Chapter-1

Particle Properties of Wave

Contains: *(Blackbody radiation, photoelectric effect, Compton effect)*

2.1: Blackbody radiation

A significant hint of the failure of classical physics arose from investigations of thermalradiation(Planck, 1900). According to Einstein (1905) electromagnetic radiation is quantized in photons.

1. Photons and Planck's quantum of action:

Photons (γ) : The energy quanta of the electromagnetic field

Photon energy (E_{Ph}) : It is proportional to the frequency f or the angular frequency $\omega = 2\pi f$. Usually it is given in electron volts (eV),

$$E_{Ph} = hf = \omega$$

Photon momentum ($\vec{P}_{Ph}$): It is proportional to the wave number vector $\vec{k}\left(\text{with } \left|\vec{k}\right|\right) = \frac{2\pi}{\lambda}, \lambda$ is the wavelength of the electromagnetic radiation),

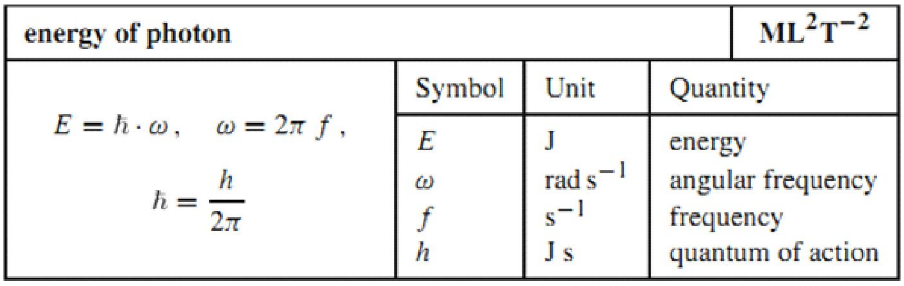
$$\vec{P}_{Ph} = \hbar\vec{k}, \qquad \left|\vec{P}_{Ph}\right| = \hbar k = h/\lambda$$

The vector $\vec{k}$ points along the propagation direction of the electromagnetic radiation.

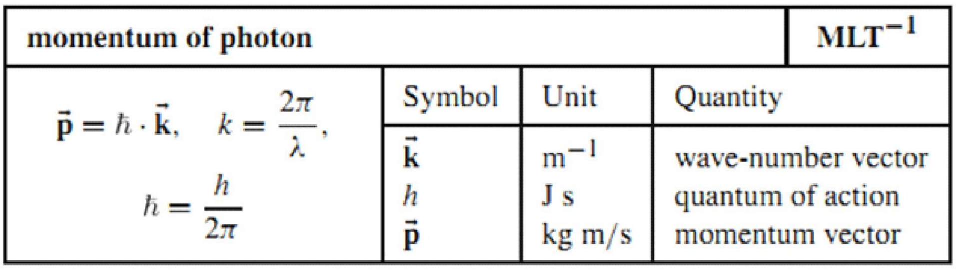
Planck's quantum of action: An universal constant,

$$h = 6.626 \times 10^{-34}\ Js,$$

$$\hbar = \frac{h}{2\pi} = 1.0545 \times 10^{-34}\ Js = 6.5821 \times 10^{-22}\ MeV\ s.$$



energy of photon			**ML^2T^{-2}**
	Symbol	Unit	Quantity
$E = \hbar \cdot \omega, \quad \omega = 2\pi f,$ $\hbar = \frac{h}{2\pi}$	E ω f h	J rad s^{-1} s^{-1} J s	energy angular frequency frequency quantum of action

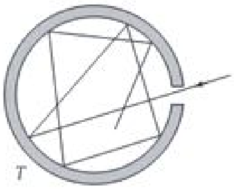


momentum of photon			**MLT^{-1}**
	Symbol	Unit	Quantity
$\vec{\mathbf{p}} = \hbar \cdot \vec{\mathbf{k}}, \quad k = \frac{2\pi}{\lambda},$ $\hbar = \frac{h}{2\pi}$	$\vec{\mathbf{k}}$ h $\vec{\mathbf{p}}$	m^{-1} J s kg m/s	wave-number vector quantum of action momentum vector

2. Thermal radiation and the blackbody radiator:

Thermal radiation, temperature radiation, the electromagnetic radiation of a body at finite temperature. The body also absorbs a fraction of the thermal radiation from its environment. There is a permanent exchange of energy between the body and its environment.

In the end, this process leads to temperature equilibrium. Blackbody radiator, a body with the reflectance zero. A blackbody absorbs any incident radiation completely.

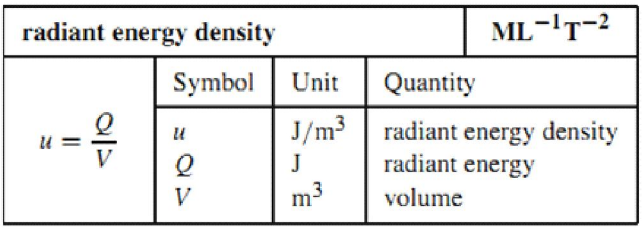


(**Figure 2.1:** Model of the blackbody)

Cavity radiator model of a blackbody radiator (Fig. 2.1): a box with a small aperture in the wall. The wall is impenetrable for radiation from inside (ideally reflecting) and has a definite temperature. The probability that a photon enters the cavity through the aperture and, after multiple reflection by the inner walls, leaves the cavity through the aperture again, is negligible (absorptance $\alpha = 1$). The aperture appears absolutely black. Cavity radiation, the thermal radiation leaving the aperture of a cavity radiator. The spectral distribution of the radiation energy density of the cavity radiation depends on the temperature of the cavity radiator.

- According to Kirchhoff's law (The absorptance is equal to the emittance), the spectral radiance $L_{e,f}$ of an arbitrary thermal radiator may be reduced to that of a black body.

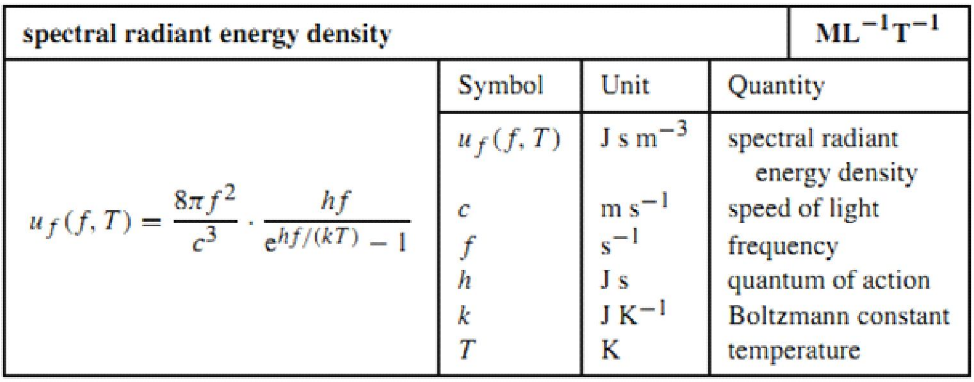
For the radiation field in the interior of the cavity, one defines



radiant energy density			$ML^{-1}T^{-2}$
	Symbol	Unit	Quantity
$u = \frac{Q}{V}$	u	J/m^3	radiant energy density
	Q	J	radiant energy
	V	m^3	volume

3. Planck's radiation law:

This law describes the frequency and temperature dependence of the radiant energy density of the cavity radiation:



spectral radiant energy density			$ML^{-1}T^{-1}$
	Symbol	Unit	Quantity
$u_f(f,T) = \frac{8\pi f^2}{c^3} \cdot \frac{hf}{e^{hf/(kT)} - 1}$	$u_f(f,T)$	$J\,s\,m^{-3}$	spectral radiant energy density
	c	$m\,s^{-1}$	speed of light
	f	s^{-1}	frequency
	h	J s	quantum of action
	k	$J\,K^{-1}$	Boltzmann constant
	T	K	temperature

4. Connection between radiant energy density and frequency:

The dependence of the spectral radiant energy density of the cavity radiation on the angular frequency ω or wavelength λ reads as follows:

$$u_\omega(\omega,T) = u_f(f,T).\frac{df}{d\omega} = \frac{1}{2\pi}.u_f(f,T),$$

$$u_\omega(\omega,T)=\frac{\hbar\omega^3}{\pi^2c^3}\frac{1}{e^{\hbar\omega/(kT)}-1},\quad u_\lambda(\lambda,T)=u_f(f,T).\left|\frac{df}{d\lambda}\right|=\frac{f^2}{c}.u_f(f,T)$$

$$u_\lambda(\lambda,T)=\frac{8\pi hc}{\lambda^5}\frac{1}{e^{hc/(k\lambda T)}-1}$$

5. Wien's displacement law and limiting cases of Planck's formula:

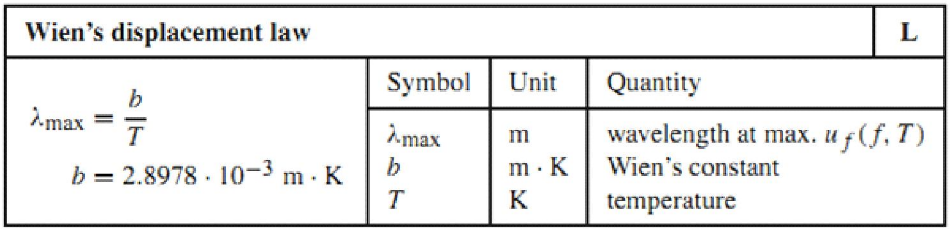
- **Wien's law:** for hf >> kT

$$u_f(f,T)=\frac{8\pi f^3h}{c^3}e^{-\frac{hf}{kT}}$$

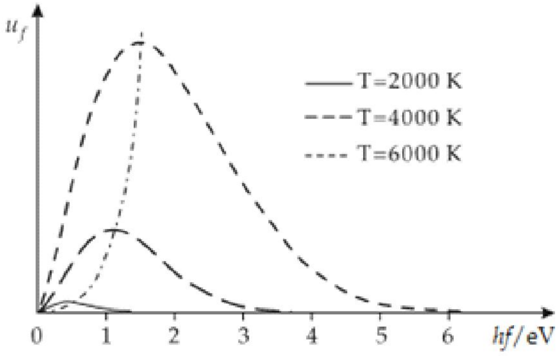
- **Rayleigh-Jeans law:** for hf << kT

$$u_f(f,T)=\frac{8\pi f^2}{c^3}kT$$

- **Wien's displacement law:** With increasing temperature, the maximum of the spectral radiant energy density $u_f(f,T)$ is shifted to higher photon energy, i.e., to higher frequencies (shorter wavelengths) (Fig. 2.2)



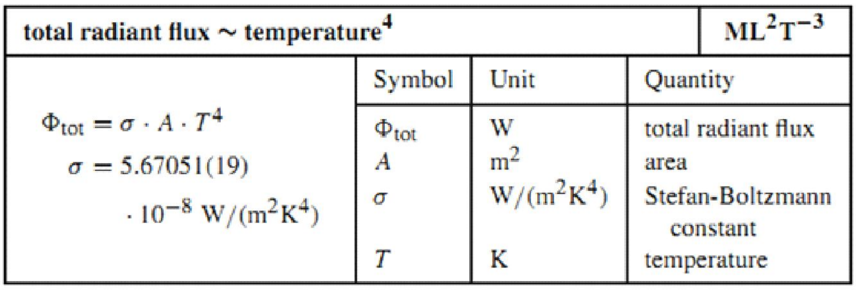
Wien's displacement law			L
	Symbol	Unit	Quantity
$\lambda_{\max}=\frac{b}{T}$ $b=2.8978\cdot10^{-3}$ m · K	$\lambda_{\max}$	m	wavelength at max. $u_f(f,T)$
	b	m · K	Wien's constant
	T	K	temperature



(Figure 2.2: Radiant energy density $u_f(f, T)$ for various temperatures according to Planck's radiation law. Dashed-dotted line: Rayleigh-Jeans law.)

6. Stefan-Boltzmann law:

Integration of the spectral radiant energy density over all frequencies yields the total radiant flux φ_{tot} of a radiation emitted by an area A. The total radiant flux φ_{tot} is proportional to the fourth power of the temperature T.



total radiant flux ~ temperature^4			ML^2T^{-3}
	Symbol	Unit	Quantity
$\Phi_{\text{tot}}=\sigma\cdot A\cdot T^4$ $\sigma=5.67051(19)$ $\cdot 10^{-8}$ W/(m^{2}K^4)	Φ_{tot}	W	total radiant flux
	A	m^2	area
	σ	W/(m^{2}K^4)	Stefan-Boltzmann constant
	T	K	temperature

2.2 Photoelectric Effect:

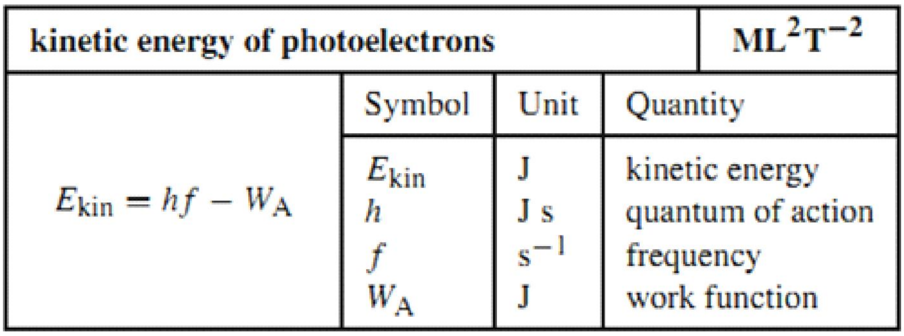
Photoeffect- photons eject electrons from a material.

1. Properties of photoelectrons

Electrons emitted, from metal when the frequency of light was sufficiently high, this phenomena is called photoelectric effect. And the emitted electrons are called photo-electrons.

Light waves carry energy, and some of the energy absorbed by metal may somehow concentrate on individual electrons and reappear as their kinetic energy.

Photoelectric Einstein equation, describes the kinetic energy E_{kin} of electrons ejected from the body by the incident radiation:



kinetic energy of photoelectrons			ML^2T^{-2}
	Symbol	Unit	Quantity
$E_{\text{kin}} = hf - W_A$	E_{kin}	J	kinetic energy
	h	J s	quantum of action
	f	s^{-1}	frequency
	W_A	J	work function

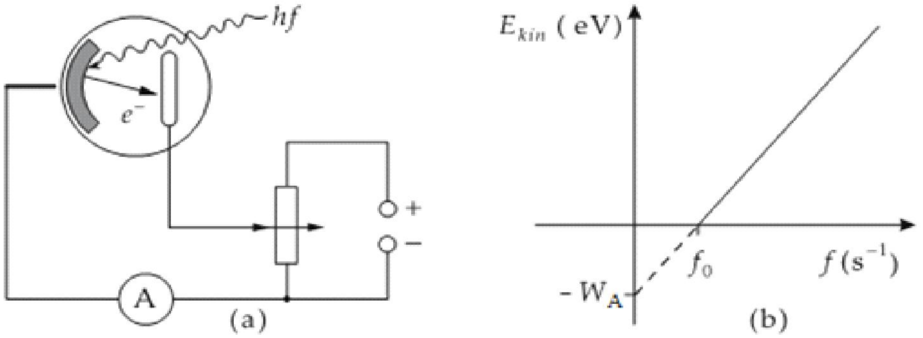
The kinetic energy of the photoelectrons depends on the frequency of the incident radiation, but not on the radiation intensity (Fig. 2.3). The radiation intensity determines only the intensity of the photocurrent (Fig. 2.4).

2. Work function

Work function, W_A, the minimum energy required for the ejection of an electron from a material. The work function typically amounts to several electron volts.

- Work function W_A of several elements (in eV): K 2.30, Na 2.75, Hg 4.49, Ge 5.0.For any material there is a threshold frequency for the photoeffect (red limit). Below this threshold frequency f_0, no photoeffect occurs (Fig. 2.3):

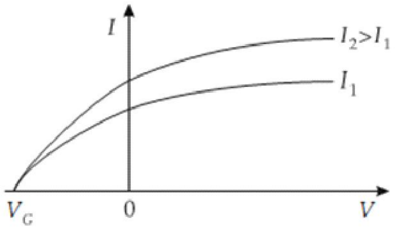
$$f_0 = \frac{W_A}{h}$$



(Figure 2.3: Left: experimental set-up for measuring the photoelectricffect. Right: dependence of the kinetic energy of photoelectrons on the frequency f of the incident radiation.).

The chemical structure and surface properties determine the work function W_A, and hence the threshold frequency f_0. The photoeffect may be explained only in the framework of the photon model of electromagnetic radiation.

When a suppression voltage is applied, the photocurrent vanishes at a threshold voltage $\boldsymbol{V_G}$, which is related to the maximum velocity $v_{\max}$ of the photoelectrons by $eV_G = mv^2{}_{\max/2}$. The quantum of action h can be determined by measuring the incident frequency f and the threshold voltage V_G. The measurement yields a linear relation between the suppression voltage at which the photocurrent vanishes, and the frequency (Fig. 2.3). The slope of the straight line yields Planck's constant, or quantum of action**,** $h = e\, dV_G / df$ **.**

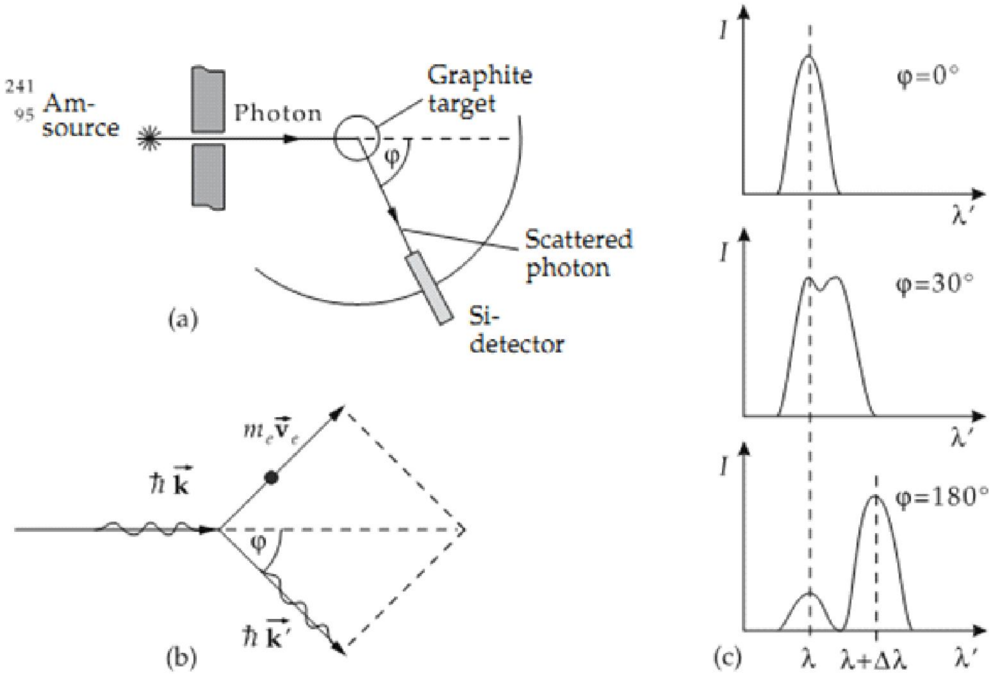


(Figure 2.4: Photocurrent I as function of the applied voltage V for different intensities I of the incident radiation.)

2.3: Compton Effect

1. Scattering of photons by electrons

Compton effect, a shift of the wavelength (and hence the frequency) in the elastic scattering of photons by free electrons. The shift increases with the scattering angle, but does not depend on the wavelength of the incident radiation (Fig. 2.5):



Compton shift of wavelength			L
	Symbol	Unit	Quantity
$\Delta\lambda = \frac{h}{m_e c}(1-\cos\varphi)$	$\Delta\lambda$	m	shift of wavelength
	h	J s	quantum of action
	m_e	kg	electron mass
	c	m s^{-1}	speed of light
	φ	1	scattering angle of photon