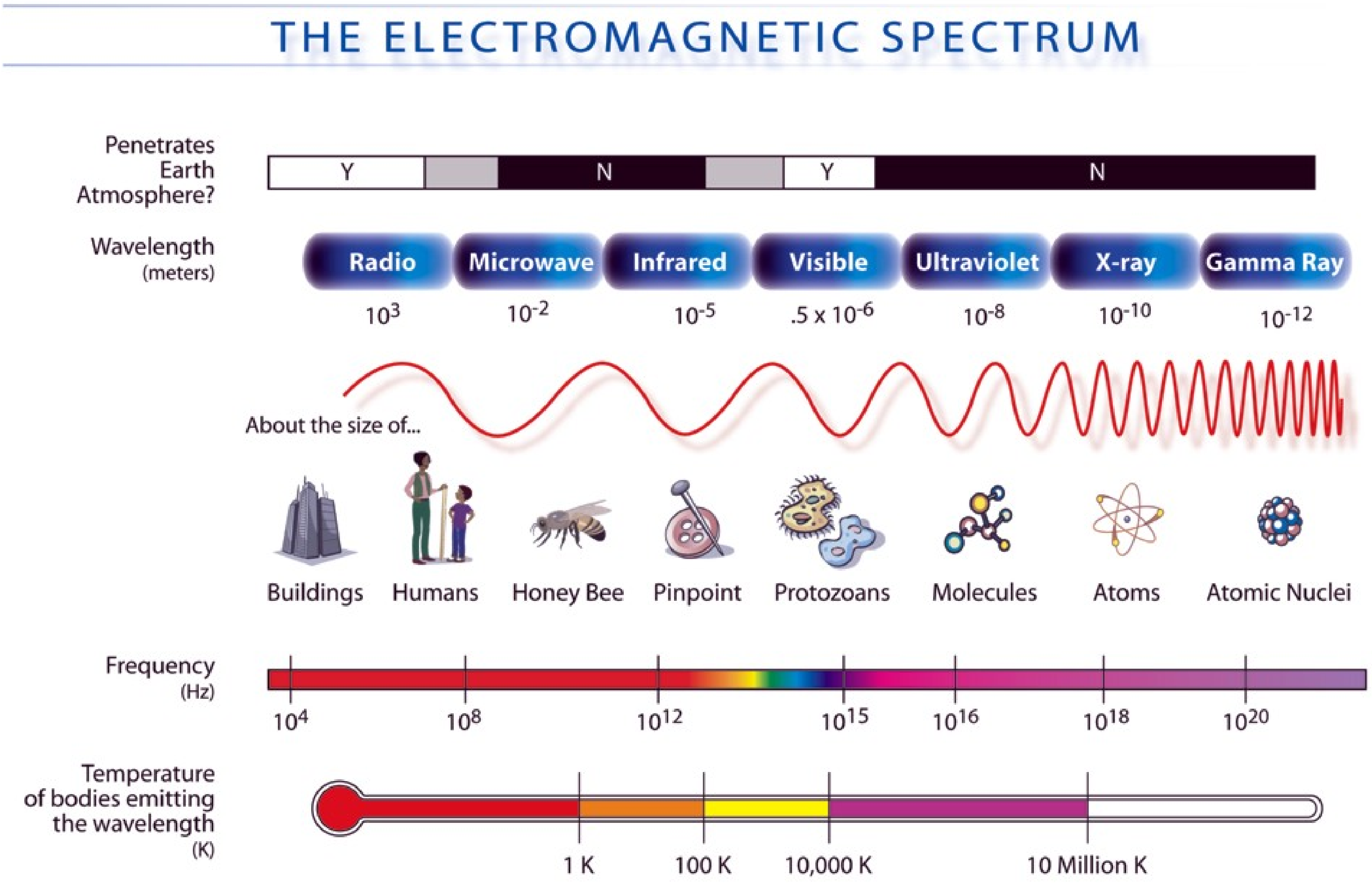
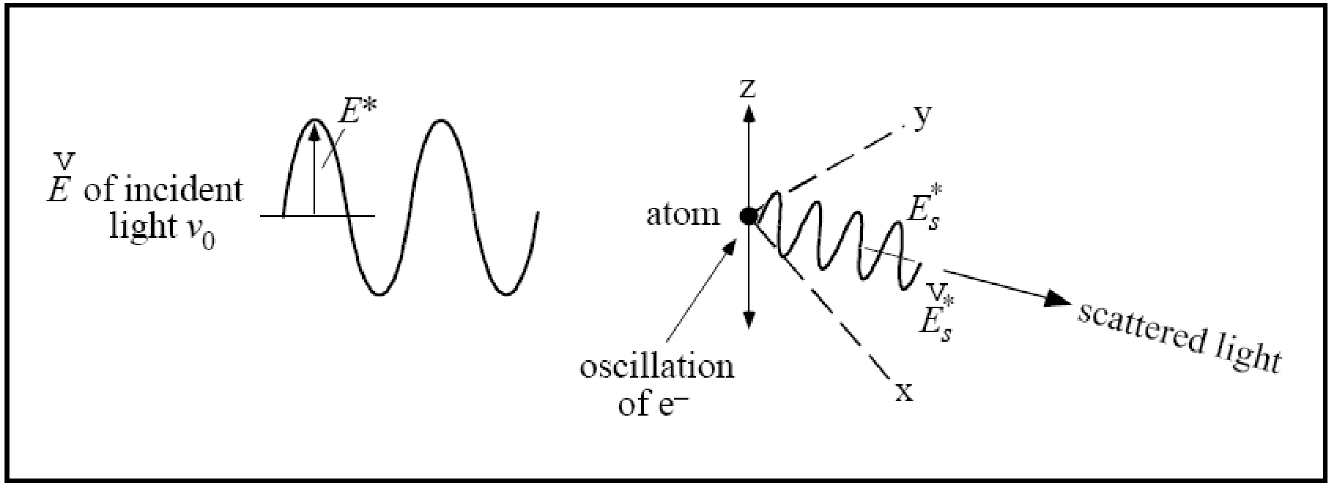
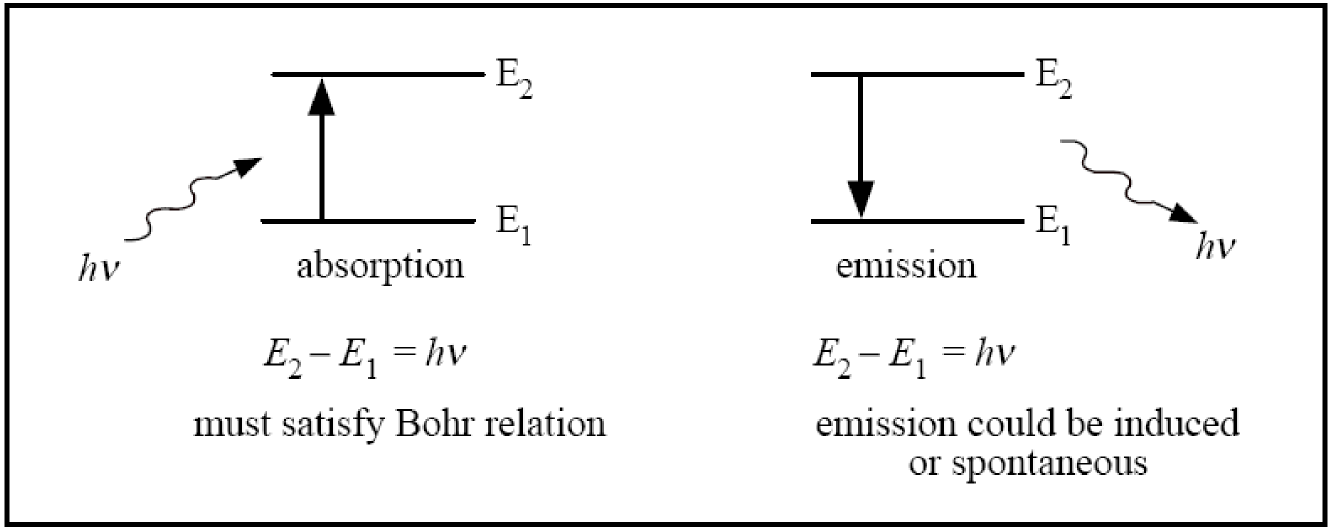
Interaction between light and matter



Scattering and absorption/emission of light





We can use light scattering and absorption to probe the dynamics of atoms and molecules in a matter because:

- Light is an electromagnetic wave consisting of oscillating electric and magnetic fields.
- Electrons and nuclei are charged particles, and their motions in atoms, molecules, and lattices generate oscillating electric fields.
- A matter can absorb energy from light if the frequency of the light oscillation and the frequency of the electron or lattice "transition motion" match. Unless these frequencies match, light absorption cannot occur. The "transition motion" frequency is related to the frequencies of motion in the higher and lower energy states.
- By measuring the frequencies of light absorbed by a matter, we can determine the frequencies of the various transition motions within the matter.

Phenomena due to light scattering

(a) Reflection : Light scattered in the opposite direction of incident light.

(b) Refraction : Light scattered in the forward direction combines with the incident beam to give rise to the phenomenon of refraction. The physical effect of this combination is to make the transmitted light appear as though it has travelled more slowly through the sample than through a vacuum.

$$\text{index of refraction } \; n \equiv \frac{\text{velocity of light in vacuum}}{\text{velocity of light in substance}}$$

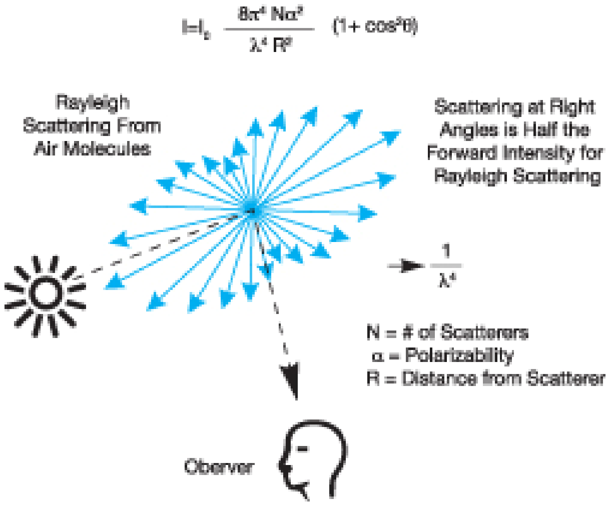
(c) Diffraction : Superposition of scattered waves from individual atoms or molecules in the sample. If the sample is highly ordered, diffraction pattern periodicity in the distribution of atoms and molecules in the sample can be used to deduce or infer the relative positions of atoms in a sample.

Rayleigh scattering

Rayleigh scattering is the elastic scattering of light (electromagnetic radiation) by particles much smaller than the wavelength of the light, which may be individual atoms or molecules. It can occur when light travels in transparent solids and liquids, but is most prominently seen in gases.

Rayleigh scattering is a function of the electric polarizability (α) of the particles:

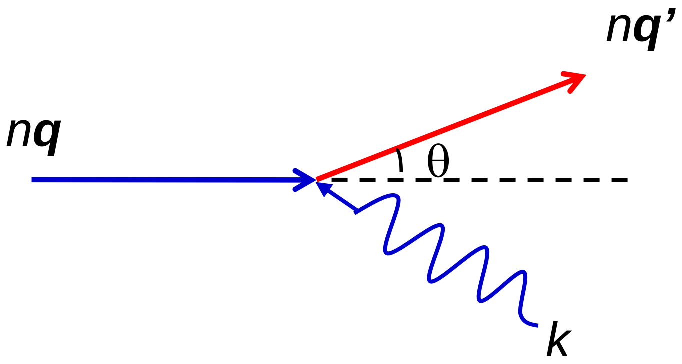
$$I = I_0 \frac{8\pi^4\alpha^2}{\lambda^4 R^2}(1+\cos^2\theta)$$



The strong wavelength dependence of rayleigh scattering enhances the short wavelengths, giving us the blue sky

Brillouin scattering

Brillouin scattering occurs when light in a medium (such as water or a crystal) interacts with time dependent optical density variations and changes its energy (frequency) and path. The density variations may be due to acoustic modes, such as phonons, magnetic modes, such as magnons. As described in classical physics, when the medium is compressed, its index (*n*) of refraction changes and the light's path necessarily bends.



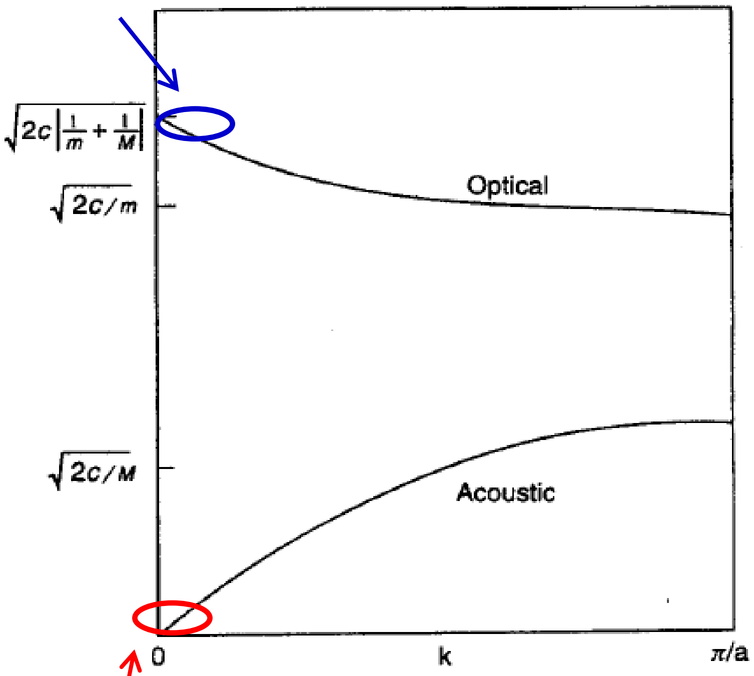
q is small in the Brillouin zone

$$k = (2n\omega/c)\sin(\theta/2)$$

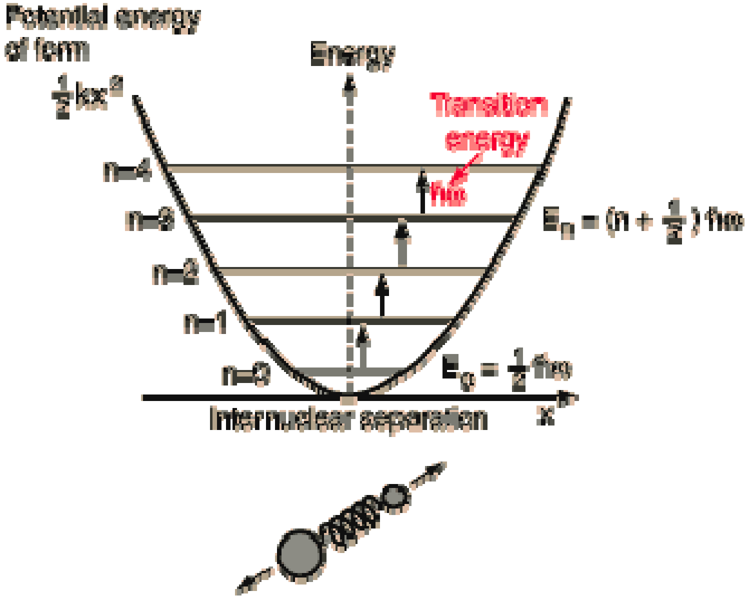
$$c_s(k) = \Delta\omega/k = (\Delta\omega/2\omega)(c/n)\csc(\theta/2)$$

Vibrational Spectroscopy

Raman scattering



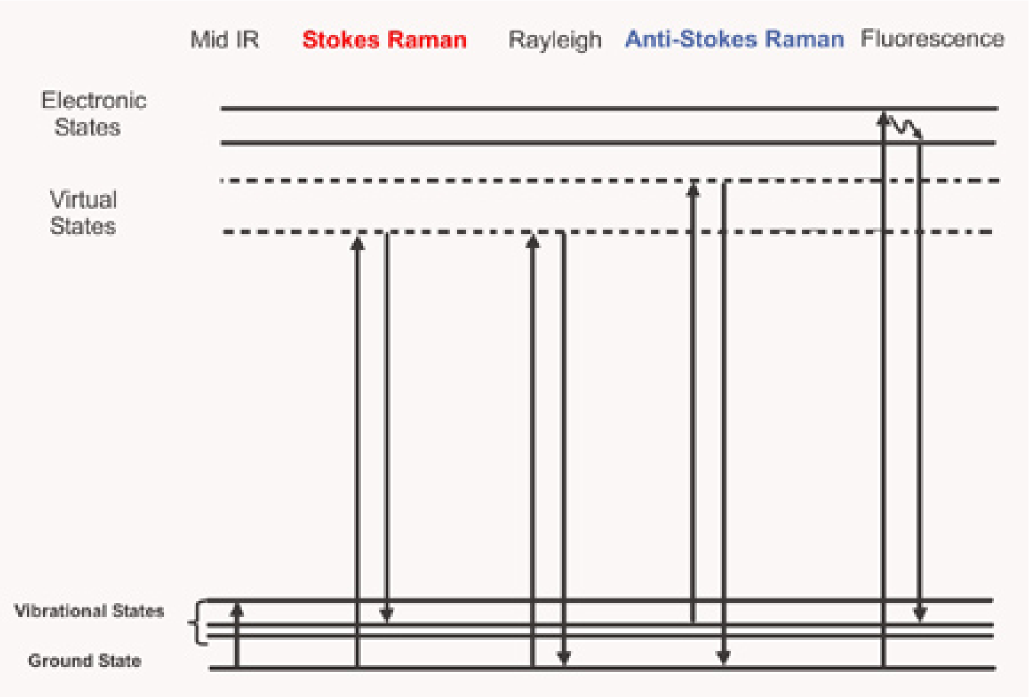
Brillouin scattering

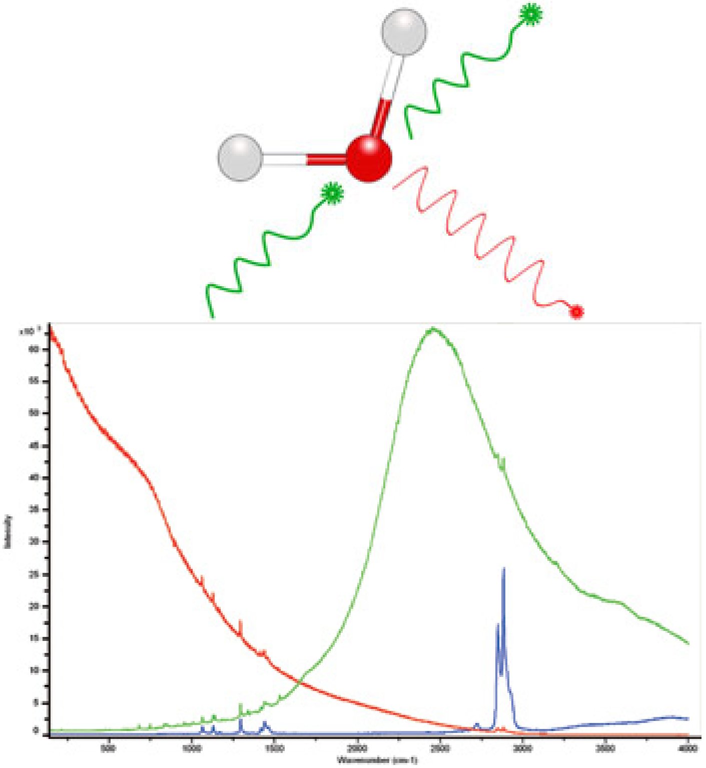


x=0 represents the equilibrium separation between the nuclei.

Raman scattering

When light is scattered from an atom or molecule, most photons are elastically scattered (Rayleigh scattering). However, a small fraction of the scattered light (approximately 1 in 10 million photons) is scattered by an excitation, with the scattered photons having a frequency different from, and usually lower than, the frequency of the incident photons. In a gas, Raman scattering can occur with a change in vibrational, rotational or electronic energy of a molecule.





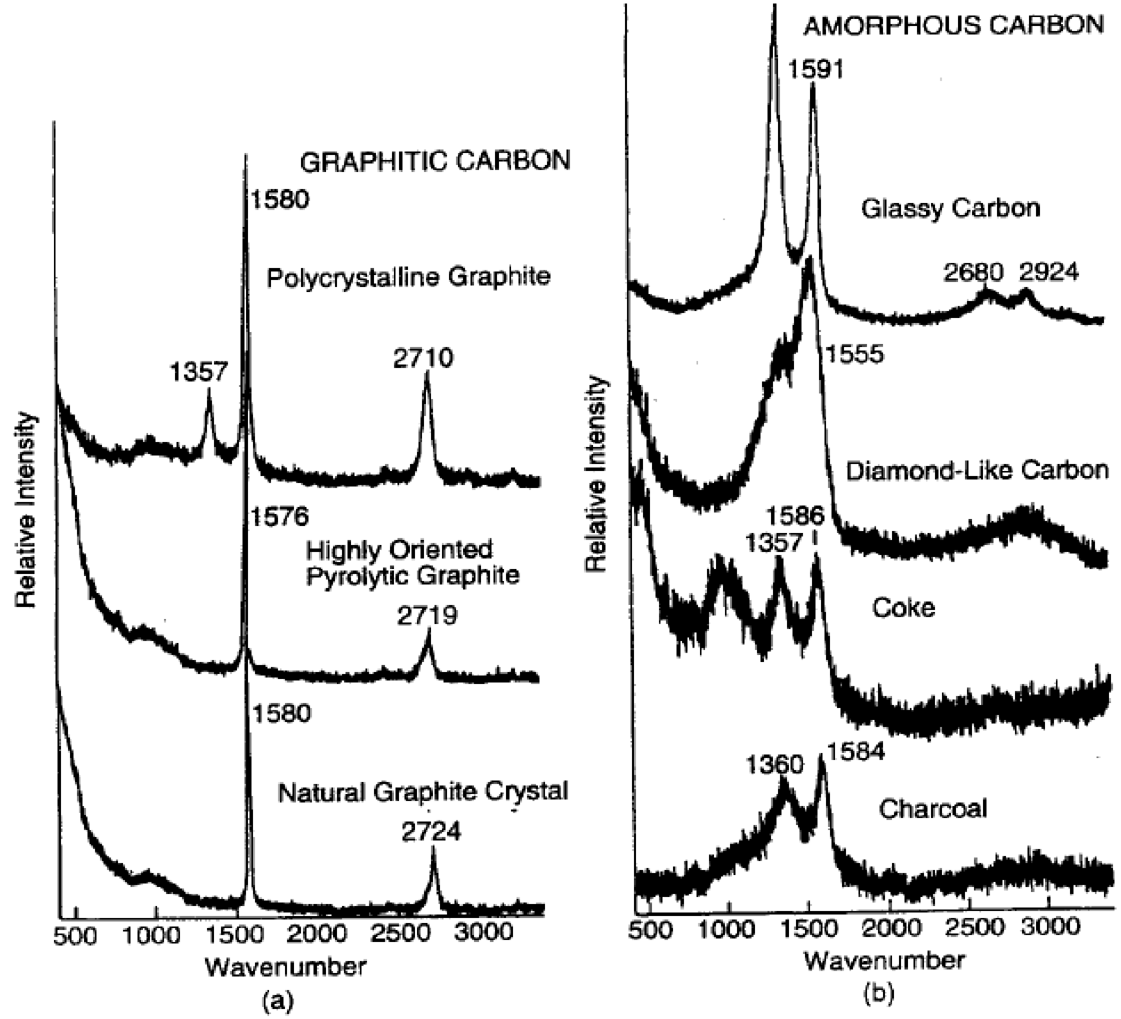
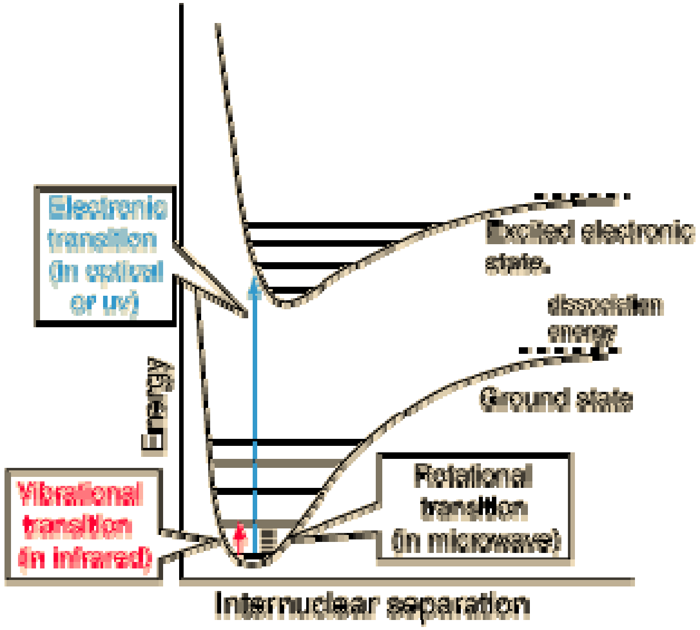


Figure 8.19. Raman spectra of (a) crystalline graphites and (b) noncrystalline, mainly graphitic, carbons. The *D* band appears near 1355 cm^{-1} and the *G* band, near 1580 cm^{-1}. [From D. S. Knight and W. B. White, *J. Mater, Sci.* **4**, 385 (1989).]

Optical and Electronic Spectroscopy

1. Photons in, photons out – PL
2. Photons in, electrons out – UPS, XPS
3. Electrons in, electrons out – EELS



Plasma oscillation of free electron gas

Drude Model (free electron gas model)

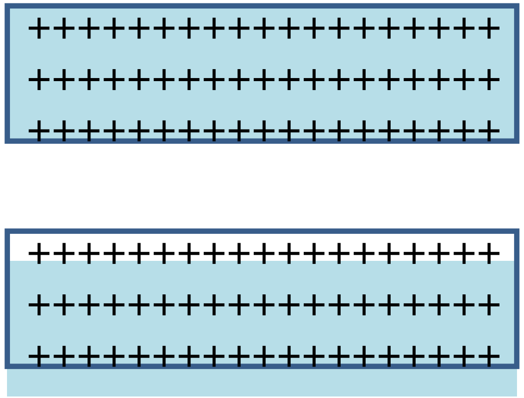
1. Electronic equation of motion

$$\frac{d}{dt}\mathbf{p}(t) = q\mathbf{E} - \frac{\mathbf{p}(t)}{\tau},$$

2. Ohm's law

$$\mathbf{J} = \left(\frac{nq^2\tau}{m}\right)\mathbf{E} = \sigma E$$

$$nmx'' + (n^2e^2/\sigma)x' = -neE$$



Fourier transformed

⇒ $[-nm\omega^2 - i(n^2e^2\omega/\sigma(\omega)]x(\omega) = -neE(\omega)$

$$\epsilon(\omega) \equiv 1 + 4\pi\frac{P(\omega)}{E(\omega)} \quad , \quad P(\omega) = -nex(\omega)$$

$$\epsilon(\omega) \equiv 1 - \frac{\omega_p^2}{\omega^2 + i\omega\omega_p^2/(4\pi\sigma(\omega))} \quad , \quad \omega_p^2 = 4\pi ne^2/m$$

Screening effect

The electric field of a positive charge embedded in an electron free gas falls off with increasing r faster than 1/r, because the electron gas tends to gather around and thus to screen the positive charge. This phenomenon can be described by the static dielectric function ϵ(0,k).

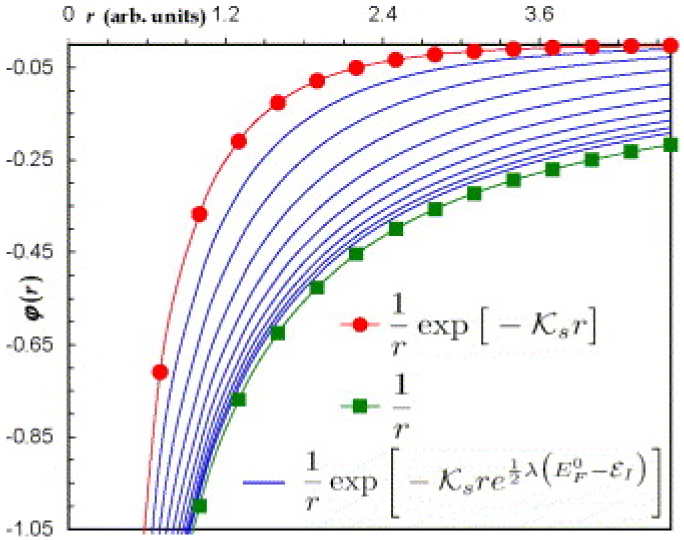
Applying Fermi-Thomas approximation to the Maxwell equation:

$$\left[\nabla^2 - k_0^2\right]\phi(r) = -\frac{Q}{\epsilon_0}\delta(r)$$

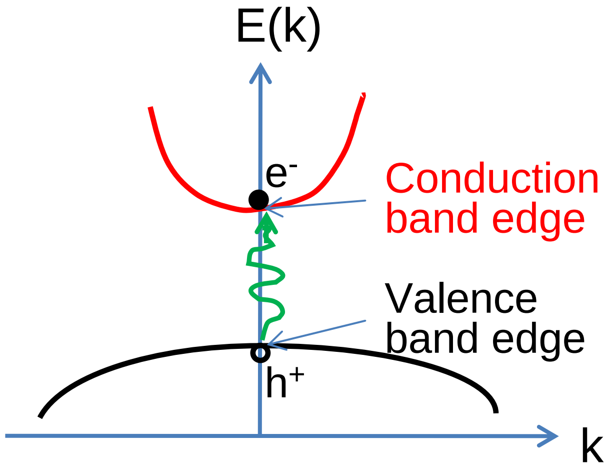
The solution is a

screened Coulomb potential

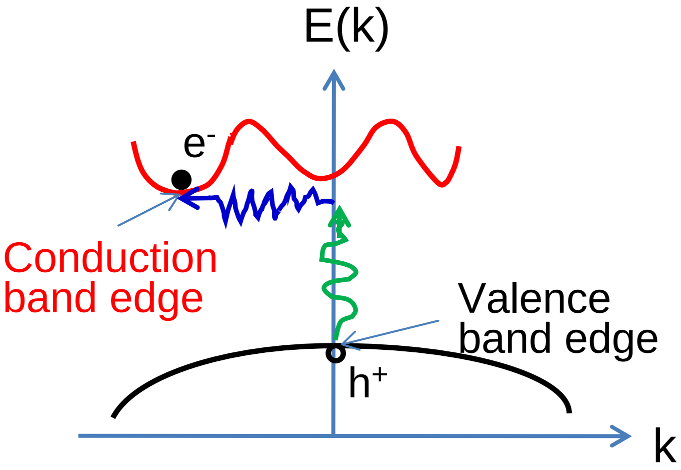
$$\phi(r) = \frac{Q}{4\pi\epsilon_0 r}e^{-k_0 r}$$



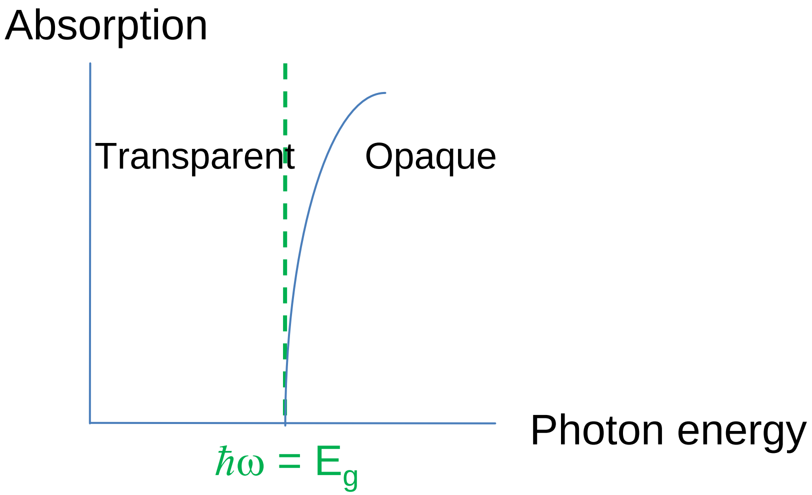
Interband transitions

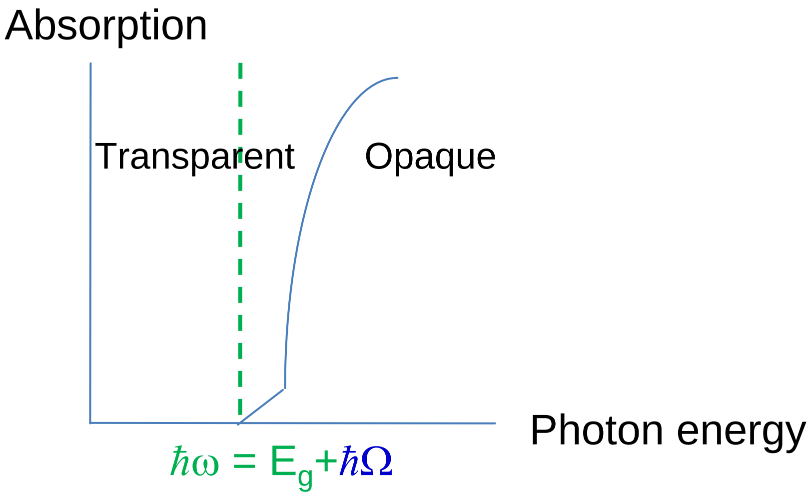


Direct band gap



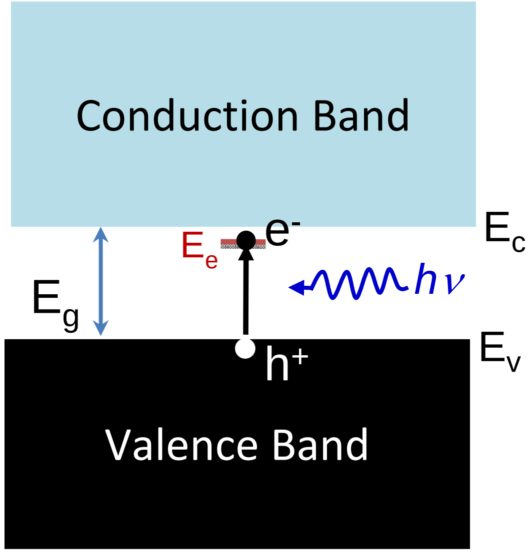
Indirect band gap

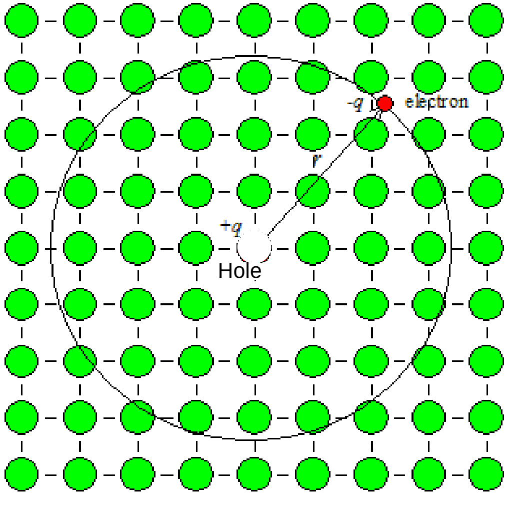




Exciton

An exciton is a bound state of an electron and an imaginary particle called a hole in an insulator or semiconductor, and such is a Coulomb-correlated *electron-hole pair.* A vivid picture of exciton formation is as follows: a photon enters a semiconductor, exciting an electron from the valence band into the conduction band. The missing electron in the valence band leaves a hole (of opposite electric charge) behind, to which the electron is attracted by the Coulomb force. The exciton results from the binding of the electron with its hole. As a result, the exciton has slightly less energy than the unbound electron and hole.





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Exciton binding

For Hydrogen atom, $E_1 = -\frac{e^4}{32\pi^2\hbar^2}\left(\frac{m_e}{\varepsilon_0^2}\right) = -13.6\ eV$

For Silicon, $E_e - E_c = -13.6\ eV\ x\left(\frac{\mu^*}{m_e}\right) x\left(\frac{\varepsilon_0^2}{\varepsilon^2}\right)$

$1/\mu^* = 1/m_e^* + 1/m_h^*$, $m_e^* \sim 0.3\ m_e$, $m_h^* \sim 0.2\ m_e$

$\mu^* \sim 0.12\ m_e$ and $\varepsilon = 12$

$\Rightarrow E_c - E_e \sim 0.011\ eV$

$r = a_0\, x\left(\frac{m_e}{\mu^*}\right) x\left(\frac{\varepsilon}{\varepsilon_0}\right) \sim 100\ a_0 \sim 53\ Å$

Fluorescence and phosphorescence