PHY 452/562
Lasers and Modern Optics

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Lecture 7: Quantum Mechanics II

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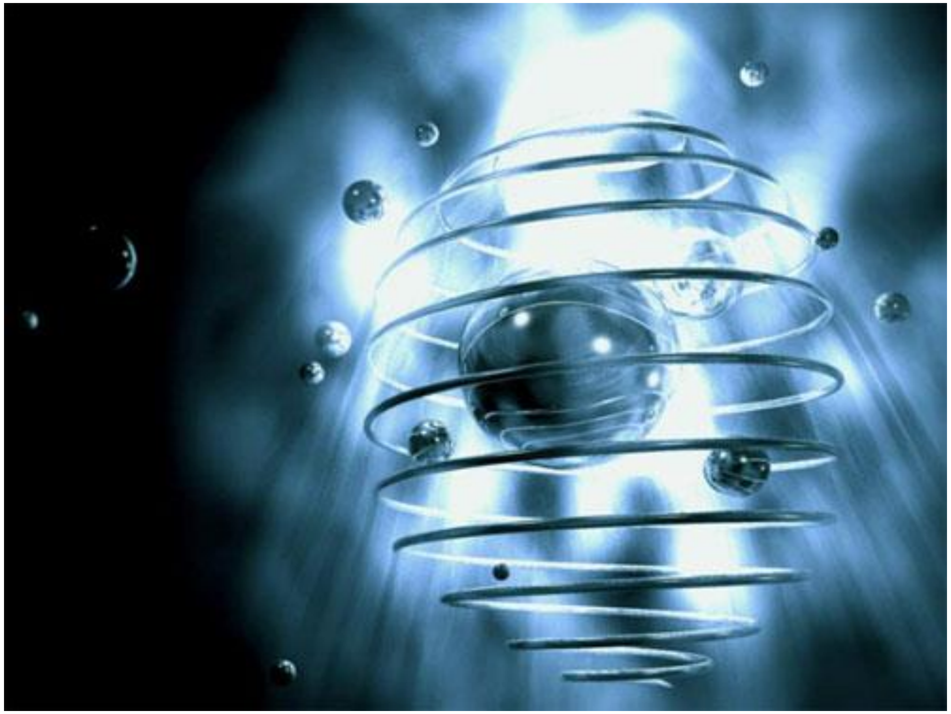
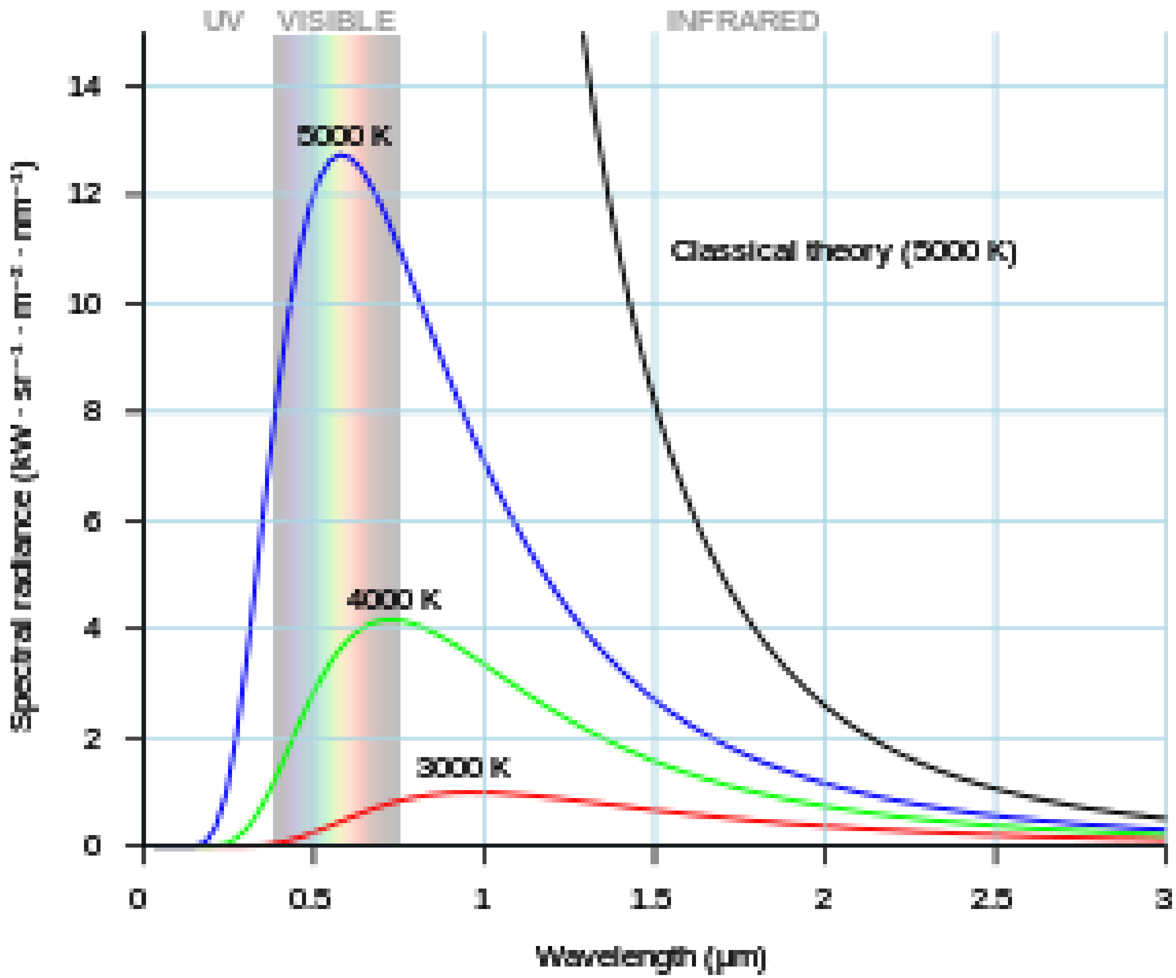
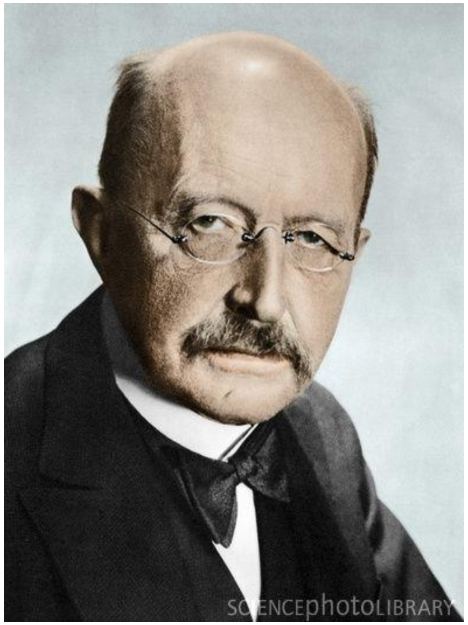
- Quantization a la Planck (cont.).
- Photoelectric effect.



$$u_{\mathrm{RJ}}(\lambda)=\frac{8\pi k_B T}{\lambda^4};\quad u_{\mathrm{W}}(\lambda)\propto\frac{e^{-\beta/\lambda T}}{\lambda^5};\quad u_{\mathrm{P}}(\lambda)=\frac{8\pi hc}{\lambda^5\left(e^{hc/\lambda k_B T}-1\right)}$$



$$M_\lambda(T) = 2\pi hc^2 \lambda^{-5} \frac{1}{e^{\frac{hc}{k\lambda T}} - 1}$$



Where *c* is the speed of light, *k* is Boltzmann's constant, *h* is Planck's constant and *e* is the base of natural logarithm.

The formula can describe the curve of blackbody radiation exactly for all wavelengths.

Planck's Hypotheses:

- The molecules and atoms composing the blackbody can be regarded as the linear harmonic oscillator with electrical charge;

- **The oscillators can only be in a special energy state. All these energies must be the integer multiples of a smallest energy (ε_0 = hν). Therefore the energies of the oscillators are $E = n\,h\nu$ with n = 1, 2, 3, …**

Planck-Einstein Energy Quantization Law:

$$E = h\nu = \frac{hc}{\lambda}$$

Quantum of energy

Frequency

Planck constant

$$h = 6.626 \times 10^{-34}\, J \cdot s$$

$$= 4.136 \times 10^{-15}\, eV \cdot s$$

$$1eV = 1.602 \times 10^{-19}\, J$$

$$1J = 6.242 \times 10^{18}\, eV$$

Example: Calculate the photon energies for the following types of electromagnetic radiation: (a) a 600kHz radio wave; (b) the 500nm (wavelength of) green light; (c) a 0.1 nm (wavelength of) X-rays.

Solution: (a) for the radio wave, we can use the Planck-Einstein law directly

$$E = h\nu = 4.136\times10^{-15}eV\cdot s\times600\times10^{3}Hz$$

$$= 2.48\times10^{-9}eV$$

(b) We can use the law in wavelength-form:

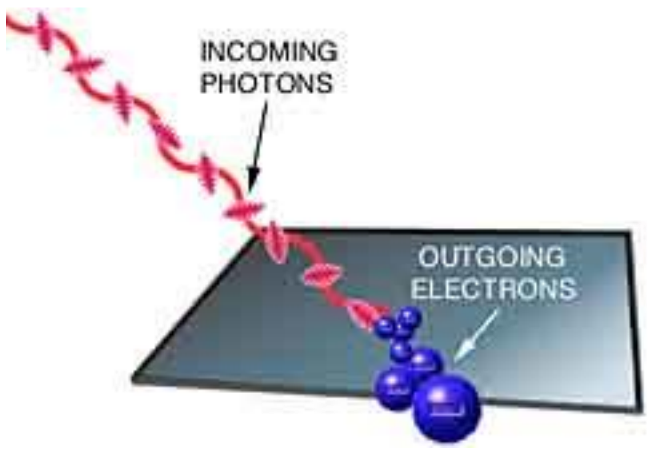
$$E = \frac{hc}{\lambda} = \frac{1.241\times 10^{-6}\, eV\cdot m}{550\times 10^{-9}\, m} = 2.26 eV$$

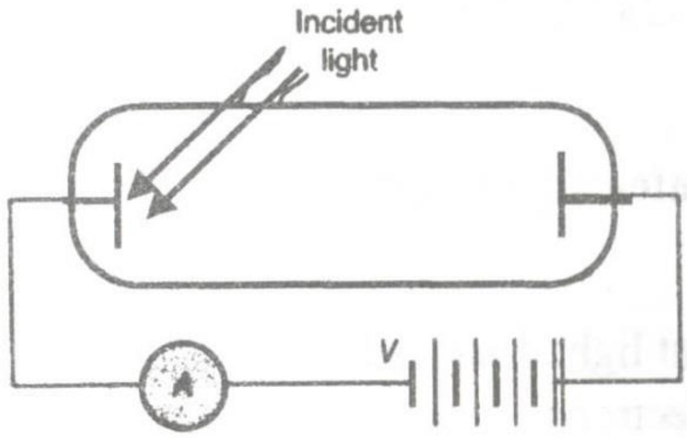
(c). For X-rays, we have

$$E = \frac{hc}{\lambda} = \frac{1.241\times 10^{-6}\, eV\cdot m}{0.1\times 10^{-9}\, m} = 1.24\times 10^{4}\, eV = 12.4 keV$$

Photoelectric Effect

A glass tube contains two electrodes of the same material, one of which is irradiated by light. The electrodes are connected to a battery and a sensitive current detector measures the current flow between them.





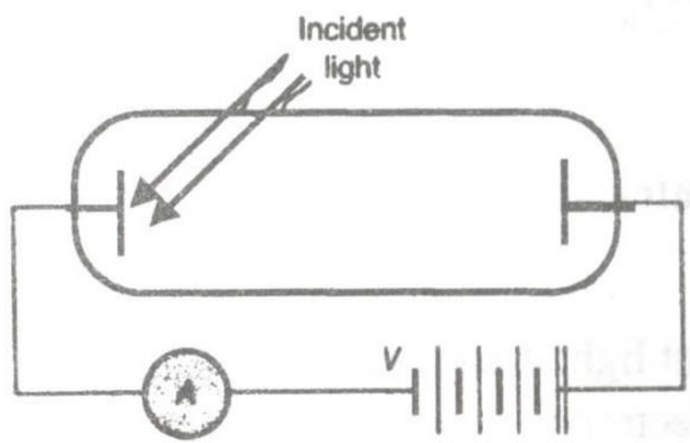
The current flow is a direct measure of the rate of emission of electrons from the irradiated electrode.

(i). For a given electrode material, no photoemission exists at all below a certain threshold frequency of the incident light.

ii) Increasing the intensity of the incident light does not increase the kinetic energy of the photoelectrons.

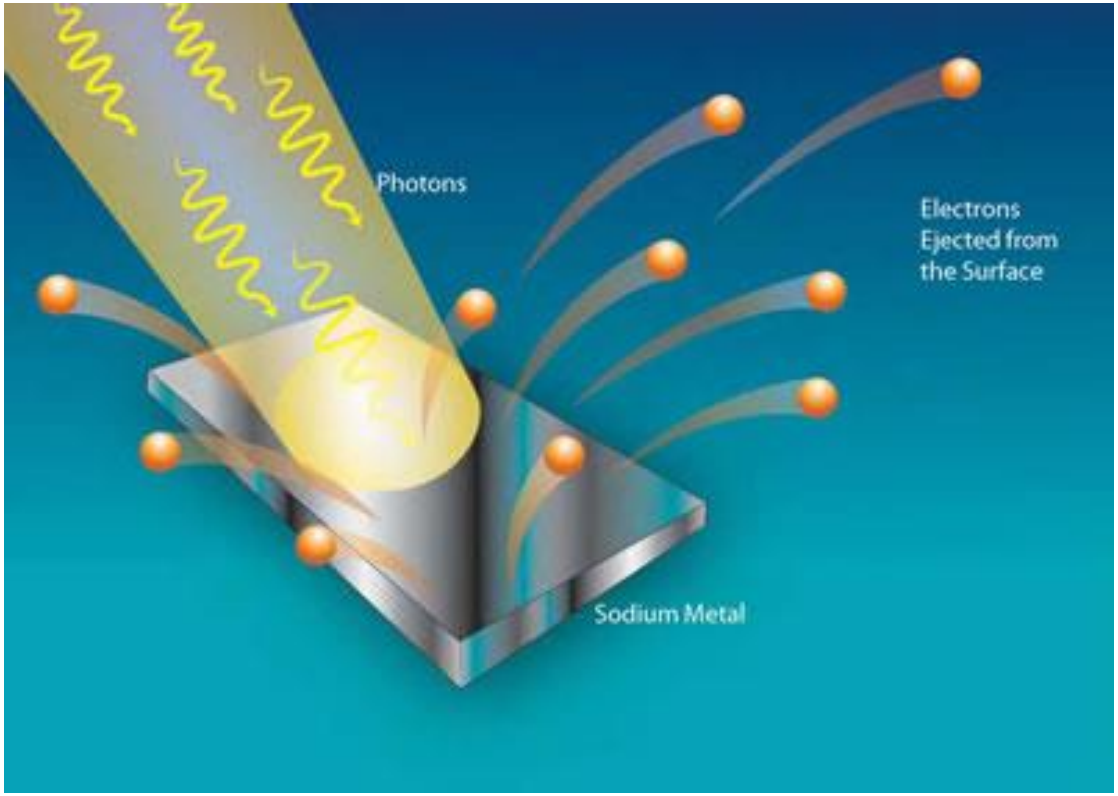
iii) Increasing the frequency of light does increase the kinetic energy of photoelectrons even for very low intensity levels.

Frequency of light $\propto$ kinetic energy of photoelectron



In 1905, Einstein solved the photoelectric effect problem by applying the Planck's hypothesis.

He pointed out that Planck's quantization hypothesis applied not only to the emission of radiation by a material object but also to its transmission and absorption.



(1) The photoemission of an electron from a cathode occurs when an electron absorbs a photon of the incident light;

(2) The photon energy is calculated by the Planck's quantum relationship: $E = h\nu$.

(3) The minimum energy required to release an electron from the surface of the cathode is a characteristic of the cathode material and the nature of its surface. It is called work function.

$$h\nu = A + \frac{1}{2}mv^2$$

Photon energy

Work function

Photoelectron kinetic energy

Example: Ultraviolet light of wavelength 150nm falls on a chromium electrode. Calculate the maximum kinetic energy and the corresponding velocity of the photoelectrons (the work function of chromium is 4.37eV).

Solution: using the equation of the photoelectric effect, it is convenient to express the energy in electron volts. The photon energy is

$$E = h\nu = \frac{hc}{\lambda} = \frac{1.241 \times 10^{-6} eV \cdot m}{150 \times 10^{-9} m} = 8.27 eV$$

and

$$h\nu = A + \frac{1}{2} m v^2$$

$$\Rightarrow \frac{1}{2} m v^2 = (8.27 - 4.37) eV = 3.90 eV$$

$$1eV = 1.602\times10^{-19}J = 1.602\times10^{-19}N\cdot m = 1.602\times10^{-19}kg\cdot m^2\cdot s^{-2}$$

$$\therefore \quad \frac{1}{2}mv^2 = 3.90eV = 3.90\times1.602\times10^{-19}kg\cdot m^2\cdot s^{-2}$$

$$\therefore \quad v = \sqrt{\frac{2\times3.90eV}{m}} = \sqrt{\frac{12.496\times10^{-19}}{9.11\times10^{-31}}} = 1.17\times10^{6}m/s$$