"Dual Nature of Radiation and Matter"

Discovery of Interference, Diffraction and Polarisation
+
Maxwell's equation of Electromagnetism and Hertz experiment on the Production and detection of EM waves

Discoveries of Photoelectric effect of Hertz, compton effect by compton, stark effect by stark explained by quantum theory of light.
↓
light consists of the Packets of energy which travels in straight line, with the speed of light. Each Packet of energy is called Photon or quantum of light $\left(= hf = \frac{hc}{\lambda}\right)$
Thus, Particle Nature of light was established.
As some Phenomena of light were explained by wave theory of light and some by Particle Nature of light. Hence it was concluded that light has Dual Nature.

Free electrons in Metals:-

These are loosely Bound electrons, which are free to Move easily within the Metal surface but can not leave the Metal surface.

NOTE As the e^- tries to leave the Metal surface a positive charge acquire by the surface. Thus due to force of Attraction, e^- held inside the Metal. This force is called restraining force, causes Potential Barrier.

* To escape from the metal surface, Potential Barrier on the metal surface has to be overcome by the e^-.

Work function of the Metal:- It is the Minimum energy required by an electron to just escape the Metal surface so as to overcome from the restraining force.

→ It is Measured in terms of 'eV' and denoted by ϕ_0.

Work function of some Metals:

Cs	2.14		
K	2.30	Ag	4.70
~~Na~~	~~2.75~~	Ni	5.15
		Pt	5.65

Higher work function $\xrightarrow{\text{Means}}$ Higher energy required to emit the e^- from Metal surface.

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NOTE: * Work function is lowest for caesium ($\phi_0 = 2.14$ eV) and Highest for Platinum ($\phi_0 = 5.65$)

* Work function depends on → Temperature of Metal
  → Nature of Metal
  → Impurities present in the Metal surface.

Electron emission: Emission of the electrons from the metal surface called electron emission.

NOTE: Electron emission is possible if energy possesed by free electron is more than the work function of the Metal.

Physical Processes to give energy to the free e^-:

(i) Thermoionic emission: Phenomena of emission of electrons from the metal surface when Heated suitably.
* Emitted electrons are called Thermal e^- or Thermions.
Number → depends on the temp^r of the Metal surface.

(ii) Photoelectric emission: when a radiation of suitable frequency fall on a metal surface, electrons emitted from the metal surface.
* Emitted electrons are called Photoelectrons.
Number → depends on intensity of incident light.

(iii) Field emission or cold cathode Method: phenomena of emission of electrons from the metal surface, when metal surface is under the application of strong Electric field.
→ Value of applied E. field is $\sim 10^8$ V/m.

(iv) Secondary emission: Phenomena of emission of electrons from the metal surface, when a fast moving electron strike the metal surface.

* emitted electrons are called secondary electrons.

Photoelectric effect:

Phenomena of emission of electrons from a metal surface, when a radiation of suitable frequency fall on it.

* Emitted electrons are called Photo electrons.
* Produced current is called Photoelectric current.

NOTE: Alkali metals like Lithium, Sodium, Potassium, caesium etc. show

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Photoelectric effect at visible light.

* Metals like zinc, cadmium, Magnesium etc. shows photoelectric effect with Ultraviolet light.

Hertz, Hallwachs and Lenard's observations on Photoelectric effect:

Hertz observation:

→ Phenomena of Photoelectric emission was discovered by Heinrich Hertz in 1887.

→ He observed that during the experiment of Production of EM waves High voltage spark across the detector loop were enhanced when the emitter plate was illuminated by ultraviolet light from an arc lamp.

→ He states that electrons will overcome from the force of attraction with Positive ions in the material when electron absorb the energy from the incident light of suitable frequency.

Hallwachs and Lenard's observation:

* Lenard's observed that if a Potential difference is applied across the two metal Plates enclosed in an evacuated tube, no current flows in the circuit.
* Lenard's observed that when a plate connected with negative terminal exposed to UV radiation, current begins to flow in the circuit as long as plate is plate is exposed to UV radiation.
* Electron leaves the Emitter plate and moves towards the collector Plate.

Hallwach's observation:

↳ connected a negatively charged zinc plate to a gold-leaf electroscope and observed that:

* Zinc Plate lost its charge when it was illuminated by UV radiations.
* Uncharged zinc Plate become Positively charged when exposed to UV radiation.
* Number of Positive charges on zinc plate increases when More UV radiations fall on it.

* He concluded that Negatively charged Particles were ejected under the action of UV radiation from zinc Plate.

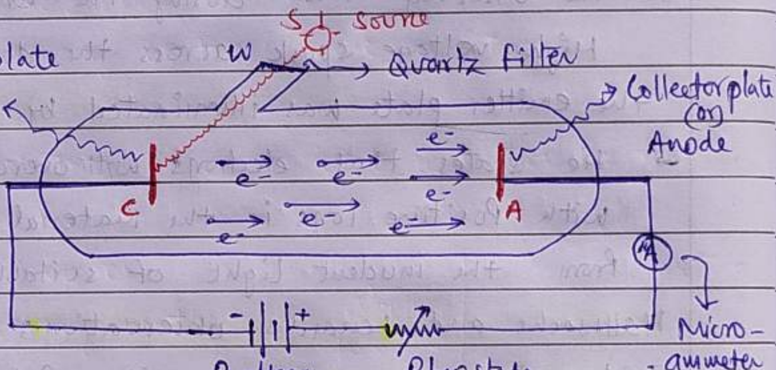
* In 1897, discovery of e^- by J. J. Thomson, it was clear that these ejected ~~or~~ ar negatively charged particles are electrons.

Threshold frequency: The Minimum frequency of the incident radiations, which is required to emit the electron from an emitter (i.e. a Metal surface) without any kinetic Energy.

→ Value of Threshold frequency depends on the Nature of Material of the emitter Plate.

Experimental study of Photoelectric current:

This Apparatus consists of an evacuated glass or Quartz glass which encloses the photosensitive Plate C and Plate A.



→ A transparent window W, covered with Quartz filter to allow the light of Particle wavelength.

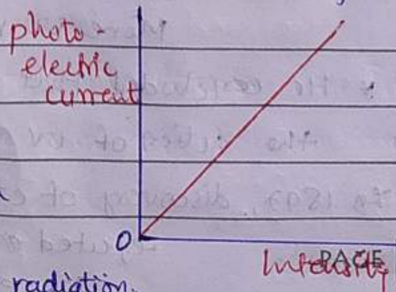
→ Plate A is given Positive or Negative Potential with respect to Plate 'C'.
When a monochromatic radiations of suitable frequency from source 'S' after Being filtered fall on Plate 'C', as a result e^- accelerated towards the Plate 'A' which causes flow of current in the outer circuit.

Space charge: If the Potential of Plate A is kept zero with respect to Plate 'C', some of the electron stuck up in between Plate C & A, known as space charge.

NOTE: Space charges decreases the Probability of the emitted Photoelectron to reach Plate 'A'.

a) Effect of intensity of the incident radiation on Photoelectric current:

; Photoelectric current varies linearly with the intensity of the incident radiation.



NOTE: As the Photoelectric current is directly proportional to the Number of Photoelectrons emitted Per second, which are directly proportional to the intensity of incident radiation.

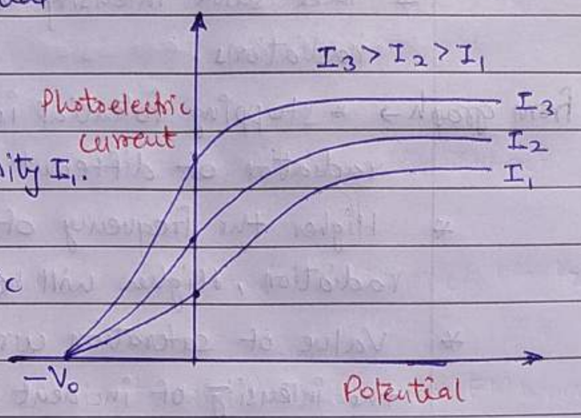
b) **Effect of Potential of Plate A w.r.t to plate 'C' on photoelectric current:**

→ Keep the plate A at some positive potential w.r.t plate 'C'.

→ Now exposed the plate 'C' to the radiation of fixed frequency and intensity I_1.

→ Vary the positive potential of plate A gradually and we see that photoelectric current also increases gradually.

→ But at one stage, for certain value of potential, current becomes maximum or saturates.



Saturation current: If we increase the positive potential of plate A, there is no increase in the value of current. This maximum value of current is known as saturation current.

Stopping potential or cut off potential: It is the minimum negative potential 'V_0' which is given to the plate A w.r.t plate 'C' at which photoelectric current becomes zero.

If e = charge on photoelectron.

then $(K.E)_{max} = eV_0 = \frac{1}{2} m v^2_{max}$ → Max^m vel. of emitted e^-.

m → Mass of an electron

Conclusions:

1) All the emitted photoelectrons from metal 'C' are not having same kinetic energy.

2) The maximum K.E of emitted photoelectrons depends on the radiation source and nature of material of plate c but is independent of the intensity of incident radiation.

NOTE: * On doubling the intensity of light, the number of photons incident on plate 'C' per unit time becomes double. Due to this no. of emitted photoelectrons per unit time would not be doubled.

Because all the incident photons do not take participation in the process of photoelectric emission.

* During photoelectric emission, emitted electrons can move in any direction with any velocity.

NOTE: [Time-lag b/w the incident radiation and emission of photo-electrons is less than 10^{-9} second.]

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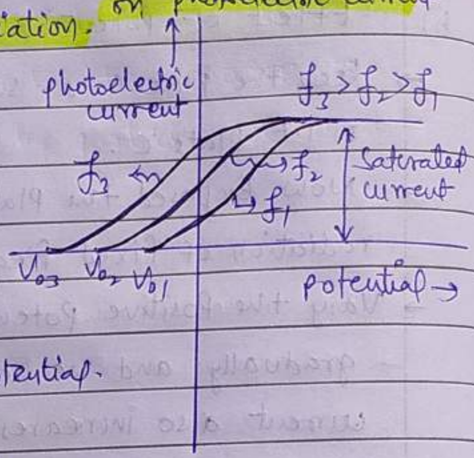
(c) Effect of frequency of the incident radiation on photoelectric current

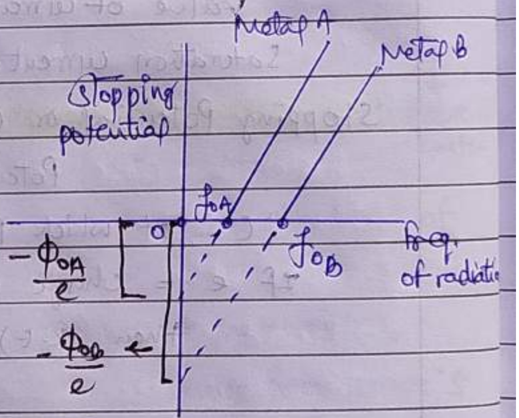
→ Take same intensity of different radiations.



from graph → * Stopping Potential is different for radiation of different frequencies.

* Higher the frequency of incident radiation, Higher will be the stopping potential.
* Value of saturation current depends on the intensity of incident radiation but is independent of the frequency of the incident radiation.

(d) Stopping Potential (Vs) frequency of incident radiation for two different metals A and B.



from graph → * Stopping Potential varies linearly with the frequency of the incident radiation.

* At Threshold frequency (f_0), stopping Potential is zero and f_{0A} & f_{0B} are different for both metal A & B.
* Higher is the work function of the metal, greater is the value of threshold frequency.
* Intercept on Potential axis $= -\frac{\phi_0}{e} = -\frac{hf_0}{e}$

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Laws of Photo-electric emission:-

1) No of ejected Photoelectrons per second ∝ intensity of incident light.

2) Below the value of threshold frequency, emission of Photoelectron is not Possible.

3) Above the threshold frequency, Maximum Kinetic Energy of the emitted photoelectrons is independent of the intensity of the incident light but depends only upon the frequency (or wavelength) of the incident light.

4) Photoelectric emission is an instantaneous Process. i.e. Time lag b/w the incidence radiation and emission of Photoelectrons is very small ($\sim 10^{-9}$ seconds).

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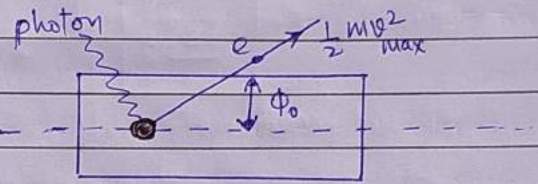
Einstein's Photoelectric Equation : Energy Quantum of Radiations.

Planck's quantum theory: Light radiations consist of tiny Particle Packets of Energy called 'quanta'. One quantum of light radiation is called a photon which travels with the speed of light.

* Energy of Photon is given by $E = hf$ → frequency of light radiation
  ↳ Planck's constant

Consider a photon of Energy hf incident on photosensitive plate,



spent in two ways:

i) to liberate the electron from the metal surface which is equal to the work function ϕ_0 of the metal.

ii) Rest of the Energy is used to give Maximum kinetic energy to the emitted photoelectron.

If v_{max} = Max^m vel. of emitted photoelectrons

m = Mass of the e^-.

$$\therefore (K.E)_{Max} = \frac{1}{2} m v^2_{Max}$$

or Total Energy of the photon = work function of metal + $(K.E)_{max}$

$$hf = \phi_0 + (K.E)_{Max}$$

$$(\text{or}) \quad (K.E)_{max} = \frac{1}{2} m v^2_{Max} = hf - \phi_0$$

Above equation is called Einstein's photoelectric equation.

Cond^n If the incident photon is of threshold frequency f_0, then the incident photon of Energy $= hf_0$ is sufficient to eject the electron from the metal surface without imparting it any kinetic energy.

$$\therefore hf_0 = \phi_0 = \text{work function of metal.}$$

$$(\text{or}) \quad K.E_{max} = \frac{1}{2} m v^2_{max} = hf - hf_0 = h(f - f_0)$$

$$(K.E)_{max} = h(f - f_0)$$

Consequences of Photoelectric emission:

The photoelectric emission is possible only, if incident light is in form of Packets of Energy, each having a definite value, more than the work

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function of the metal. This shows that light is not of wave Nature but of Particle Nature. It is due to this reason that Photoelectric emission was accounted by particle Nature of light.

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Relation between cut off potential, Frequency of incident photon and Threshold frequency/wavelength.

$W = qV$
$W = eV$
↳ work stored in the form of K.E
$\therefore K.E = eV$

We know, $(K.E)_{Max} = hf - \phi_0$ — (I) and $(K.E)_{Max} = eV_0$ — (II)

If f_0 is the threshold frequency then work function

$$\phi_0 = hf_0 \quad \text{— (III)}$$

from equation (I) & (II) $\longrightarrow$ $eV_0 = hf - \phi_0$ — (IV)

Put value of ϕ_0 in equ^n (IV)

$$\therefore eV_0 = hf - hf_0$$

(or) $eV_0 = (K.E)_{Max} = h(f - f_0)$

As $c = f\lambda$ and $c = f_0\lambda$
↳ or, $f = \frac{c}{\lambda}$ ↳ or, $f_0 = \frac{c}{\lambda_0}$

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$$\therefore eV_0 = (K.E)_{Max} = h\left(\frac{c}{\lambda} - \frac{c}{\lambda_0}\right) = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$$

Now, we can write equ^n (IV) as

$$V_0 = \frac{hf}{e} - \frac{\phi_0}{e} \quad \text{— (V)}$$

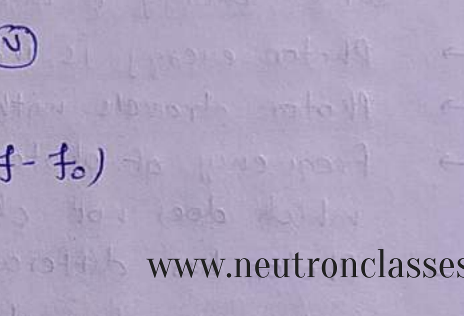
compare the above equation with $y = mx + c$ — (VI) (m → slope of line $(= \tan\theta)$)

from graph $\tan\theta = \frac{\Delta V_0}{\Delta f}$ (slope of line)

After comparison of equ^n (V) & (VI) we get,

$$m = \frac{h}{e}$$

$$\therefore \tan\theta = \frac{h}{e} = \frac{\Delta V_0}{\Delta f}$$



(or) $h = e\tan\theta = e \times$ slope of V_0 vs f → To find Planck's const.

Again, from Graph $OC = -\frac{\phi_0}{e}$

(or) $|-\phi_0| = e \times OC$ → To find work function of Metal.

Particle Nature of Light (The Photon)

A/c quantum theory of light, light consists of the packet of Energy which travels in straight line, with the speed of light. Each packet of energy is called photon or quantum of light. ($= hf = hc/\lambda$)

Characteristics of a photon:

- Each photon has Energy ($E = hf$) and momentum ($p = \frac{hf}{c} = \frac{h}{\lambda}$).
- All photons of a particular frequency f or wavelength λ have the same energy E and momentum.
- Photon energy is independent of the intensity of radiations.
- Photon travels with the speed of light.
- frequency of photons gives the radiations, a definite energy (or colour) which does not change when photon travels through different media.
- Photon has different velocity in different media. (c & wavelength changes)
- Rest mass of a photon is zero.

$$\text{as} \quad M = \frac{M_0}{\sqrt{1 - v^2/c^2}} \quad \text{(or)} \quad M_0 = M\sqrt{1 - v^2/c^2}$$

Rest Mass → $M_0 = 0$ (because $v = c$ for photon)

- photons are not deflected by Electric field and Magnetic field. (This shows that photons are electrically Neutral)
- During collision of photons - particles (photo-electrons), the energy and momentum are conserved. However number of photons may not be conserved. (photon may be create or destroy).
- Power of a light source in terms of Number of photons (n)

$$\text{Power} = \frac{\text{Energy}}{\text{time}} = \frac{nhf}{1} = nhf$$

NOTE:
- Photon is not a material particle But it is a packet of energy.
- Intensity of radiation depends on Number of photons present in it.
- Energy of photons depends on the frequency of radiation, Not on intensity of radiation.
- Equivalent mass of a photon $= \frac{hf}{c^2} = \frac{h}{\lambda c}$

Failure of wave Theory of light to explain the photoelectric effect:

Huygen's Theory failed because:

1. As, Maximum K.E of the ejected photoelectrons is independent of the intensity of incident light.

   But A/c Huygen's Theory photoelectrons will have Maximum K.E if a light of Maximum intensity fall on the metal surface.

2. As, No photoelectric emission takes place from a metal surface if the frequency of the incident light is less than the threshold frequency, no matter whatsoever may be its intensity.
But A/c Huygen's theory, photoelectric emission will take place even the frequency of light is < threshold frequency of metal.

3. As, The emission of photoelectrons takes place immediately after the light is incident on the metal surface.
But A/c Huygen's theory, incident light distributed its energy to metal surface in equal manner. As a result electrons take time to acquire the required energy to leave the metal surface.

DE-BROGLIE DUALISTIC HYPOTHESIS:

A/c him, " A moving material particle sometimes acts as a wave and sometimes as a particle or a wave is associated with moving particle which controls the particle in every respect.

The wave associated with moving particle is called matter wave or de-Broglie wave whose wavelength called de-Broglie wavelength. and given as.

$$\lambda = \frac{h}{mv}$$

h → Planck's constant
v → velocity of Particle
m → Mass of Particle

Derivation of de-Broglie wavelength:

Energy of photon we know $E = hf$

and A/c Einstein $E = mc^2$

$\therefore hf = mc^2$ (or) $m = \frac{hf}{c^2}$

Momentum of photon is given as

$p = \text{Mass} \times \text{velocity}$

$p = \frac{hf}{c^2} \times c = \frac{hf}{c} = \frac{h}{\lambda}$

(or) $\lambda = \frac{h}{p}$ → De-Broglie assumed that this equation is equally applicable for Both the photons of radiation and other material Particle.

If m is Mass of material Particle
v is the velocity
Then momentum $p = mv$

$\therefore \lambda = \frac{h}{p} = \frac{h}{mv}$ → De-Broglie wave equation for material Particle.

Conclusions from de-Broglie Hypothesis:

→ As, $\lambda \propto \frac{1}{v}$ → Higher will be velocity of material particle, smaller will be the wavelength or vice-versa

→ $\lambda \propto \frac{1}{m}$ → Heavier the mass of material particle, smaller will be the wavelength. or vice-versa

→ If $v = 0 \rightarrow \lambda = \infty$ or vice versa

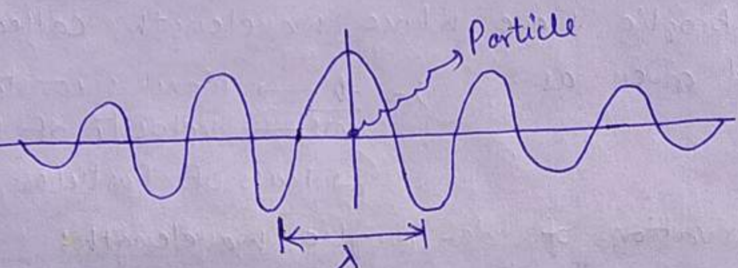
→ De-Broglie waves associated with material particle is independent of charge and nature of particles.

→ De-Broglie waves are not the electromagnetic waves. Because EM waves are produced by motion of charged particles.

→ Mass of moving particle of rest mass m_0 is given as

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}} \Rightarrow \lambda = \frac{h}{mv} = \frac{h\sqrt{1 - v^2/c^2}}{m_0 v}$$

→ Since the position of wave cannot be located exactly, ∴ the wave nature of material particle introduces the problem of particle location.



→ De-Broglie Hypothesis led Heisenberg's Uncertainity principle which states that it is impossible to measure both the position and momentum of a moving particle at a time very accurately.

$$\Delta x \, \Delta p = \frac{h}{2\pi}$$

(Δx → Uncertainity in the specification of position; Δp → uncertainity in the specification of momentum.)

Relation for de-Broglie wavelength and temperature:

From kinetic theory of matter, the average K.E of a particle at a given tempr T kelvin is

$$K = \frac{3}{2} kT \quad (k = \text{Boltzmann constant})$$

and kinetic Energy $K = \frac{1}{2} m v^2$

Momentum of particle $p = mv = m\sqrt{2K/m} = \sqrt{2Km}$

$$(\text{or}) \quad p = \sqrt{2m \tfrac{3}{2} kT} = \sqrt{3mkT}$$

De-Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{\sqrt{3mkT}}$

De-Broglie wavelength of an Electron:

let m = mass of an electron
e = charge on electron
v = velocity of electron
V = Potential applied

$\therefore$ Gain in K.E $= \frac{1}{2}mv^2$

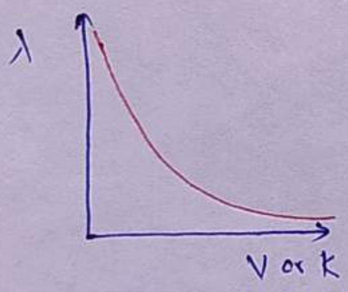
work done on e^- = eV (or) $v = \sqrt{\frac{2eV}{m}}$

A/c De-Broglie Hypothesis

$$\lambda = \frac{h}{mv} = \frac{h}{m\sqrt{\frac{2eV}{m}}} = \frac{h}{\sqrt{2meV}}$$

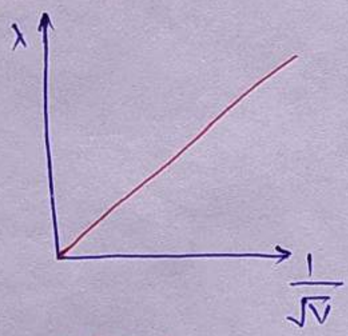
$$(\text{or})\ \lambda = \frac{6.63\times10^{-34}}{\sqrt{2\times9\times10^{-31}\times1.6\times10^{-19}\times V}}$$

$$\lambda = \frac{12.27}{\sqrt{V}}\times10^{-10}\,m = \frac{12.27}{\sqrt{V}}\,\mathring{A}$$



λ (VS) V or K.E

λ (VS) $\sqrt{V}$



λ (VS) $\frac{1}{\sqrt{V}}$

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