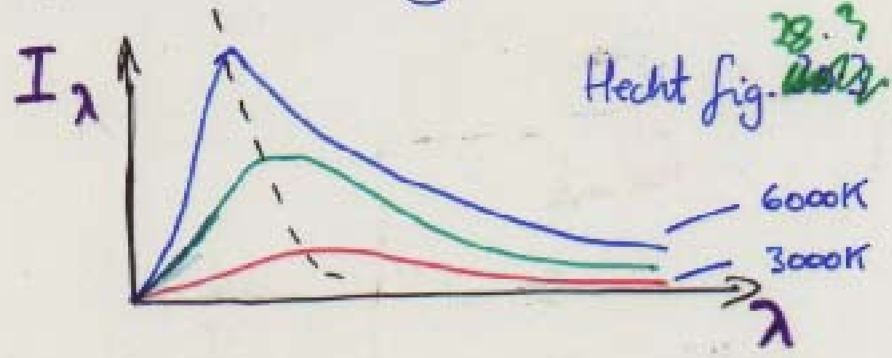
Blackbody Radiation: Condensed Version!

Blackbody = perfect absorber. Emits EM radiation to remain in thermal eqm. Spectral intensity $I_\lambda = \frac{dI}{d\lambda}$ depends on T only.



e.g. Sun 6000K
pupil 300K
universe 2.7K

Planck found (ca. 1900): $I_\lambda \propto \frac{1}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]$

$\frac{dI_\lambda}{d\lambda}=0 \Rightarrow$ Wien's Law: $\lambda_{max} T = \text{constant} = 3\times10^6\ \text{nm.K}$

$\int_0^\infty I_\lambda d\lambda \Rightarrow$ Stefan's Law: Power $P = A.\sigma T^4$
↑area of BB emitter

e.g. double temp $T \Rightarrow \lambda_{max}\downarrow$ by 2, $P\uparrow$ by $2^4 = 16$!

Explained by: need to restrict possible energies of EM wave to
$E_n = nhf : n = 0, 1, 2 \ldots$

(avoids UV catastrophe by forcing $I_\lambda \to 0$ as $\lambda \to 0$)

∴ energy gain/loss in discrete quanta of energy $E = hf = \frac{hc}{\lambda}$

Reading Quiz 3

1. When the temperature of a blackbody is increased, the spectral intensity at long wavelengths ($\lambda >> \lambda_{peak}$)..... I_λ

a) decreases

b) stays the same

c) increases

d) increases or decreases, dependent on the temperatures

2. The Photo-Electric Effect explained by Einstein occurs when:

a) electrons strike a target to produce X-rays

√ b) photons are absorbed by a metal, ejecting electrons

c) atoms excited by electrical dischage emit spectral lines

d) X-rays are absorbed by atomic nuclei

3. In the Rutherford-Bohr atomic model, after an atom emits a quantum of EM radiation, the orbit of its electron...

a) decreases in radius

b) decreases in speed

c) increases in radius

d) is unaffected

4. X-rays are diffracted by some crystals because:

a) they have wavelengths ~ size of nucleus

b) they have wavelengths ~ size of atomic spacing

c) X-rays are photons, not waves

d) only X-rays can penetrate into the crystal

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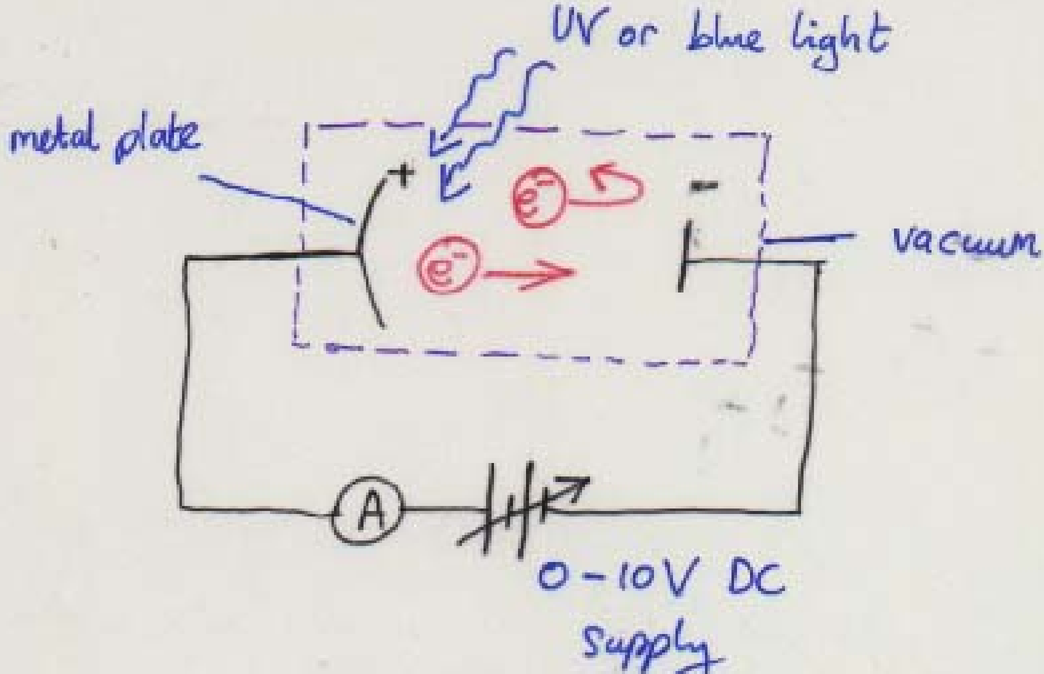
Photoelectric Effect : Photons !

The Effect: UV or blue light hits metal plate

→ electrons "kicked out", producing current :



Vary: Irradiance (I) and wavelength (λ) of light source

Measure:

1: "Photocurrent" when voltage = 0 ($\propto$ number of electrons ejected)

2: Increase voltage V and measure V required to prevent e^- from completing circuit (current → 0).

Then, k.e. of electrons $\frac{1}{2}mv^2 = eV_s$

↑ "stopping potential"

Photo-electric Effect : Predictions and Results

Classical EM wave theory ⇒ atoms absorb EM energy continuously until electrons ejected.

∴ We predict :

1. Electron k.e. $(= eV_s)$ should be $\propto$ irradiance I (W/m^2) and independent of λ (i.e. should work for any color)

2. Time needed for atom to absorb enough energy to eject electron of k.e. $\frac{1}{2}mv^2$ is:

$$\tfrac{1}{2}mv^2 = eV_s \approx I . A . t$$

← "area" of atom (A)

$\Rightarrow t \gtrsim 0.1s$, so should be a delay.

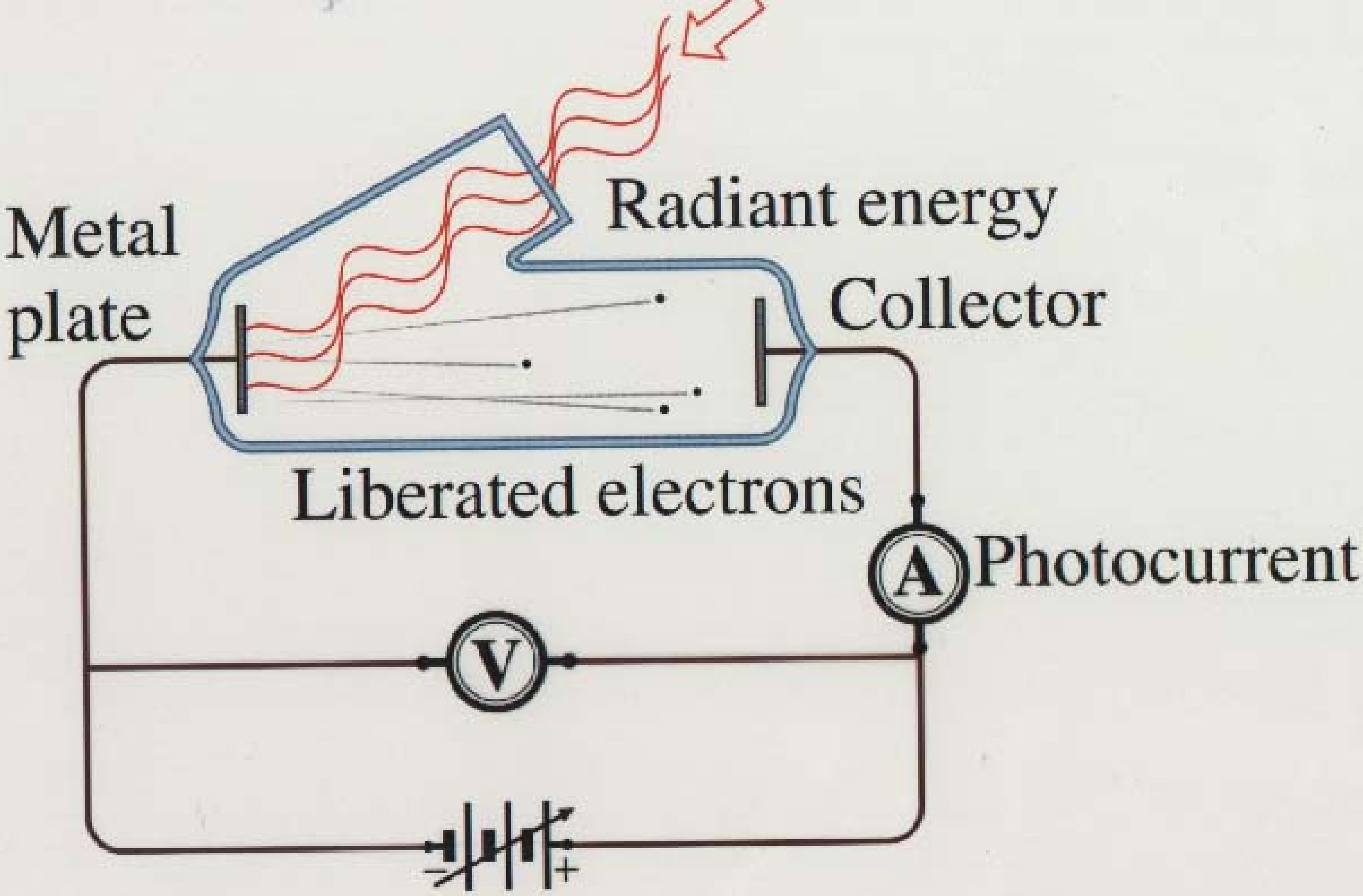
BUT We observe :

- electron k.e. depends on $f = c/\lambda$
  - no electrons ejected above a "cutoff wavelength" $\equiv \lambda_c$
  - k.e. independent of irradiance
- Photocurrent ($\propto$ # of electrons ejected / second) $\propto I$
- electrons ejected immediately ! ($<1ns$).

Transparency 158

Figure 28.6

Photoelectric effect



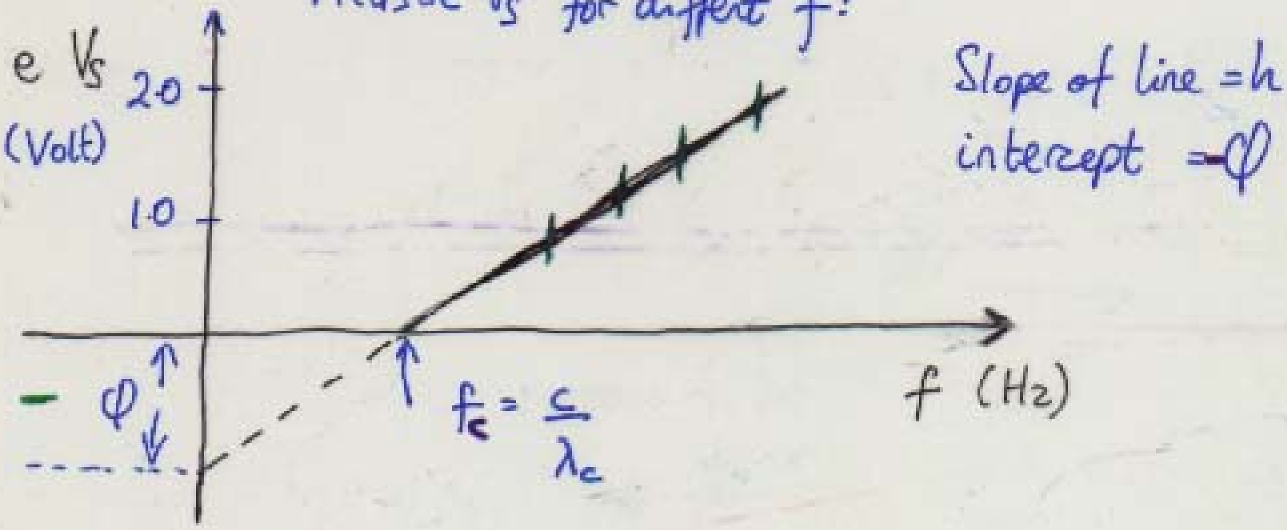
Einstein's Explanation (1905)

- EM energy is absorbed in "quanta" with $E = hf = \frac{hc}{\lambda}$
- 1 quantum ejects 1 electron

$\Rightarrow$ k.e. of electrons $\boxed{\frac{1}{2}mv^2 = eV_S = hf - \phi}$

ϕ = "threshold energy" or "work function", i.e. energy tax needed to "unstick" electron from metal surface

Measure V_S for differt f:



When $eV_S = 0$ the effect disappears at the cutoff wavelength, i.e. $hf - \phi = 0$, or $\frac{hc}{\lambda_c} = \phi$

Conclude: light has particle-like properties!
i.e. transfers energy in "packets" (photons)

Worked Example: $\lambda = 450\,nm$ light incident on Sodium (Na) target with $\phi = 2{\cdot}28\,eV$

Photon energy $E = hf = \frac{hc}{\lambda} = \frac{6{\cdot}6\times10^{-34} \times 3\times10^{8}}{450\times10^{-9}} = 4{\cdot}4\times10^{-19}\,J$

Better to use "electron-volts" : 1eV = change of energy of 1 electron passing through potential diff. of 1 Volt

i.e. 1eV = charge [C] × potential [Volts = $\frac{\text{Joules}}{\text{Coulomb}}$]

$1eV = 1{\cdot}6\times10^{-19}\,C \times 1\,V = 1{\cdot}6\times10^{-19}\,J$

∴ photon energy in eV $= \frac{4{\cdot}4\times10^{-19}\,J}{1{\cdot}6\times10^{-19}\,J/eV} = 2{\cdot}75\,eV$

So from Einstein's equation, k.e. $= \frac{1}{2}mv^2 = eV_s = \frac{hc}{\lambda} - \phi$

$\Rightarrow eV_s = 2{\cdot}75\,eV - 2{\cdot}28\,eV = 0{\cdot}47\,eV$

$\Rightarrow$ stopping potential $V_s = 0{\cdot}47$ Volt.

Cutoff λ (when k.e. = 0) given by $\frac{hc}{\lambda_c} = \phi$

$\Rightarrow \lambda_c = \frac{hc}{\phi} = \frac{6{\cdot}6\times10^{-34}\,Js \times 3\times10^{8}\,m/s}{(1{\cdot}6\times10^{-19} \times 2{\cdot}28)\,J} = 542\,nm$

so no effect above 542nm

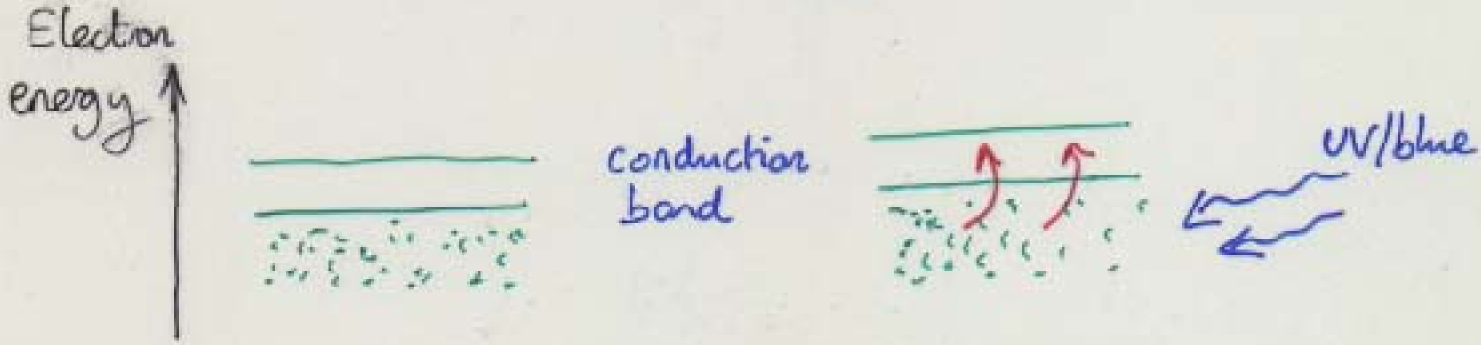
Photoelectric Effect: Applications

1. Since $\underline{eV_s} = \underline{h}f \underline{-\phi}$, can determine
   $y = mx + c$
   measure

   Planck's constant "h" from slope of line.

2. Given h, and ϕ for metal, can measure V_s and determine $f = \frac{c}{\lambda}$: a "photon spectrometer" using an entirely quantum effect!

3. Semiconductors = normally poor conductors



Incident photons "kick" e^- into conduction energy band where they can move freely.

$\Rightarrow$ resistance $\downarrow$ as irradiance $\uparrow$

– used in light-meters.

Bremsstrahlung (= "braking radiation")

Observe: high energy e^- strike metal target

$\Rightarrow$ X-ray photons kicked out

i.e. opposite of photoelectric effect.

Effect: electrons decelerate inside target

Maxwell's Equations $\Rightarrow$ EM radiation produced

If electron's entire k.e. goes into a single photon,

then observe: $\frac{1}{2}mv^2 = eV_a = hf_{max}$

(V_a: accel. voltage of electron beam; f_{max}: highest possible frequency)

$$\Rightarrow f_{max} = \frac{eV_a}{h} \quad \text{or} \quad \lambda_{min} = \frac{c}{f_{max}} = \frac{hc}{eV_a}.$$

e.g. 20 kV electron beam $\Rightarrow \lambda_{min} = \frac{hc}{eV_a} = 0.062\,nm$

(Hecht ex. 28.4)

Photons! Quanta of EM energy.

BB radiation + Photoelectric Effect teach us light behaves as "energy packets" with

$$E = hf = \frac{hc}{\lambda} \quad : \quad h = 6.6 \times 10^{-34}\ \text{Js}$$

⇒ dual nature of EM radiation:

<u>Wave?</u> Polarization, interference, diffraction

<u>Particle?</u> Photoelectric effect, bremsstrahlung, BB radiation

i.e. "wave/particle" duality

<u>Einstein</u>: "All the 50 years of conscious brooding have brought me no closer to answering the question: "What <u>are</u> light quanta?" Of course today every rascal thinks he knows, but they are deluding themselves."