PH211: Nuclear Magnetic Resonance

Hiranmay Das[†], Karnpriya Pandey[*]
Department of Physics, Indian Institute of Science, Bengaluru, India
[†]hiranmayd@iisc.ac.in, [*]karnpriyap@iisc.ac.in

August 19, 2025

For people with low attention span

- Some nuclei have magnetic moments due to net spins.
- Keeping them in the magnetic field causes energy gap between different spin states.
- An additional oscillating magnetic field of particular frequency forces the system to oscillate between different energy states.
- Oscillating magnetic fields produced by these spins, generate NMR signal.
- NMR signal not only depends on the nuclear property but also depends on the electronic environment around the nucleus.

1 Introduction

The basic principle of NMR is based on the fact that some nuclei possess a net spin angular momentum, which arises from the combined contributions of the orbital motion and intrinsic spins of their constituent protons and neutrons. These spins give rise to net magnetic moments in the nucleus. In some nuclei, such as protium(^1H) and fluorine(^{19}F), the nuclear spin turns out to be half, meaning they have only two spin states: spin-up and spin-down. In the absence of a magnetic field, these two spin states are degenerate (having the same energy), but in the presence of a magnetic field $\mathbf{B}$, the degeneracy is lifted, which can be shown using the Hamiltonian for a spin-half system[1]

$$H = g\mu_N \boldsymbol{B}.\boldsymbol{S} = g\mu_N \frac{\hbar}{2}\left(B_x\sigma_x + B_y\sigma_y + B_z\sigma_z\right), \tag{1}$$

where μ_N is the nuclear-magneton, g is the Lande g-factor and σ_i's are the pauli matrices. We can choose the z axis to be in the direction of the magnetic field and we rewrite the Hamiltonian as

$$H = g\mu_N B\frac{\hbar}{2}\sigma_z \tag{2}$$

The eigenvalues of the Hamiltonian are $\pm g\mu_N B$ and we can see that there is an energy gap $\Delta = g\mu_N B\hbar$ between the up-spin state and down-spin state. If you understand this, you have understood NM (nuclear magnetic) part of the NMR, i.e. two thirds of the NMR (Just kidding!). The next step is to understand the resonance. For this, we have to remind ourselves what we studied in school. We learned about two kinds of hydrogen spectra: emission spectra and absorption spectra. Emission spectrum is obtained when electron jumps from the higher

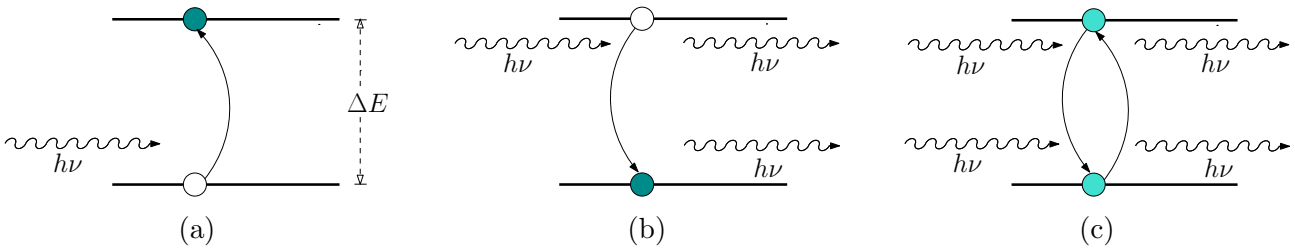


Figure 1: (a) Absorption: A photon of energy $h\nu$ causing transition from lower energy state to higher energy state. (b) Stimulated Emission: A photon causing transition from higher energy state to lower energy state and two photons are emitted in this process. (c) Rabi Oscillation: Long exposure to light causes the electron to oscillate between two energy states. So, during a complete cycle, two photons are absorbed and two photons are emitted.

energy states to lower energy states and emits photons of definite frequencies. On the other hand, absorption spectrum is formed when light causes transition of electron from a lower energy state to higher energy state and a photon of the corresponding frequency is absorbed. We were told that this transition takes place when the frequency of light

$$\nu = \Delta/h, \tag{3}$$

where Δ is the energy gap and h is the Planck's constant. What is not told in school however, is that the same light can cause transition from the higher energy state to lower energy state by emission of *additional* photon of the same frequency ν. This phenomenon was discovered by Einstein and known as stimulated emission[1]. In fact, when the light interacts with the hydrogen atom, the chance of transition from the lower energy state to higher energy state is exactly same as the transition from the higher energy state to lower energy state. So, in presence of the light, the electron in hydrogen atom can oscillates between two energy states, and this is known as Rabi oscillation, named after American physicist Isidor Isaac Rabi[1].

In the case of spin-half system, the same phenomena is observed when we introduce an oscillating magnetic field (remember light is also of similar nature) whose frequency is exactly same (upto a factor of h) as the energy gap between the spin-up and spin-down states

$$h\nu = \hbar\omega = g\mu_N B\hbar. \tag{4}$$

In the presence of this oscillating magnetic field, the nuclear spin oscillates between spin-up and spin-down states. These oscillations of the nuclear spins lead to a rotating magnetic field since the nuclei have a magnetic moment due to their spins. This rotating magnetic field can induce current/voltage if a coil/solenoid is placed around the material, and that is what we call the NMR signal. For a given magnetic field, ω varies from nucleus to nucleus since the Landé g factor and the nuclear spins are different for different nuclei. Moreover, the magnetic field that is 'seen' by the nucleus depends on the electronic environment around the nucleus (electron can screen the magnetic field). That's why NMR can be used to selectively detect specific nuclei in a molecule and to probe their local chemical environments, which in turn allows identification and structural analysis of molecules. It's important to note that not all nuclei have net spin and thus they are not 'NMR active'. The most commonly used nuclei for NMR are ^{1}H, ^{13}C, ^{19}F, ^{31}P, etc.

2 Theory of NMR

Here we will discuss the theory of NMR in details. First let us understand why the nucleus have spins and how is it giving rise to magnetic moment.

2.1 Nuclear Spin

The nucleons which form the nucleus have their own intrinsic spins. Moreover, the nucleons are moving inside the nucleus and can give rise to orbital angular momentum. One need to refer to the 'Shell' model of nucleus for more details about this topic[2]. These angular momentums of the individual nucleons add up and results a net spin angular momentum for the nucleus [3]

$$\mathbf{J}_N = \sum_{p\in\{\text{Protons}\}} \mathbf{L}_p + \sum_{p\in\{\text{Protons}\}} \mathbf{S}_p + \sum_{n\in\{\text{Neutrons}\}} \mathbf{L}_n + \sum_{n\in\{\text{Neutrons}\}} \mathbf{S}_n. \tag{5}$$

Being charged particles, proton's orbital angular momentum $\mathbf{L}_p$ and spin angular momentum $\mathbf{S}_p$ produces magnetetic moment

$$\mathbf{m}_p = g_p^{(l)}\mu_N \mathbf{L}_p + g_p^{(s)}\mu_N \mathbf{S}_p, \tag{6}$$

where $g_p^{(l)}$, and $g_p^{(s)}$ is the Lande g-factor for orbital angular momentum and spin angular momentum respectively. Since the net charge of a neutron is zero, the orbital angular momentum of neutron doesn't contribute to the magnetic moment, however the spin angular momentum does contribute to the magnetic moment (why?)

$$\mathbf{m}_n = g_n^{(s)}\mu_N \mathbf{S}_n. \tag{7}$$

Combining these two contributions, the magnetic moment of the nucleus become

$$\mathbf{m}_N = \sum_{p\in\{\text{Protons}\}} \left(g_p^{(l)}\mu_N \mathbf{L}_p + g_p^{(s)}\mu_N \mathbf{S}_p\right) + \sum_{n\in\{\text{Neutrons}\}} g_n^{(s)}\mu_N \mathbf{S}_n. \tag{8}$$

Since the Lande g-factors are different, the resulting magnetic moment should not be aligned to the total magnetic moment. However, we can approximately say that they are aligned in the same direction

$$\mathbf{m}_N = g\mu_N \mathbf{J}_N, \tag{9}$$

where g is an effective Lande g-factor for the nucleus.

2.2 Rabi Oscillation

Let's now discuss how the nuclear spin behaves in the presence of a fixed and a time varying magnetic field. For simplicity we can work with a two level system comprised of the states $|1\rangle$ and $|2\rangle$. In the context of NMR these states are $|\uparrow\rangle$ and $|\downarrow\rangle$. In the presence of a magnetic field, the Hamiltonian of this two level system

$$H = -g\mu_B B\frac{\hbar}{2}\sigma_z = -\frac{\Delta}{2}\sigma_z \equiv \begin{pmatrix} -\Delta/2 & 0 \\ 0 & \Delta/2 \end{pmatrix}, \tag{10}$$

where $\Delta = g\mu_B\hbar B$. To make the calculation easier we will raise the energy of both states by $\Delta/2$ resulting a Hamiltonian

$$H = -\frac{\Delta}{2}\sigma_z + \frac{\Delta}{2}\sigma_0 = \begin{pmatrix} 0 & 0 \\ 0 & \Delta \end{pmatrix} \tag{11}$$

Now we add a time dependent magnetic field along the x direction leading to a Hamiltonian

$$H = -g\mu_B B\frac{\hbar}{2}\sigma_z + g\mu_B B\frac{\hbar}{2}\sigma_0 + g\mu_B B_{\text{RF}}\frac{\hbar}{2}\sin(\omega t)\sigma_x = \frac{\Delta}{2}\sigma_z + \frac{\Delta}{2}\sigma_0 + \Delta_1\sin(\omega t)\sigma_x \tag{12}$$

This is a time dependent Hamiltonian, so our usual trick for finding the eigenvalues of the matrix won't work in this case. We have to go back to the time dependent Schrodinger equation. Any general quantum state for this two level system is a linear combination of the two basis states

$$|\psi(t)\rangle = c_1(t)\,|1\rangle + c_2(t)\,|2\rangle\,. \tag{13}$$

This state can be represented by a column vector

$$|\psi(t)\rangle \equiv \begin{pmatrix} c_1(t) \\ c_2(t) \end{pmatrix}. \tag{14}$$

Now, substituting the expression of the state into Schrodinger equation results

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} c_1(t) \\ c_2(t) \end{pmatrix} = \begin{pmatrix} 0 & \Delta_1\sin(\omega t) \\ \Delta_1\sin(\omega t) & \Delta \end{pmatrix}\begin{pmatrix} c_1(t) \\ c_2(t) \end{pmatrix}. \tag{15}$$

Writing the above vector equation component-wise we obtain

$$\begin{aligned} i\hbar\frac{\partial c_1(t)}{\partial t} &= \Delta_1\sin(\omega t)c_2(t), \\ i\hbar\frac{\partial c_2(t)}{\partial t} &= \Delta c_2(t) + \Delta_1\sin(\omega t)c_1(t). \end{aligned} \tag{16}$$

We can now substitute $c_1 = b_1$ and $c_2 = b_2 e^{-i\omega t}$ and rewrite the above equations in terms of $b_1(t)$ and $b_2(t)$

$$\begin{aligned} i\frac{\partial b_1(t)}{\partial t} &= \frac{\Delta_1}{\hbar}e^{-i\omega t}b_2(t)\sin(\omega t), \\ i\frac{\partial b_2(t)}{\partial t} &= \left(\frac{\Delta}{\hbar} - \omega\right)b_2(t) + \frac{\Delta_1}{\hbar}b_1(t)e^{i\omega t}\sin(\omega t) \end{aligned} \tag{17}$$

These equations are difficult to solve exactly but we can use the rotating wave approximation to solve it. We write the $\cos(\omega t)$ as $(e^{i\omega t} + e^{-i\omega t})/2$ and ignore the terms with $e^{\pm 2i\omega t}$ since they are rapidly varying term. This approximation modifies the equations to

$$\begin{aligned} i\frac{\partial b_1(t)}{\partial t} &= \frac{\Delta_1}{2i\hbar}b_2(t), \\ i\frac{\partial b_2(t)}{\partial t} &= \left(\frac{\Delta}{\hbar} - \omega\right)b_2(t) - \frac{\Delta_1}{2i\hbar}b_1(t). \end{aligned} \tag{18}$$

We partially differentiate both sides of the second equation with respect to time to obtain

$$\begin{aligned} i\frac{\partial^2 b_2(t)}{\partial t^2} &= \left(\frac{\Delta}{\hbar} - \omega\right)\frac{\partial b_2(t)}{\partial t} - \frac{\Delta_1}{2i\hbar}\frac{\partial b_1(t)}{\partial t} \\ &= \left(\frac{\Delta}{\hbar} - \omega\right)\frac{\partial b_2(t)}{\partial t} + \frac{\Delta_1}{2\hbar}\left(i\frac{\partial b_1(t)}{\partial t}\right) \\ &= \left(\frac{\Delta}{\hbar} - \omega\right)\frac{\partial b_2(t)}{\partial t} - i\frac{\Delta_1^2}{4\hbar^2}b_2(t) \\ &= -\delta\frac{\partial b_2(t)}{\partial t} - i\frac{\Omega^2}{4}b_2(t) \end{aligned} \tag{19}$$

We can write the equation in a bit more readable form

$$\frac{\partial^2 b_2}{\partial t^2} - i\delta\frac{\partial b_2}{\partial t} + \frac{\Omega^2}{4}b_2 = 0, \tag{20}$$

where $\delta = (\omega - \Delta/\hbar)$ and $\Omega = \Delta_1/\hbar$. This equation can now be solved by taking ansatz $b_2(t) = Ae^{imt}$, resulting the algebraic equation

$$m^2 - m\delta - \frac{\Omega^2}{4} = 0 \tag{21}$$

The solution of this quadratic equation is

$$m_\pm = \frac{\delta \pm \sqrt{\delta^2 + \Omega^2}}{2}. \tag{22}$$

The general solution of the problem is given by

$$b_2(\omega t) = Ae^{im_+ t} + Be^{im_- t}. \tag{23}$$

If we now assume that at $t = 0$ all the states were in up-spin state, i.e. $c_1(0) = 1$ then, we get two conditions for the coefficients A and B,

$$A + B = 0 \tag{24}$$

and, using the second equation in 18,

$$\begin{aligned} -Am_+ - Bm_- &= \frac{i\Delta_1}{2\hbar} \\ \implies A(m_- - m_+) &= \frac{i\Delta_1}{2\hbar} \\ \implies A &= \frac{i}{2}\frac{\Omega}{m_- - m_+} \\ \implies \boxed{A &= -\frac{i}{2}\frac{\Omega}{\sqrt{\Omega^2 + \delta^2}}} \end{aligned} \tag{25}$$

So, the final solution for the $b_2(t)$ is

$$b_2(t) = -\frac{i}{2}\frac{\Omega}{\sqrt{\Omega^2 + \delta^2}} e^{i\delta t/2}\left[e^{i\sqrt{\Omega^2+\delta^2}\, t/2} - e^{-i\sqrt{\Omega^2+\delta^2}\, t/2}\right]. \tag{26}$$

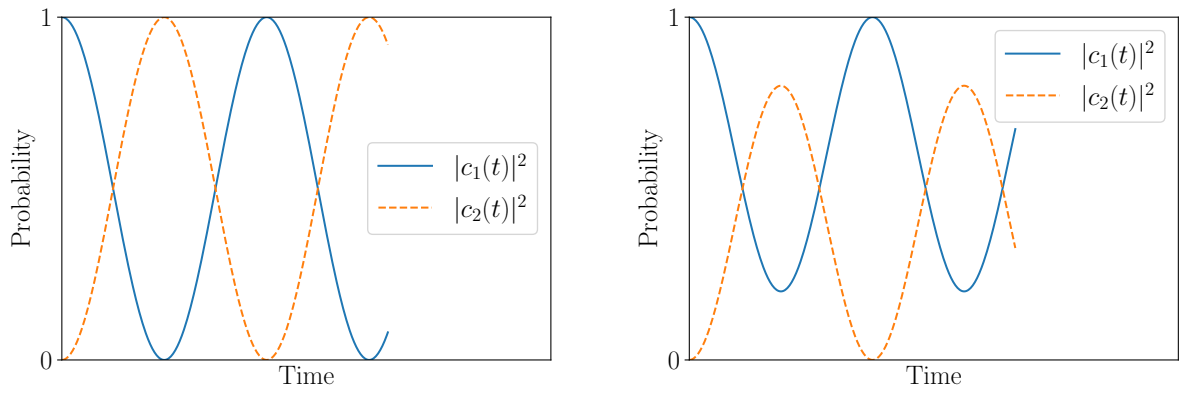
Further simplifying this, we obtain

$$b_2(t) = \frac{\Omega}{\sqrt{\Omega^2 + \delta^2}} e^{i\delta t/2} \sin\left(\frac{\sqrt{\Omega^2 + \delta^2}}{2}\, t\right). \tag{27}$$

What we are interested in is the probability amplitude $|b_2(t)|^2$ which tells us the chance of finding the state in state $|2\rangle$ if we start from state $|1\rangle$,

$$\boxed{|c_2(t)|^2 = |b_2(t)|^2 = \frac{\Omega^2}{\Omega^2 + \delta^2} \sin^2\left(\frac{\sqrt{\Omega^2 + \delta^2}}{2}\, t\right)}. \tag{28}$$

In Fig. 2a, the probability of finding the system in state $|1\rangle$ and $|2\rangle$ has been shown as a function of time. We can clearly see that in the resonance condition $\delta = 0$, the system oscillates perfectly from $|1\rangle$ state to $|2\rangle$ state with time. This oscillation of the system between two states is called the 'Rabi Oscillation'. In the context of *nuclear magnetic resonance*, 'resonance' means, Rabi oscillation between up-spin and down-spin at $\delta = 0$ or in other words, when the perturbative frequency ω matches the frequency corresponding to energy gap Δ.



(a) (b)

Figure 2: Variation of the weights of the state $|1\rangle$ and $|2\rangle$ with time. (a) $\delta = 0.0, \quad \Omega = 1$ (b) $\delta = 0.5, \Omega = 1$

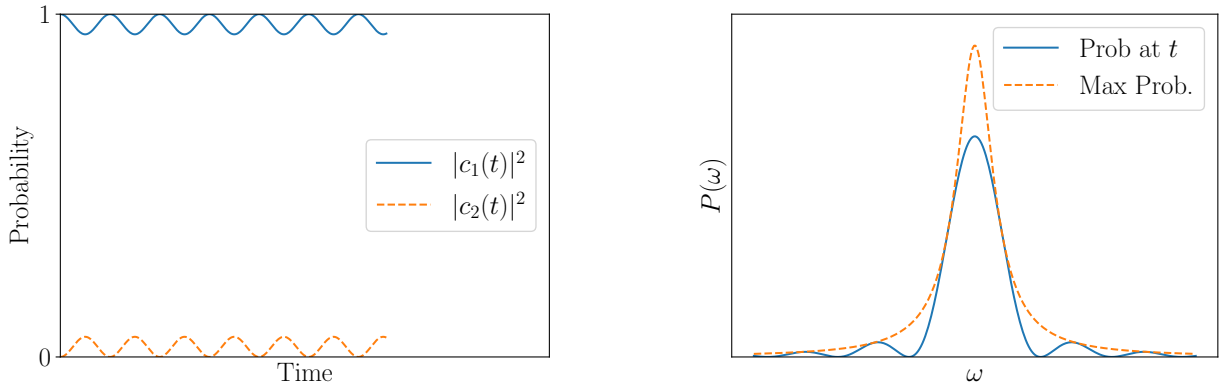
At this point, we must pause and appreciate what we have found here. In the context of hydrogen atom, Rabi oscillation is the reason why electron jumps from the lower energy state to higher energy states when we shine light on hydrogen atoms. Now you can appreciate the fact that in principle, the transition takes place for all possible frequencies. However, the probability of transition is maximum when $h\nu \simeq E_{\text{high}} - E_{\text{low}}$, and the probability is effectively zero for other frequencies. As a result, even though the photons of higher frequencies have enough energy to cause the transition, the transition takes place only for extremely narrow range of frequencies. This is the reason we get dark lines in the absorptions spectrum of hydrogen as shown in 3a.

(a) (b)

Figure 3: (a) Absorption, and (b) emission spectrum of hydrogen.
Source: https://ch301.cm.utexas.edu/section2.php?target=atomic/H-atom/line-spectra.html

Rabi oscillation further suggests that if the system is in higher energy state, because of the time varying perturbation, the system will go to the lower energy state and vice versa. As a consequence, if we shine a light on a hydrogen atom where electron is already in the higher energy state, the electron will jump to the lower energy state and emit a photon of energy equal to the energy gap. This emission is caused by the incident light and the phenomenon is called stimulated emission. This forms the basis of the 'light amplification by stimulated emission of radiation', also known as LASER[1].

In the Fig. 2b, $\delta = 0.5$ case is shown to demonstrate that the Rabi oscillation is not perfect if the frequency of the perturbation doesn't match with the energy gap. In fact, we can plot how the probability of finding the system in state $|2\rangle$ (if we start from state $|1\rangle$) at some later time t varies with δ (see Fig. 4b). Fig. 4b also shows the maximum probability of transition as a function of the detuning parameter $\delta = \omega - \Delta/\hbar$.



(a) (b)

Figure 4: (a)Variation of the weights of the state $|1\rangle$ and $|2\rangle$ with time at $\delta = 4.0$, and $\Omega = 1$ (b) The probability of the transition from the state $|1\rangle$ to the state $|2\rangle$ as function of ω

One can now investigate how exactly this transition is taking place. In case of classical continuous spins, if we change from spin-up state to spin-down state, we must rotate the spin continuously about an axis in the XY plane. This continuous rotation of spin would result some oscillating magnetic field along x or y direction. In the case of Rabi oscillation we can also see if such thing happens. We can calculate the expectation value of the x component of the magnetic moment

$$m_x = \langle g\mu_B \sigma_x \rangle = g\mu_B \langle \sigma_x \rangle = \begin{pmatrix} c_1^*(t) & c_2^*(t) \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} c_1(t) \\ c_2(t) \end{pmatrix} = c_1^*(t)c_2(t) + c_2^*(t)c_1(t). \tag{29}$$

Without even performing any calculation, we can see from the figure 2a that m_x oscillates with the same frequency as the Rabi frequency $\Omega/2$. We can solve the $b_1(t)$ in resonance condition $\delta = 0$ where the expression for $b_2(t)$ simplifies to

$$b_2(t) = -i \sin(\Omega t/2). \tag{30}$$

Substituting the above expression for $b_2(t)$ to

$$i\frac{\partial b_1(t)}{\partial t} = \frac{\Omega}{2} b_2(t), \tag{31}$$

, we obtain,

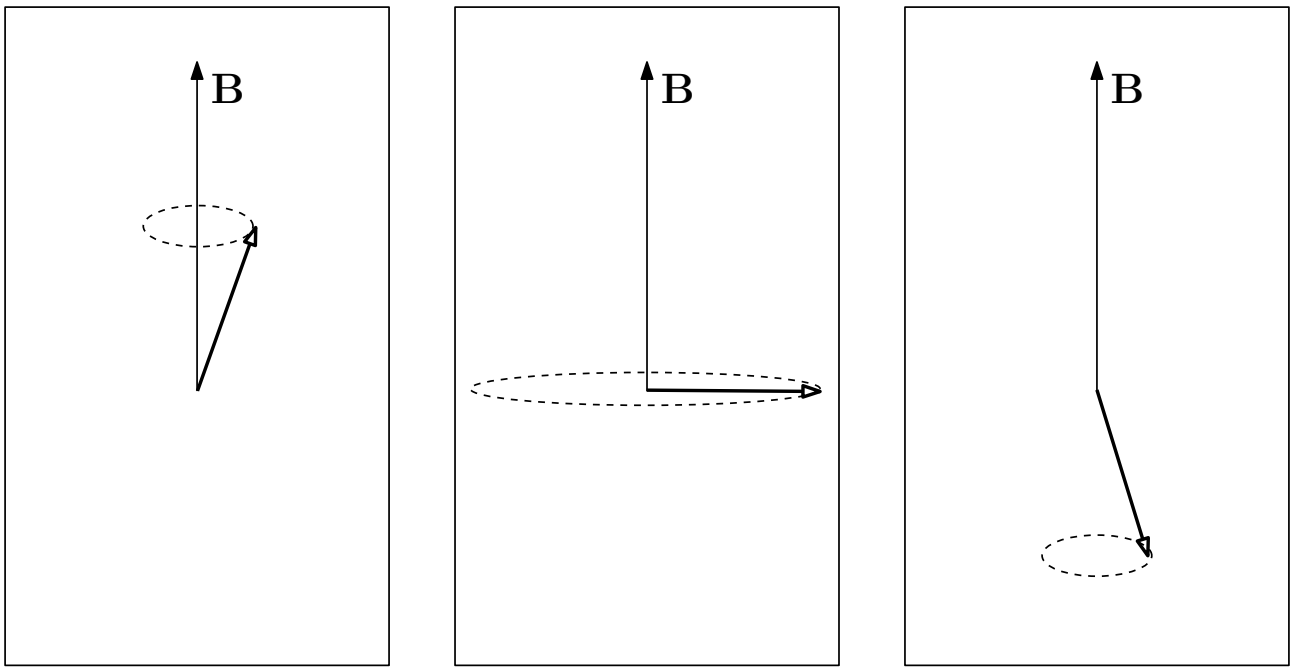
$$\frac{\partial b_1(t)}{\partial t} = -\frac{\Omega}{2} \sin(\Omega t/2). \tag{32}$$

The solution to this is

$$b_1(t) = \cos(\Omega t/2) \tag{33}$$

Now, one can calculate the expectation value of the magnetic moment m_x

$$\begin{aligned} m_x(t) &= b_1(t)b_2^*(t)e^{i\omega_0 t} + b_1(t)b_2(t)e^{-i\omega_0 t} \\ &= \cos(\Omega t/2)\sin(\Omega t/2)\left(ie^{i\omega_0 t} - ie^{-i\omega t}\right) \\ &= -\sin(\Omega t)\sin(\omega_0 t). \end{aligned} \tag{34}$$



(a) (b) (c)

Figure 5: The spin precesses about the Z axis and also slowly rotates from up spin to down spin in the resonance condition. Only half of the Rabi oscillation is shown. (a) $\Omega t = 0$, (b) $\Omega t = \pi/2$, (c) $\Omega t = \pi$

In this case, ω_0 is much larger compared to Ω, thus the m_x oscillates very slowly compared to the frequency of RF signal in the resonance condition. For the completion we can calculate the expectation value of $m_y(t)$ as well

$$\begin{aligned} m_y(t) &= -ic_1^*(t)c_2(t) + ic_2^*(t)c_1(t) \\ &= \sin(\Omega t)\cos(\omega_0 t) \end{aligned} \tag{35}$$

Physically, we can think as if the nuclear spin is transitioning from up spin to down spin with frequency Ω, as well as precessing about the z axis with frequency ω_0, in the resonance condition $\omega_0 = \Delta/\hbar$. The remarkable thing is that if we start from a system where all the nucleus are in up-spin state, then in presence of resonance frequency, all the spins will rotate together causing a detectable rotating magnetic field. This rotating magnetic field can induce a voltage in a coil which can be amplified and analyzed. This ac voltage induced by the Rabi oscillation is the NMR signal.

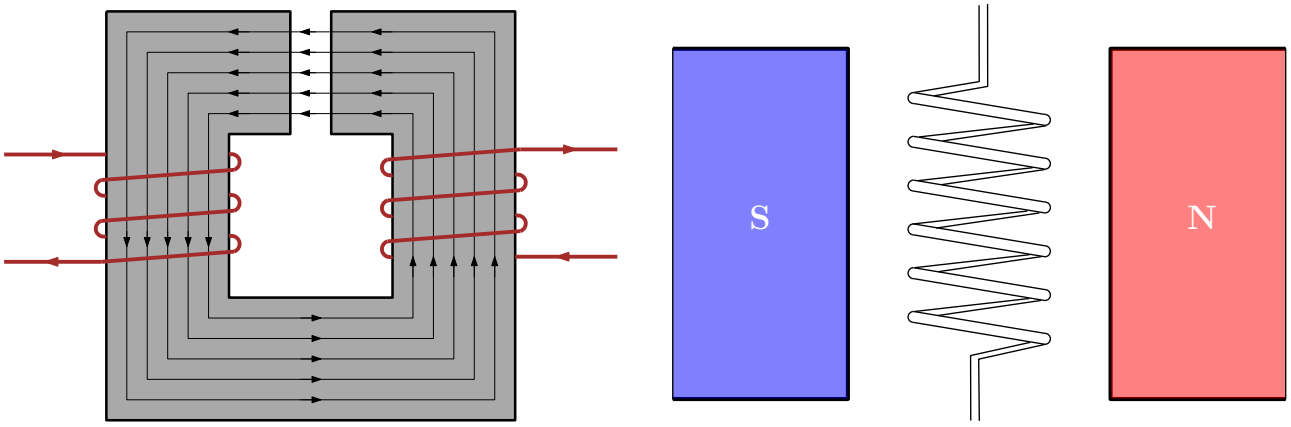
3 Experimental Setup

Let's now discuss how exactly we can perform NMR in an experiment. The first thing we need is a magnetic field B that creates energy gap between two spin states.

3.1 Magnetic Field

For NMR, we need a strong and uniform magnetic field (why?) that can be generated using a C-core electromagnet as shown in Fig. 6a. The current I running through the coil creates a magnetic field [4]

$$B_0 = \mu_{\text{core}} N I, \tag{36}$$



(a) (b)

Figure 6: (a) C-core electromagnet. (b) RF coil placed in the air gap of C-core electromagnet.

where μ_{core} is the magnetic permeability of ferromagnetic core and N is the number of turns in the coil. The magnetic field lines run through the magnetic core and open only at the air gap resulting an uniform magnetic field at the center of the air gap. We place the material in this air gap and the magnetic field causes an energy gap between up-spin and down-spin nucleus. The next thing is to provide an oscillating magnetic field *perpendicular* to the strong magnetic field B_0. The reason why the oscillating magnetic field needs to be in perpendicular direction has been discussed in the previous section.

3.2 RF field

The oscillating magnetic field is generated by a solenoid whose axis is perpendicular to the direction of $\mathbf{B}_0$ (see Fig. 6b). The sample is kept inside the solenoid and a high frequency AC current is passed through the coil which produces a magnetic field

$$B_{RF} = \mu_0 n I_{\text{RF}} \cos(\omega t). \tag{37}$$

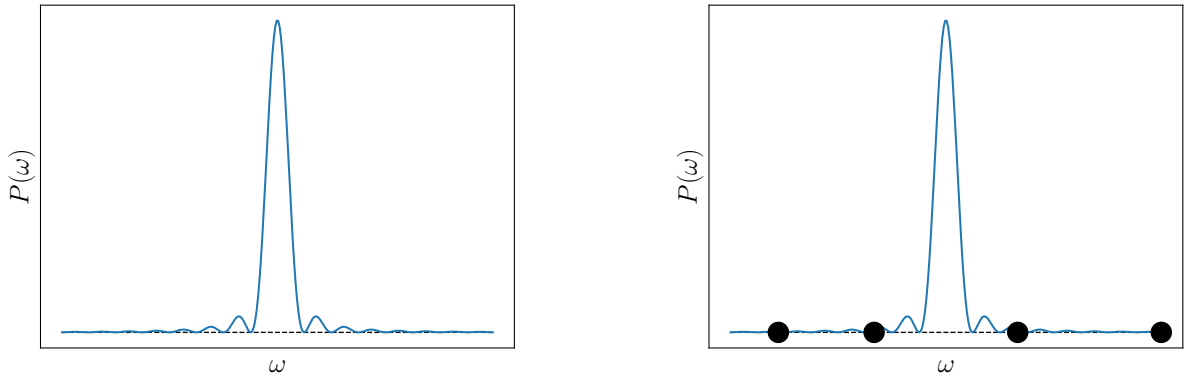
This magnetic field causes the transition between the spin-up and spin-down states with transition probability

$$P_{\text{trans}} = \frac{\Omega^2}{\Omega^2 + (\omega - \omega_0)^2} \sin^2\left(\frac{\sqrt{\Omega^2 + (\omega - \omega_0)^2}}{2}\, t\right). \tag{38}$$

The transition probability is maximum when $\omega = \omega_0 = \Delta/\hbar$ as shown in Fig. 7a. At frequency ω_0, the nuclear spin oscillates between the up and down causing an oscillating magnetic field in the x direction if the fixed magnetic field is along z direction. This oscillating magnetic field induces an EMF in the RF coil in the opposite direction of the RF signal, causing a drop in the amplitude of RF signal between the two ends of the RF coil (recall Lenz's Law). This voltage drop is a signature of the nuclear magnetic resonance.

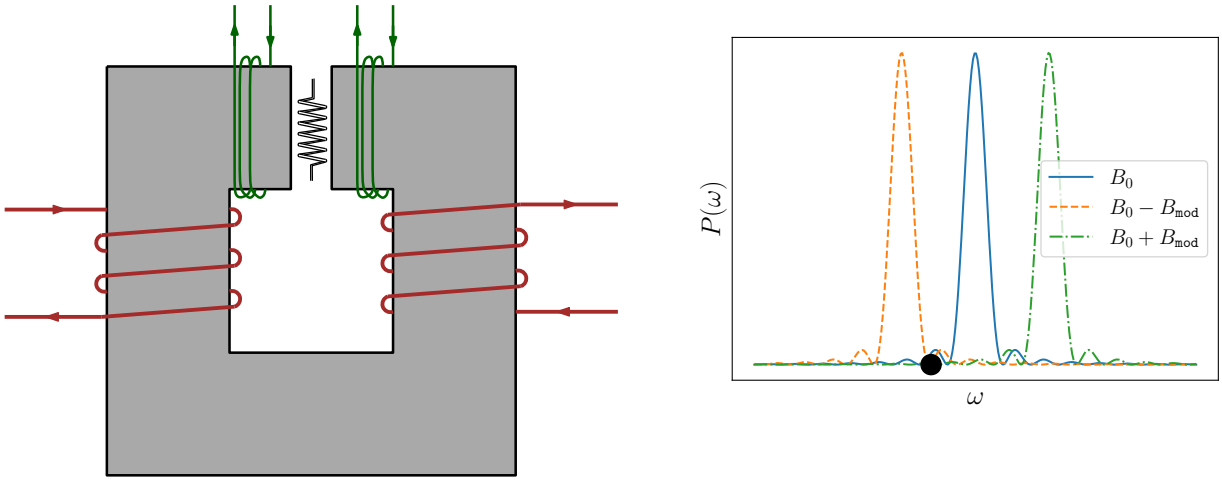
3.3 Observing the Resonance

The amplitude drop in the RF signal (we can call it RF voltage for future reference) occurs when the frequency of the RF field ω matches with the resonance frequency ω_0. So, one can in principle find out the resonance frequency by changing the RF frequency slowly and observing the drop of RF voltage. However, if we change the frequency of the signal by rotating some knob, the frequency doesn't change continuously irrespective of how carefully you do it. So,



(a) (b)

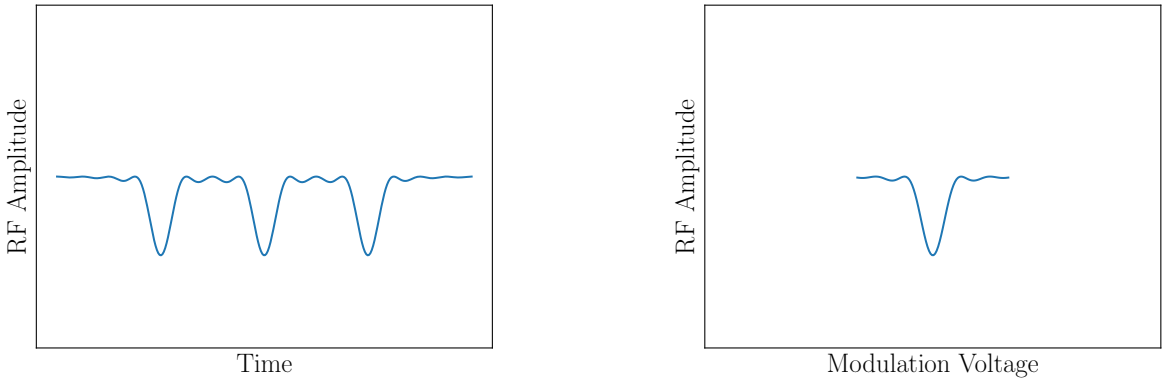
Figure 7: (a) Transition probability as function of the angular frequency. (b) Changing the frequency discretely might miss the resonance frequency. The black circles are representing the frequencies set by the knob.



(a) (b)

Figure 8: (a) The resonance frequency ω_0 changes as the magnetic field is modulated from $B - B_{\text{mod}}$ to $B + B_{\text{mod}}$ continuously. (b) The modulation coils are shown in green.

there is very high chance that one can miss the resonance frequency as demonstrated in the Fig. 7b. One very clever way to detect the resonance is to change the resonance frequency ω_0 continuously by changing the magnetic field. This is done by adding additional coils (known as modulation coil) to the C-core electromagnet as shown in Fig. 8a. The magnetic field B is modulated continuously by sending an extremely low frequency (few hertz) ac current through the modulation coils. This changes the resonance frequency from $\omega_0 - \Delta\omega_0$ to $\omega_0 + \Delta\omega_0$. If the frequency of the RF signal ω (set by rotating a knob) lies in the range of $\omega_0 - \Delta\omega_0$ to $\omega_0 + \Delta\omega_0$, the RF voltage drop occurs whenever the resonance frequency matches with the fixed RF frequency ω (see Fig. 8b). To observe this drop we can plot the amplitude of the RF voltage with time which will have periodic voltage drop as shown in Fig. 9a. In an oscilloscope this can be nicely observed by feeding the modulating signal to channel 1 and the voltage across the RF coil to channel 2 and plotting the channel 1 in X axis and channel 2 in Y axis (see Fig. 9a, 9b).



(a) (b)

Figure 9: (a) Drop in RF amplitude due to resonance. (b) Expected voltage drop in XY mode in oscilloscope.

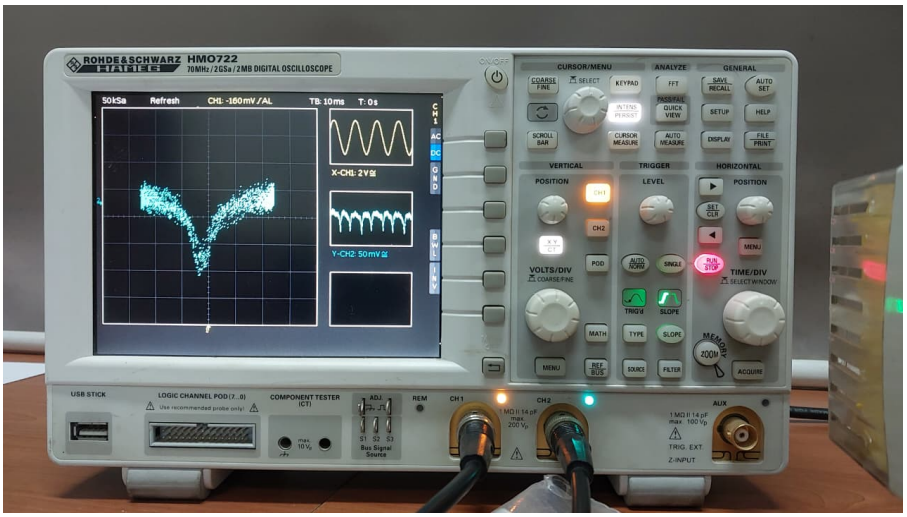


Figure 10: Voltage drop as seen in our lab oscilloscope in XY mode for the Teflon. The modulation signal is fed to CH1 (X) and the NMR signal is fed to CH2 (Y).

Figure 11: The complete experimental setup. Try to identify different parts as discussed above.

References

[1] David J. Griffiths and Darrell F. Schroeter. *Introduction to Quantum Mechanics*. Cambridge University Press, Cambridge, 3 edition, 2018.

[2] Kenneth S. Krane. *Introductory Nuclear Physics*, chapter 2, and 5. Wiley, New York, 1 edition, 1987.

[3] R. Shankar. *Principles of Quantum Mechanics*. Springer, 2nd edition, 1994.

[4] David J. Griffiths. *Introduction to Electrodynamics*. Cambridge University Press, 4th edition, 2017.