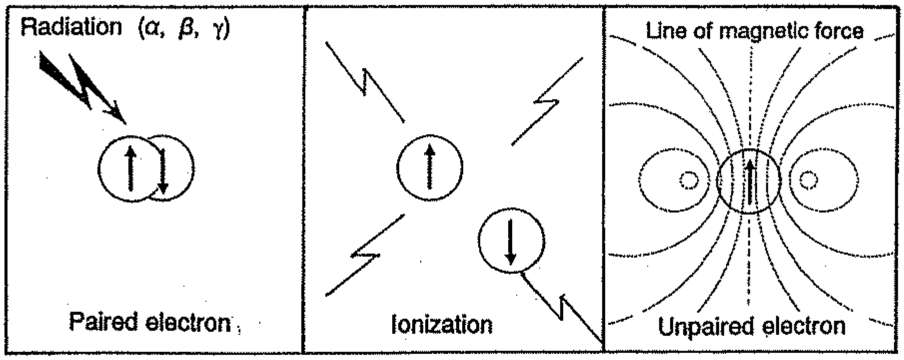


Figure 2.1 (a) Nonmagnetic paired electrons and radiation, (b) Ionization and (c) Formation of an unpaired electron. The self rotation (spin) of a negatively charged sphere of an unpaired electron acts as a small magnet. Magnetic field is produced in the vicinity of an unpaired electron. Defects with unpaired electrons are called *paramagnetic defects*.

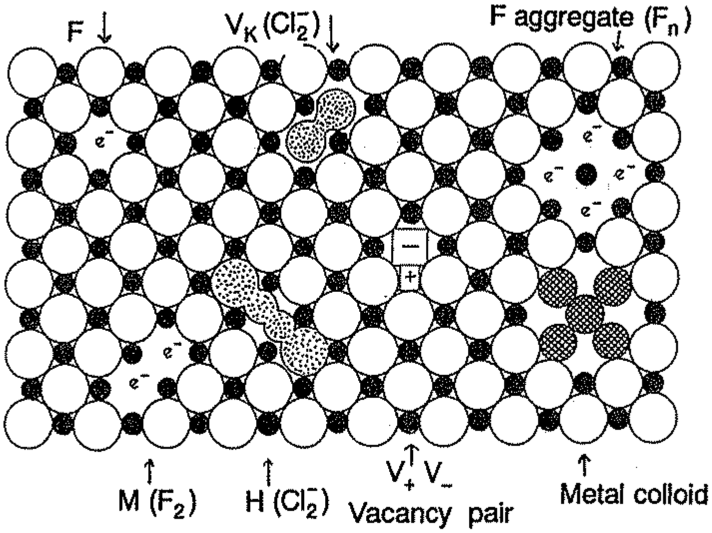
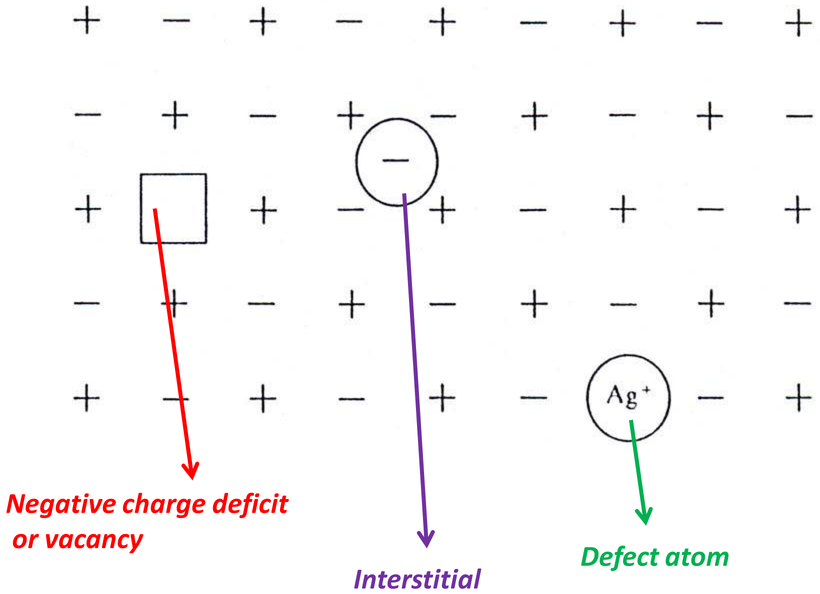


Figure 2.2 Lattice defects called "*color centers*" created by ionizing radiation in NaCl. Some have an unpaired electron and so are paramagnetic.



Negative charge deficit or vacancy

Interstitial

Defect atom

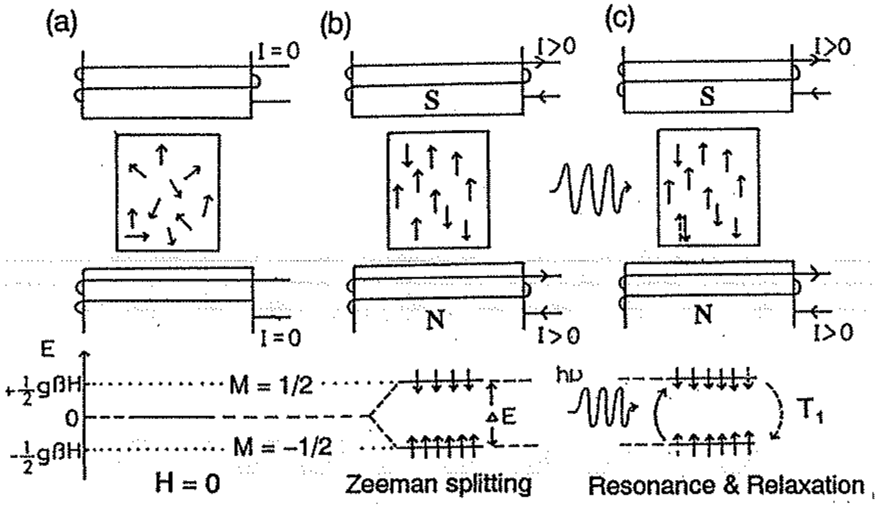
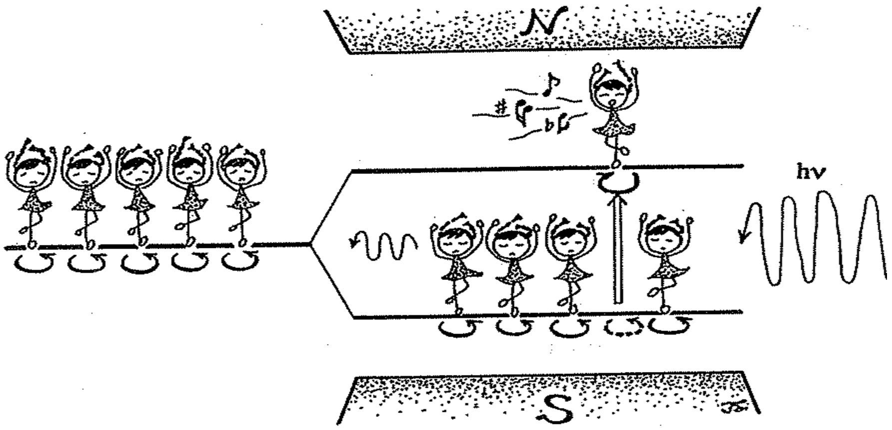


Figure 2.3 Energy separation of an unpaired electron spin under a magnetic field (Zeeman effect). (a) Random orientation of spins without current in the electromagnet, (b) a partial orientation under the magnetic field and (c) flipping of spins by microwave absorption and flopping of spins in the spin-lattice relaxation time, T_1.



The principle of ESR. The unpaired electrons are excited to a high energy state under a magnetic field by the absorption of microwave "music". The excited electron changes its direction of spin and relaxes into the ground state by emitting phonons (song). Microwave absorption is measured as a function of the magnetic field by ESR spectroscopy.

Spin angular momentum, $S(h/2\pi)$ (*h : Planck constant*)
Spin quantum number, S : $S = 1/2$ for an electron.
Magnetic quantum number, M : $M = +1/2$ and $M = -1/2$ are allowed.
Bohr magneton, β : the basic unit of a small magnet for an electron spin.
Magnetic moment, μ_e : $\mu_e = -g\beta S$
Spectroscopic splitting factor, g : $g = 2.0023$ for a free electron.

The energy yielding different spin states under the external magnetic field H is known as the "*Zeeman effect*" and depends on H and the *magnetic moment* ($g\beta M$) of the electron. The *Zeeman energy*, $E_Z = -\mu_e H$, is

$$E_Z = g\beta HM \quad , \tag{2.1}$$

where H is expressed in **Tesla** (**T** ; 1 T = 10^4 gauss) or in **mT** (1 mT = 10 gauss). The energy level of an electron with $S = 1/2$ splits for $M = 1/2$ and $M = -1/2$ and is shown as a function of H in Figure 2.4 (a).

The resonance condition is represented by

$$g\beta H_o = h\nu \quad , \tag{2.2}$$

Table 2.1 The resonance magnetic field H_0 for the signal at $g = 2.0$ at typical microwave frequency bands (wavelengths) using $h\nu = g\beta H_0$.

Band	Wavelength (cm)	ν [a] (GHz)	H_0 [b] (mT)
L–band	20.0	1.5	53.5
S–band	9.4	3.2	114
X–band	3.2	9.5	339
K–band	1.2	25	892
Q–band	0.86	35	1,250

a: $\nu = g\beta H_0/h = 0.0140 \times g\,H_0$ [GHz]

b: $H_0 = (h/\beta)(\nu/g) = 71.455 \times (\nu/g)$ [mT]

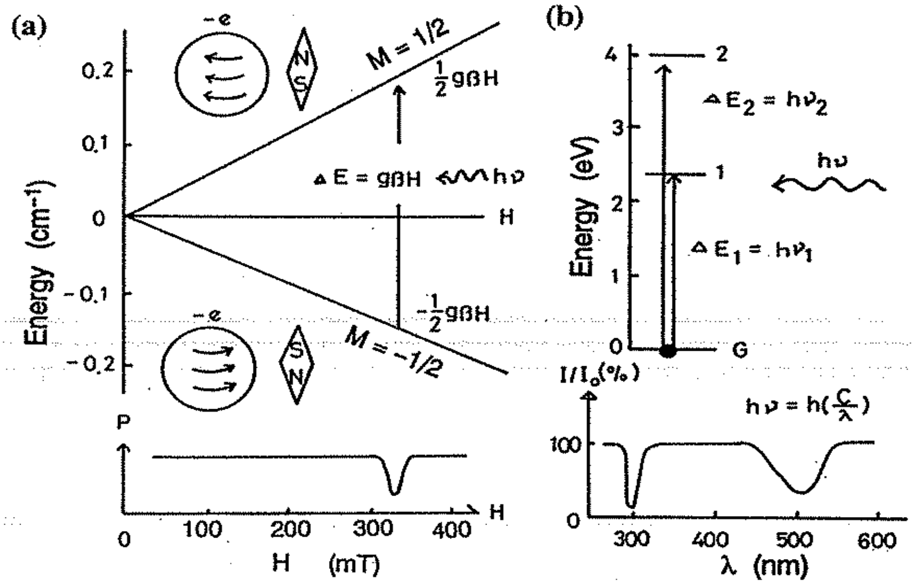


Figure 2.4 (a) Energy levels of an electron spin as a function of a magnetic field. The resonance by microwave absorption occurs at $H_0 = h\nu/g\beta$. (b) Electronic ground and excited levels and a transition induced by an optical absorption: E [eV] $= 1239/\lambda$ (λ is a wavelength in [nm]).