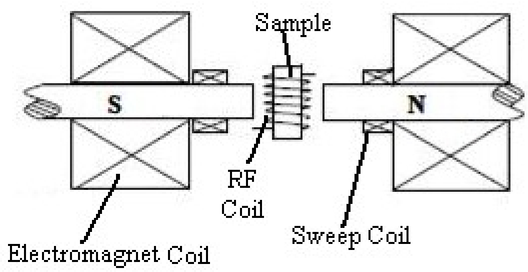

Figure 4 Electromagnet, sweep and RF coils

As shown in Figure 4, the electromagnet produces a constant DC magnetic field (B_0), whose strength can be continuously changed from a few to thousands Gauss through the excitation current. The sweep coil produces a weak low-frequency (50/60 Hz) AC magnetic field (B_m) through the sweeping current, which is superimposed to the constant magnetic field (B_0). Hence, within a period of the AC sweep signal, stable NMR absorption signal of ^{1}H nucleus in the sample can be observed on the oscilloscope.

It is apparent from Eq. (4) that there is one-to-one relationship between magnetic field and RF frequency for resonance absorption. Because it is difficult to find the frequency for resonance absorption, a weak low-frequency AC magnetic field B_m is usually superposed to the constant magnetic field B_0, as shown in Figure 5, in which the upper trace is the superimposed magnetic field (B_0+B_m), and the lower trace is the amplitude change in oscillation voltage over time. B_0' is the resonance magnetic field at a specific RF frequency. Under such case, the actual magnetic field at the sample location is B_0+B_m. Since the sweeping amplitude is small, the direction of the superimposed magnetic field remains unchanged. As the amplitude of the superimposed magnetic field varies periodically with the sweeping field, the Larmor precession angular frequency (ω_0) of the nuclear magnetic moment also varies periodically, as

$$w_0 = \gamma(B_0 + B_m) \tag{5}$$

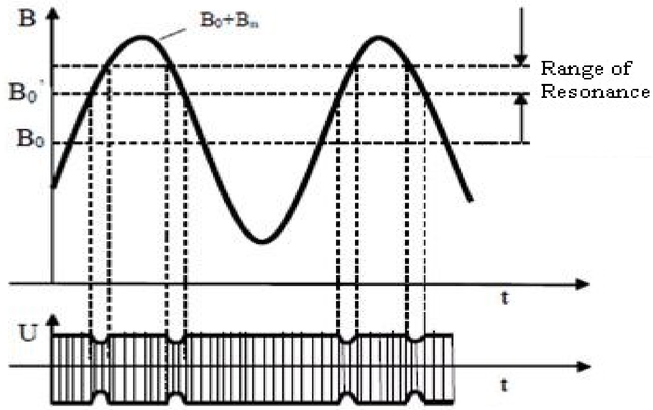

Figure 5 Magnetic field and resonance absorption

If the angular frequency (ω') of the sweeping field falls within the variation range of ω_0' and the valley-to-peak value of the sweeping field exceeds the range of the resonance field, NMR occurs. Resonance absorption signal can be observed on an oscilloscope, only when the resonance magnetic field, B_0', is passed by the superimposed magnetic field (B_0+B_m). As otherwise, no NMR signal will be observed. Within one period, the resonance magnetic field is passed twice by the superimposed magnetic field, so two resonance absorption signals can be observed.

If the time or frequency interval between adjacent resonance absorption signals varies from period to period as shown in Figure 6 (a), this is caused by the fact that the resonance magnetic field (B_0') is not equal to the constant magnetic field (B_0). By changing the constant magnetic field (B_0) or the frequency of the RF field, the relative positions of the resonance signals will shift. When the interval between adjacent resonance absorption signals remains constant from period to period as shown in Figure 6 (b), the relative positions of the resonance absorption signals are independent of the amplitude of the sweep magnetic field (B_m), and the width of the resonance absorption signals increases with a decrease in sweep magnetic field (B_m) as shown in Figure 6 (c), at this time, B_0' and B_0 are equal.

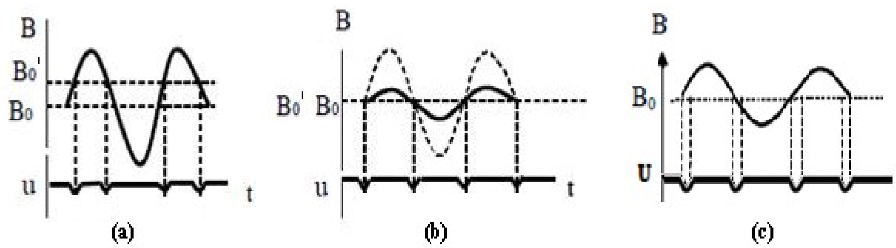

Figure 6 Relationship between resonance absorption signal waveform and magnetic field