

MAGNETIC RESONANCE

Consider a toy top on a table. If it is not rotating, it will immediately fall down because of gravity. If it is spun, however, it will rotate about the z direction keeping the angle θ constant as shown in Fig. 1. Now let a rod-shaped magnet (a nail with a small flywheel) in a magnetic field between the poles be the long axis R at an angle θ from the direction z of the field,

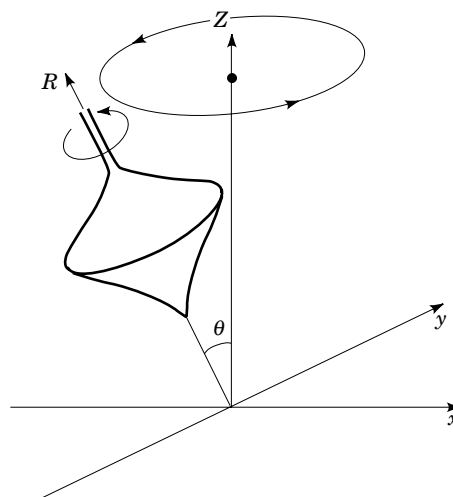


Figure 1. Precession of a top.

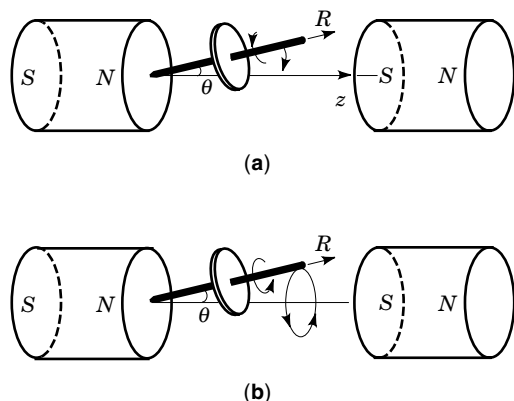


Figure 2. Small iron rod (nail) in magnetic field. To avoid the gravitational effect, the long axis is along the horizontal direction.

as shown in Fig. 2(a). It will tend to align in parallel like a magnetic compass with the line of magnetic force. If one spins it about the long axis R , however, it will rotate about z , keeping θ constant as shown in Fig. 2(b). Both of these motions are called precession and are perpetual in the absence of friction. In this case, the toy top or the rod-shaped magnet has angular momentum, and the direction of force is perpendicular to the plane defined by R and z . This force is called torque. The precession occurs also on a microscopic scale. Consider a single free electron or a single proton in a uniform field H_0 along the z axis. It has a magnetic dipole moment μ_e or μ_N , respectively, which is considered to be a tiny magnet. In this case, one does not need to spin it because it has an angular momentum a priori, and the magnetic moment is caused by the rotation of the charged particle. Because of this angular momentum, it exhibits similar motion in a magnetic field as earlier and as shown in Fig. 3. This motion is called Larmor precession. The frequency of the Larmor precession is derived from the following torque equation, which is similar to the case of a top:

$$\frac{d\mu}{dt} = \gamma[\mu \times \mathbf{H}] \quad (1)$$

where γ is a coefficient called the gyromagnetic ratio and μ is either μ_e or μ_N . \mathbf{H} is the magnetic field described as $\mathbf{H} = (0, 0, H_0)$. Equation (1) can be solved easily. The z component of Eq. (1) is

$$\frac{d\mu_z}{dt} = 0 \quad (2)$$

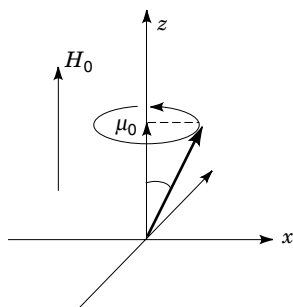


Figure 3. Precession of a magnetic moment μ .

Then one finds that μ_z , which is the z component of μ , is constant. The magnitude of μ_z depends on the initial condition and is unknown here. μ is also unknown but is given by $\cos \theta = \mu_z/|\mu|$. This is reasonable and easily understood by Fig. 3. The x and y components of Eq. (1) are described as

$$\frac{d\mu_x}{dt} = \gamma\mu_y H_0, \quad \frac{d\mu_y}{dt} = -\gamma\mu_x H_0 \quad (3)$$

From these equations, one can obtain

$$\mu_x + i\mu_y \propto \exp(-i\gamma H_0 t) = \cos(\gamma H_0 t) - i \sin(\gamma H_0 t) \quad (4)$$

This means that the magnetic moment rotates about the z axis in the direction of a right-handed screw for $\gamma < 0$ (in the case of an electron) or the opposite way for $\gamma > 0$ (in the case of a proton) with an angular frequency

$$\omega_0 = |\gamma|H_0 \quad (5)$$

where ω_0 is called the Larmor frequency. As will be explained later, γ is expressed as

$$\gamma = g \frac{\mu_0 e}{2m} \quad (6)$$

where g is the so-called g -value and equal to $g_e = 2.0023$ for an electron and $g_N = 2.7896$ for a proton. e and m are the charge, which is negative for electrons and positive for protons, and the mass of the particle, respectively. μ_0 is the permeability of vacuum. The frequencies are easily calculated using $\omega = 2\pi f$ and are approximately

$$f_0 = 28.0 \text{ GHz} \quad \text{and} \quad f_0 = 42.6 \text{ MHz} \quad \text{at} \quad B_0 = \mu_0 H_0 = 1 \text{ T} \quad (7)$$

for moments of electrons and protons, respectively. Notice that the mass of the nucleus depends on the atom and that the g of the other nucleus is different from that of the proton.

When an ac magnetic field (electromagnetic wave at radio frequency) perpendicular to the z -axis with amplitude h_{rf} whose frequency and polarization satisfy Eqs. (4) and (5) is applied, what is its effect on the magnetic moment? First, consider a magnetic moment without an ac field in a coordinate system $x'y'z$ rotating about the z axis with ω_0 as shown in Fig. 4(a). The magnetic moment points to the fixed direction in the $x'z$ plane keeping the angle θ constant and never moves in this coordinate system. When an ac field is applied, \mathbf{H} in Eq. (1) must be replaced by $\mathbf{H} = (h_{rf} \cos \omega_0 t, h_{rf} \sin \omega_0 t, H_0)$. The magnetic moment starts to rotate about the y' axis in the $x'z$ plane as shown in Fig. 4(b) in the rotating coordinate system. θ is no longer constant in this case and changes as a function of time as $\theta = 2\pi f_r t + \theta_0$, where θ_0 is the initial angle and f_r is the repetition rate given by

$$2\pi f_r = \gamma h_{rf} \quad (8)$$

In a fixed coordinate system this means that first the precession is accelerated absorbing the electromagnetic wave power with increasing amplitude of μ_x and μ_y and with decreasing μ_z , and then with decreasing amplitude of μ_x and μ_y and with increasing μ_z toward the $-z$ direction as shown in Fig. 4(c) as

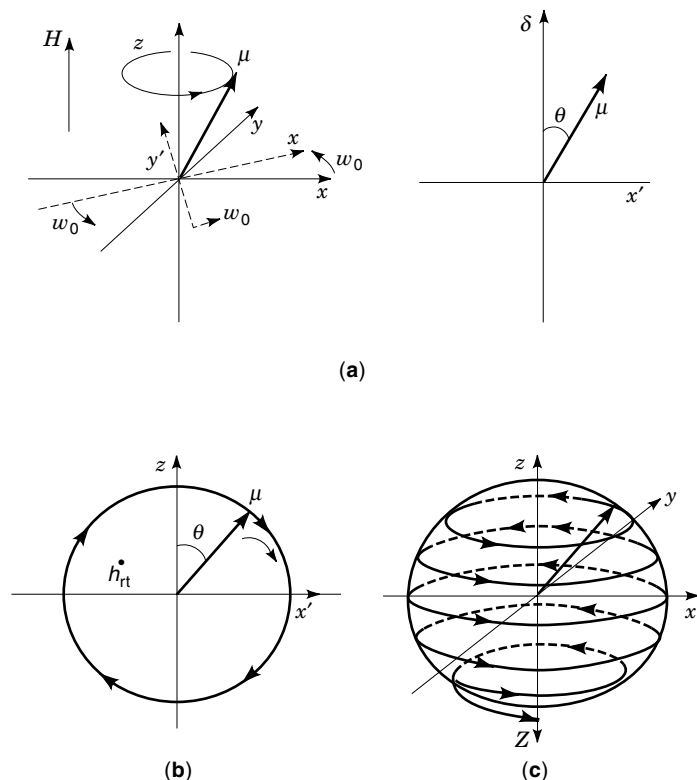


Figure 4. (a) Precession in the rotating coordinates $x'y'z'$ without h_{rf} , (b) rotation of μ in the $x'z'$ -plane with h_{rf} , and (c) trajectory of the top of μ .

the trajectory of the top of the moment. As soon as μ completely points in the $-z$ direction, it returns until μ points in the z direction emitting electromagnetic wave power this time. Neither absorption nor emission occurs on average. Usually f_r is much smaller than f_0 , so the real precession not like that in Fig. 4(c), (i.e., f_0 is 10^4 times greater than cycle of f_r). This phenomenon is called magnetic resonance in general and more directly electron spin resonance (ESR) or nuclear magnetic resonance (NMR) depending on which moment is in question. Magnetic resonance occurs when the frequency of the ac field coincides with the Larmor frequency.

As mentioned earlier, the magnetic moment of an electron is caused by the angular momentum of the electron. If one calculates μ classically, assuming that an electron is a uniformly charged sphere with radius r rotating with angular frequency ω , then μ is obtained as

$$\mu = -\frac{\mu_0 e \omega r^2}{2} = -\frac{\mu_0 e}{2m_e} L \quad (9)$$

where e and m_e are the charge and mass of an electron, respectively, and $L = m_e \omega r^2$ is the angular momentum of an electron. We now must introduce quantum mechanics. According to this theory, L must be given by $L = s\hbar$ using Planck's constant \hbar , where s is called the spin angular momentum quantum number or simply the spin and $s = 1/2$. This means an angular momentum of an electron can be only $\hbar/2$ or $-\hbar/2$. From the theory of quantum mechanical electrodynamics, however, it has been shown that g_e must be

multiplied by Eq. (9) for the magnetic moment of an electron. Then the relation between the magnetic moment of electron μ_e and spin s is

$$\mu_e = g_e \mu_B s \quad (10)$$

where

$$\mu_B = -\frac{\mu_0 e \hbar}{2m_e} = 1.165 \times 10^{-29} [\text{Wb} \cdot \text{m}] \quad (11)$$

is the unit of the magnetic moment of an electron and is called the Bohr magneton. The energy of the magnetic moment in a field is $-\mu_e H$, which is called Zeeman energy. Then the Hamiltonian described by the energy in quantum mechanics is written as

$$H = -g_e \mu_B H s \quad (12)$$

Because of $s = 1/2$ for an electron, only eigenstates of $\pm 1/2$ are allowed. The energy states are then shown in Fig. 5(a), and the energy difference between these two levels is

$$\Delta E = g_e \mu_B H \quad (13)$$

In an electromagnetic wave whose frequency satisfies $\hbar\omega = \Delta E$, the electron at the ground state is excited to the upper state absorbing the electromagnetic wave energy as shown in Fig. 5(b) and then immediately comes back to the ground state emitting an electromagnetic wave as shown in Fig. 5(b) because the transition probabilities of both transitions are identical. No energy dissipation occurs in this model. This phenomenon corresponds to that explained in Fig. 4. Equation (5) is also obtained from this argument. In the case of a proton, g_e and μ_B must be replaced by $g_N = 2.7896$ and

$$\mu_N = \frac{\mu_0 e \hbar}{2m_p} \quad (14)$$

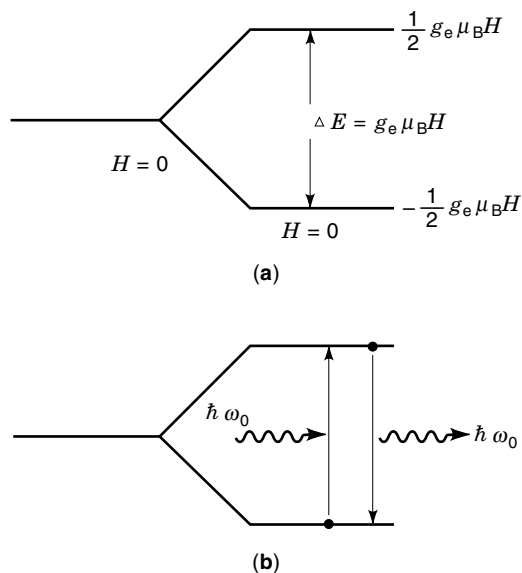


Figure 5. Schematic energy levels of a spin in magnetic field.

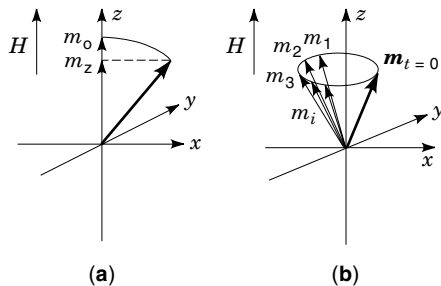


Figure 6. (a) z component of \mathbf{m} increases up to m_0 in a time scale of T_1 . (b) All moments start simultaneously at $t = 0$, but they diffuse in a time scale of T_2 . m_1, m_2, \dots, m_i are each moment.

where m_p is the mass of proton. In this case, $\gamma_N = -g_N\mu_N/\hbar$ is positive because the charge of the proton is positive. In the case of an electron in an atom, it has an orbital motion around the nucleus, and it also contributes to the magnetic moment. But it is not mentioned here for simplicity.

In real materials, the magnetic resonance phenomenon is more complicated because an electron or a nucleus is located in an atom or a molecule and is no longer free. In this case, we deal with the magnetic moment \mathbf{m} , which is the average or sum of all moments on lattices in the material. Each magnetic moment in a material interacts with other moments on other lattices and with lattice vibrations (phonons). These interactions cause the relaxation phenomenon, which is another important aspect of magnetic resonance. Because of the relaxation, energy dissipation occurs in the resonance condition, and we can observe the magnetic resonance as the absorption of applied electromagnetic wave power. If a magnetic moment undergoes friction during precession, the amplitude of oscillation is supposed to damp and finally the moment becomes parallel to the z axis as shown in Fig. 6(a) instead of as shown in Fig. 3. In this case, m_z increases as a function of time t and reaches full length $m_0 = |\mathbf{m}|$ finally. Assuming that the time rate is constant and defined as T_1 , one can rewrite the equation of motion given by Eq. (2) as

$$\frac{dm_z}{dt} = -\frac{m_0 - m_z}{T_1} \quad (15)$$

and obtain $m_0 - m_z = \Delta m \exp(-t/T_1)$, where Δm is the initial difference. Because this damping comes from the interaction between spin motion and lattice vibration and then corresponds to direct dissipation of energy to the lattice, T_1 is called as “spin-lattice relaxation time” or simply pronounced “tee-one.” On the other hand, the x, y components of the averaged magnetic moment m_x and m_y have a finite magnitude when each magnetic moment starts to rotate about the z axis simultaneously at $t = 0$. However, because of interactions between magnetic moments (mainly magnetic dipole interaction), the local magnetic field acting on each magnetic moment and consequently the Larmor frequency varies from site to site in the material. Then the phase of precession of each magnetic moment randomly distributes, as shown in Fig. 6(b). This effect results in decay of the x, y components of the averaged magnetic moment m_x and m_y , which finally becomes 0. The characteristic time of this decay is defined as T_2 , and this is considered to be faster than T_1 because T_2 also includes the energy dissipation effect in addition to the dephasing effect of

precession. This effect modifies Eq. (3) as

$$\frac{dm_x}{dt} = \gamma m_y H_0 - \frac{m_x}{T_2}, \quad \frac{dm_y}{dt} = \gamma m_x H_0 - \frac{m_y}{T_2} \quad (16)$$

Equations (15) and (16) are called the Bloch equations. From these equations, one can easily obtain

$$m_x + im_y \propto \exp\left(-i\omega_0 t - \frac{t}{T_2}\right) \\ = [\cos(\omega_0 t) - i \sin(\omega_0 t)] \exp\left(-\frac{t}{T_2}\right) \quad (17)$$

where $\omega_0 = \gamma H_0$ is used. T_2 is called the spin-spin relaxation time or simply “tee-two.” This is the same as a damping oscillation. The general theory, which deals with the relaxation phenomenon more exactly, is difficult and more complicated. Because of these relaxation phenomena, the magnetic moment finally points to the z direction even if it starts to precess from some angle θ , and the magnitude of m is not kept constant during the precession because of the difference of T_1 and T_2 . When an ac field $h_{rf} e^{i\omega t}$ is applied perpendicularly to the z direction, the averaged magnetic moment \mathbf{m} , which first points into the z direction starts to rotate at $\omega = \gamma H_0$ and θ increases. If $(\gamma h_{rf} T_1 T_2)^2 \ll 1$ (usually this condition is valid for ESR), not like Fig. 4(c), the Larmor precession becomes stationary, and the tilting angle θ is small. If $(\gamma h_{rf} T_1 T_2)^2 \gg 1$ (sometime this condition is valid for NMR), the Larmor precession is similar to Fig. 4(c). It is, however, complicated to solve the equation of motion precisely. It should be emphasized in this case that applied power of the ac field is absorbed at resonance condition by the spin system, and the absorbed power transmitted as lattice vibrations of the material via the relaxation mechanisms. This process results in temperature increase of the material. Resonance occurs not only exactly at $\omega = \gamma H_0$ but also at frequencies near $\omega = \gamma H_0$. The distribution of the resonant frequency, namely response intensity or spectrum of the characteristic oscillation as a function of ω , is obtained by the Fourier transformation of Eq. (17) as

$$1(\omega) \propto \frac{1}{(\omega - \omega_0)^2 + \left(\frac{1}{T_2}\right)^2} \quad (18)$$

and it shows a Lorentzian line shape with a half width of $\Delta\omega = 1/T_2$ (or full half width $2/T_2$) as shown in Fig. 7. By sweeping frequency of the electromagnetic wave and by observing the power dissipation in the material as a function of frequency, one can see that magnetic resonance with a line

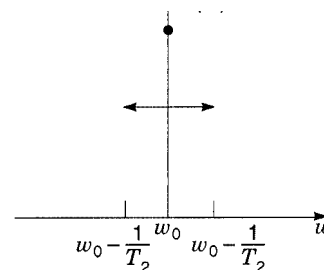


Figure 7. Spectrum of damping oscillation is Lorentzian.

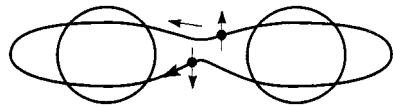


Figure 8. Electrons in hydrogen molecule moving opposite in an orbit with magnetic moments caused by spins, as indicated by arrows.

shape of Fig. 7 occurs. The experimental method will be discussed later.

ELECTRON PARAMAGNETIC RESONANCE

To observe electron spin resonance, there must be isolated and independent electrons in the system. Namely, the materials we are considering must be composed of atoms or molecules that have magnetic moments. Every atom or molecule, however, does not necessarily have a magnetic moment. Electrons in an atom or in a molecule strongly couple with each other, and usually spin and orbital angular momenta are compensated by making pairs of electrons. For example, a hydrogen atom has only one electron, but it becomes a molecule when coupling with another hydrogen atom, and the angular moments of two electrons in a molecule are directly opposite as shown in Fig. 8. Then the molecule has no magnetic moment. The helium atom has two electrons whose spin and orbital angular moments are also compensated. In this manner, the net magnetic moment for most atoms and molecules disappears as a result of pairing by the strong intraatomic or intramolecular electron correlation that cancels spins and orbits. For example, in the case of iron group atoms (i.e., Sc, Ti, V, Cr, Mn, Fe, Co, Ni, and Cu in the periodic table), spin and orbital angular moments of electrons are not compensated because of Hund's rule, which was a result of the quantum mechanics. This means that these atoms have an unpaired electron and have magnetic moments. Figure 9 shows the example of Mn^{2+} and Cu^{2+} . For compounds that have these atoms as divalent or trivalent ions, the magnetic moments are isolated, and ESR can be observed. These ions are called paramagnetic ions and the ESR concerning these ions is called electron paramagnetic resonance (EPR). The atoms belonging to the palladium group, platinum group, and rare earth group also have similar properties. In these

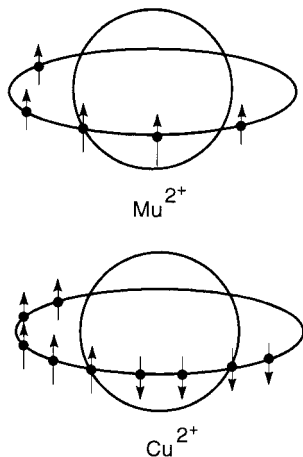


Figure 9. Electrons in 3d orbit in Mn^{2+} and Cu^{2+} ions.

ions, the orbital motion of electrons caused by orbital angular momentum creates a magnetic field acting on the magnetic moment caused by spin angular momentum or vice versa. So the orbital angular momentum and spin angular momentum are not completely independent. This effect is called spin-orbit coupling, and this interaction energy is of the order of 10^{-21} J. A paramagnetic ion in compounds is usually surrounded by negative ions called anions, which make a strong electric field called a crystalline field on the paramagnetic ion at the center. The energy of the crystalline field for an electron is on the order of 10^{-19} J. The electrons in the paramagnetic ion suffer electric fields from both the central nucleus and surrounding anions, and the motion of the electrons are no longer simple orbital motions. This effect gives rise to a reduction of orbital angular momentum, which is called quenching. Then the contribution of the orbital angular momentum to the magnetic moment is small and the magnetic moment μ per ion is usually expressed as

$$\mu = g\mu_B S \quad (19)$$

where S is the total spin. This is, for example, $S = 5/2$ or $S = 1/2$ for our Mn^{2+} or Cu^{2+} ion, respectively, as easily is understood by Fig. 9. g is the so-called g -value, which reflects the effects of spin-orbit coupling and the crystalline field and is different from g_e depending on the material.

Paramagnetic ions in a crystal interact with each other by dipole interaction and exchange interaction. These interactions give rise to dephasing of Larmor precession, as mentioned previously, and result in the width of the absorption line as $1/T_2$. If the dipole interaction is dominant, the half width is approximately given by

$$\Delta\omega = 1/T_2 \cong \omega_d \quad (20)$$

where ω_d is the sum of dipole interaction divided by \hbar . The sum is over all magnetic moments on the crystal lattice. If the exchange interaction is larger than the dipole interaction, the half width is approximately given by

$$\Delta\omega = 1/T_2 \cong \omega_d^2/\omega_e \quad (21)$$

where ω_e is the nearest neighbor exchange interaction divided by \hbar .

The unpaired electron is also realized in organic materials as the free radical, in semiconductors as the donor or acceptor impurity, and in color centers as some special molecules like O_2 or NO . By studying EPR, one can obtain microscopic information about materials via g -value and line width.

HOW TO OBSERVE EPR (EXPERIMENTAL METHOD)

A simple method to observe EPR is described here. The equipment necessary for this experiment is an oscillator, a detecta cavity, and a magnet. The Larmor frequency of electron spin is in the microwave region at an easily available magnetic field, namely $B = 0.1$ to 1 T, as discussed, see Eqs. (5) and (7). The most popular way is to use X-band microwaves whose wave length is around 3 cm because the size of microwave components is moderate, and the resonance field is about 0.3 T. A Gunn oscillator with detector is now commercially available and most convenient for this purpose. This

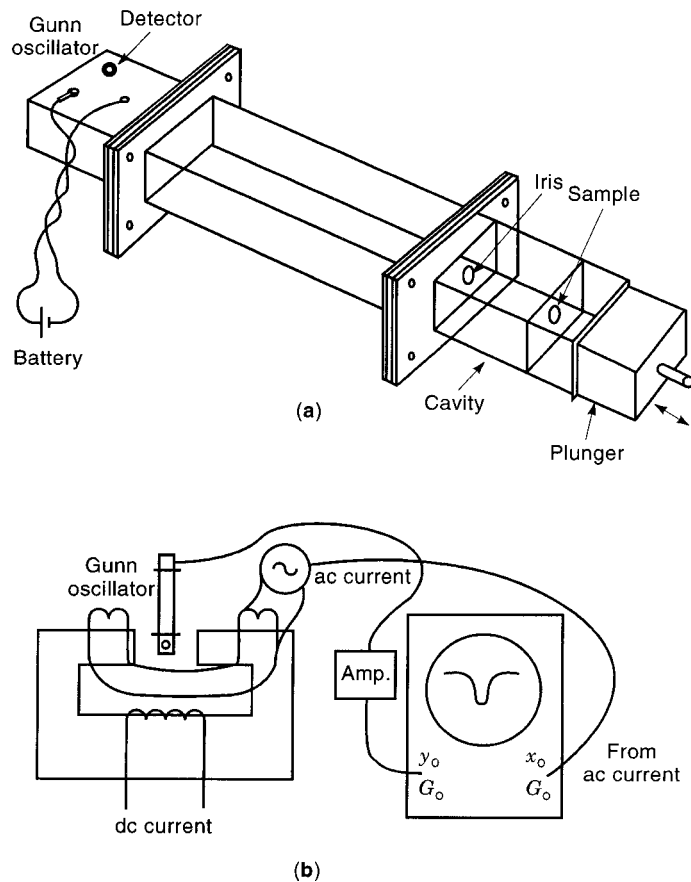


Figure 10. Experimental set-up to observe EPR.

oscillator is commonly used for detection of speeding automobiles by policemen. Assemble the equipment as Fig. 10(a). The Gunn oscillator is connected with a short wave guide and terminated by a cavity. First, operate the Gunn oscillator and tune the cavity by moving a plunger so as to resonate at the oscillator frequency. A sample [A small amount of DPPH (α, α -diphenyl- β -picryl hydrazyl) may be good as a test sample] is put in advance on the bottom of the cavity where the high-frequency magnetic field is strongest. Install the cavity between the poles of the magnet as shown in Fig. 10(b). A low-frequency ac (50 Hz or high) field of a few hundred microteslas must be superposed on the main dc field by modulation coils. Then sweep a magnetic field up to about 0.3 T. In this discussion, the absorption spectrum is given as a function of frequency at constant field. In the real experiment, however, changing frequency is so difficult that usually a magnetic field is swept at constant frequency. The detected signal through an amplifier is displayed on an oscilloscope as shown in Fig. 10(c). The resonance absorption line is obtained as a function of magnetic field and the half width of the resonance line must be converted by

$$\Delta H = \frac{\Delta\omega}{\gamma} \quad (22)$$

FERROMAGNETIC RESONANCE

In the case of ferromagnetic materials, all magnetic moments point to same direction below a certain temperature T_c be-

cause of the strong exchange interaction among magnetic moments. The transition temperature T_c is called the Curie temperature. At a temperature sufficiently below T_c , the average magnetic moment m saturates and the total magnetic moment M of the specimen is given by

$$M = Ng\mu_B S \quad (23)$$

where N is the magnetic moment per unit volume in the specimen. The magnitude of M is comparable to the applied flux density $B_0 = \mu_0 H_0$, whereas in the case of paramagnetic materials, the averaged moment m is about 10^{-3} of the saturation moment at room temperature and at 1 T as a result of thermal fluctuation. Then the magnetic moments experience a field produced by themselves pointing in the opposite direction to the applied field. This field is called the demagnetizing field, and it must be taken into account when the equation of motion is solved. The field acting on the magnetic moment M including demagnetizing field is given for each direction as

$$H_x = -N_x M_x, \quad H_y = -N_y M_y, \quad H_z = H_0 - N_z M_z \quad (24)$$

where N_s are the demagnetizing factor and $N_x + N_y + N_z = 1$ and H_0 is parallel to the z axis. From the equation of motion

$$\frac{d\mathbf{M}}{dt} = \gamma[\mathbf{M} \times \mathbf{H}] \quad (25)$$

one can obtain the resonance conditions as

$$\frac{\omega}{\gamma} = \sqrt{\{H_0 + (N_y - N_z)M_z\}\{H_0 + (N_x - N_z)M_z\}} \quad (26)$$

When the sample shape is spherical, $N_x = N_y = N_z = 1/3$, then

$$\frac{\omega}{\gamma} = H_0 \quad (27)$$

In the case of a thin disk, $N_x = 1, N_y = N_z = 0$ or $N_x = N_y = 0, N_z = 1$ for an applied field parallel or perpendicular to the disk surface, respectively. In the case of a thin rod, $N_x = N_y = 1/2, N_z = 0$ or $N_x = 0, N_y = N_z = 1/2$ for an applied field parallel or perpendicular to the rod, respectively. To observe the absorption of ferromagnetic resonance, there must be energy dissipation caused by the relaxation mechanism. Different from the case of paramagnetic resonance, however, the magnetic moments are tightly bound to each other, and no dephasing effect in the xy plane is expected. So we cannot define T_2 . Instead, the Landau-Lifshitz damping model is introduced for the ferromagnetic resonance. The equation of motion is described as

$$\frac{d\mathbf{M}}{dt} = \gamma[\mathbf{M} \times \mathbf{H}] - \lambda_L[\mathbf{M} \times [\mathbf{M} \times \mathbf{H}]] \quad (28)$$

where λ_L is the Landau-Lifshitz damping factor. This means that the direction of the second term is perpendicular to the direction of \mathbf{M} in the plane made by \mathbf{M} and \mathbf{H}_0 . Then the motion of the total magnetic moment \mathbf{M} is a damping oscillation

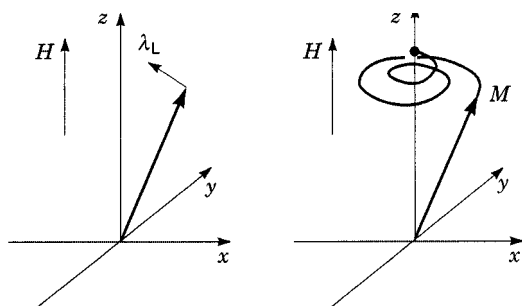


Figure 11. Direction of Landau–Lifshitz term and precession of ferromagnetic moment M .

as shown in Fig. 11. In this case, the length of M is kept constant, whereas in the case of paramagnetic resonance, the relaxation times T_1 and T_2 are independent, and the length of the averaged moment m is not constant during the motion. The magnitude of λ is related to the interaction between the motion of magnetic moments and lattice vibration and then the energy of the Larmor precession is transferred to the lattice vibration via this mechanism. The line width of FMR is expressed using this damping factor as

$$\Delta H = \frac{MH_0}{\gamma} \lambda_L \quad (29)$$

NUCLEAR MAGNETIC RESONANCE

In the case of nuclear spin, interactions with surrounding electrons, lattice vibration (phonon), other nuclear spins are weak, and a nuclear spin is considered to be almost isolated, which means that γ is almost constant and different from the

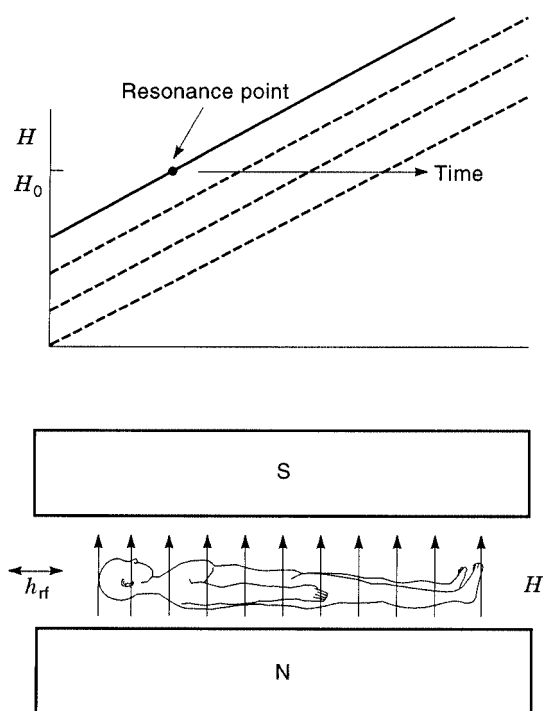


Figure 12. Schematic view of MRI.

case of EPR. The magnetic interactions with surrounding electrons can be replaced by the effective field H_{eff} which is included in Eqs. (1) and (5) as additional fields. Interactions also contribute to the change of relaxation time from that of free nucleus. Observing the shift of resonance frequency caused by this effective field and the change of relaxation time, one can obtain information about the microscopic behavior of materials. This is the reason why NMR is so useful as a probe to investigate properties of materials. Every nucleus does not necessarily have nuclear spin, and γ varies depending on the nucleus. All γ are listed in a standard table. NMR of copper nucleus is useful to investigate high T_c superconductors composed of copper oxide. Mn and Co nuclei are also important to study magnetic properties of materials composed of these atoms.

The most popular nucleus is the proton, which is the nucleus of hydrogen. All materials containing hydrogen show proton NMR. Water is the best example. To investigate molecular structures of organic molecules, polymers, proteins, and other biological materials, the proton NMR is useful and is now being used widely. In these cases, the absorption spectra of proton NMR have a complicated structure as a result of interactions with neighboring atoms. By analyzing the structure of spectra, one can determine the molecular structure like neighboring atoms and distance. Because the resolution increases with increasing resonance frequency, high-field and high-frequency NMR is more useful, and now frequencies higher than 750 MHz are available in fields above 17 T by using high homogeneous superconducting magnets.

Magnetic resonance imaging (MRI) is well known as an important tool in finding tumors or other abnormal tissue in the human body. Every cell in organs contains hydrogen atoms and NMR is observable in any part of the body. But the shift or relaxation time varies depending on the organ. As shown in Fig. 12, a body is placed between the poles of a big magnet and h_{rf} is applied to it. The magnetic field has a gradient with respect to the position of the body, and the NMR is observed at only one point on the body. This gradient field is scanned, and the resonance point moves from head to foot. By analyzing the data by a computer, one can see the structure of the body. If the organ is abnormal, the density and relaxation times of NMR at the affected part are different from those at a normal part. This allows NMR is used for diagnosis.

BIBLIOGRAPHY

1. A. Abragam, *The Principle of Nuclear Magnetism*, New York: Oxford, 1961.
2. G. E. Pake, *Paramagnetic Resonance*. New York: W. A. Benjamin, 1962.
3. C. P. Slichter, *Principle of Magnetic Resonance*. New York: Harper & Row, 1963.

MITSUHIRO MOTOKAWA
Tohoku University