The photoelectric effect

The Compton effect

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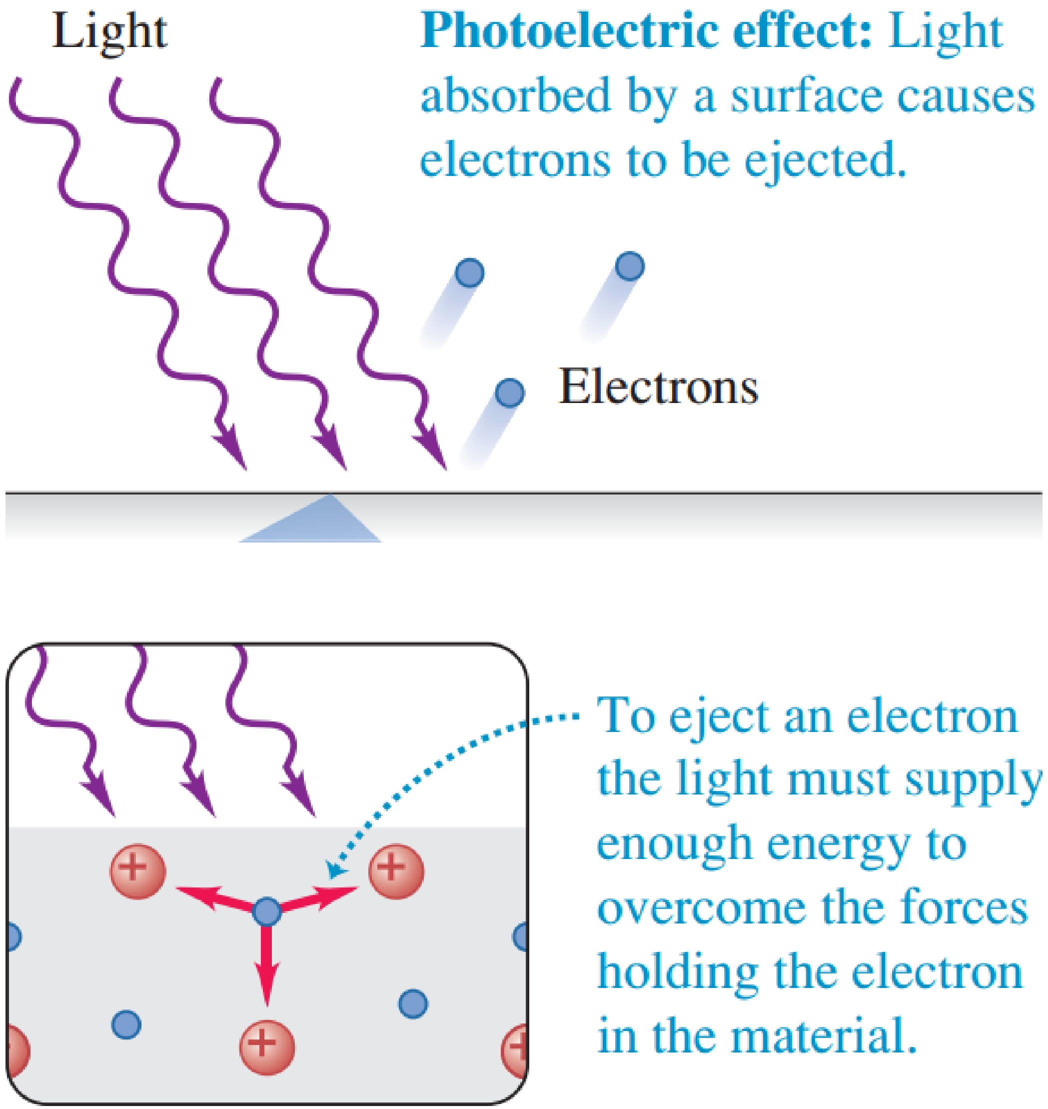
Reference

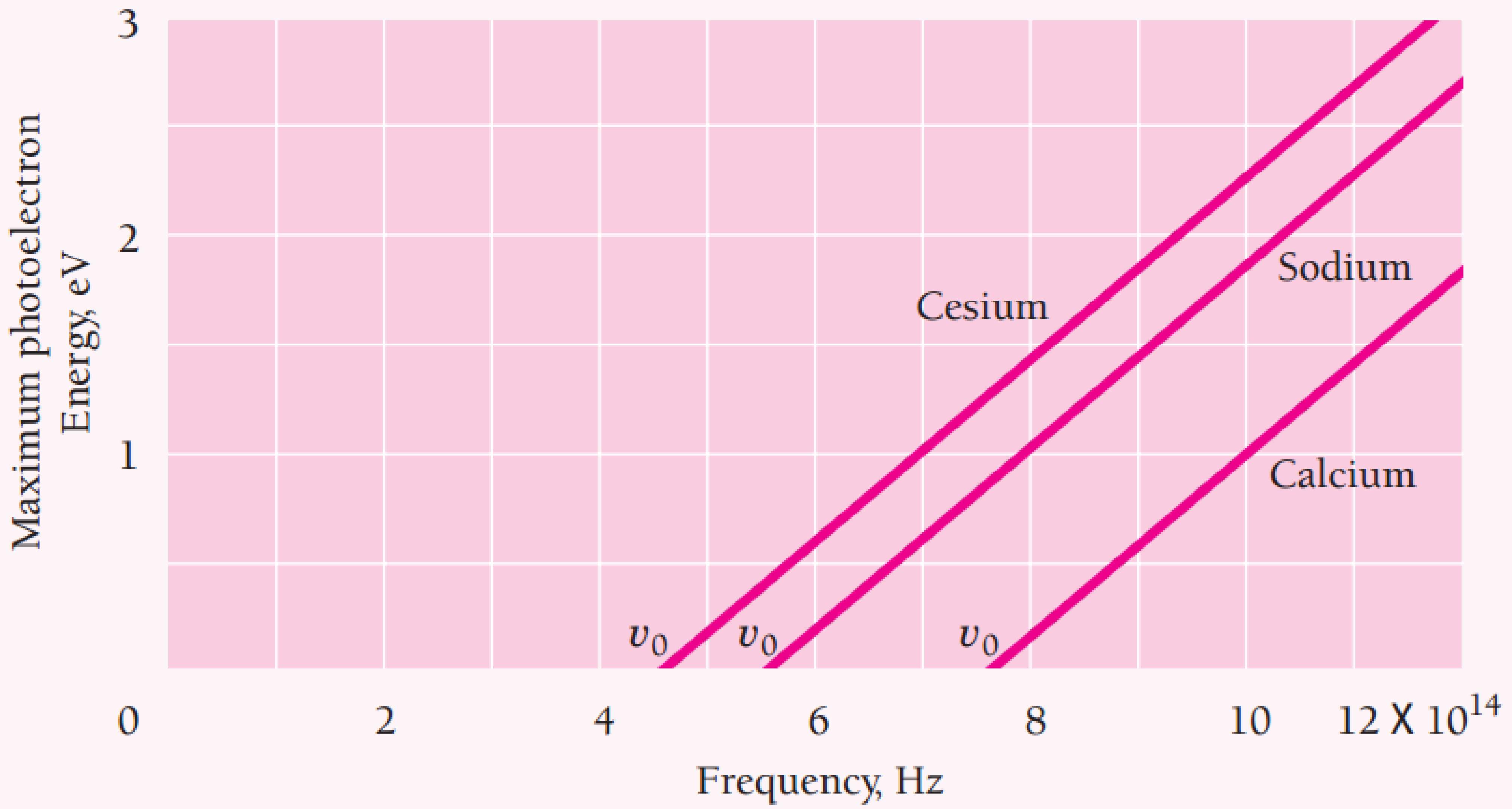
Concepts of Modern Physics (6th Ed) – Arthur Beiser

University Physics with Modern Physics (13th Ed) – Young, Freedman

What is light?

Photoelectric effect





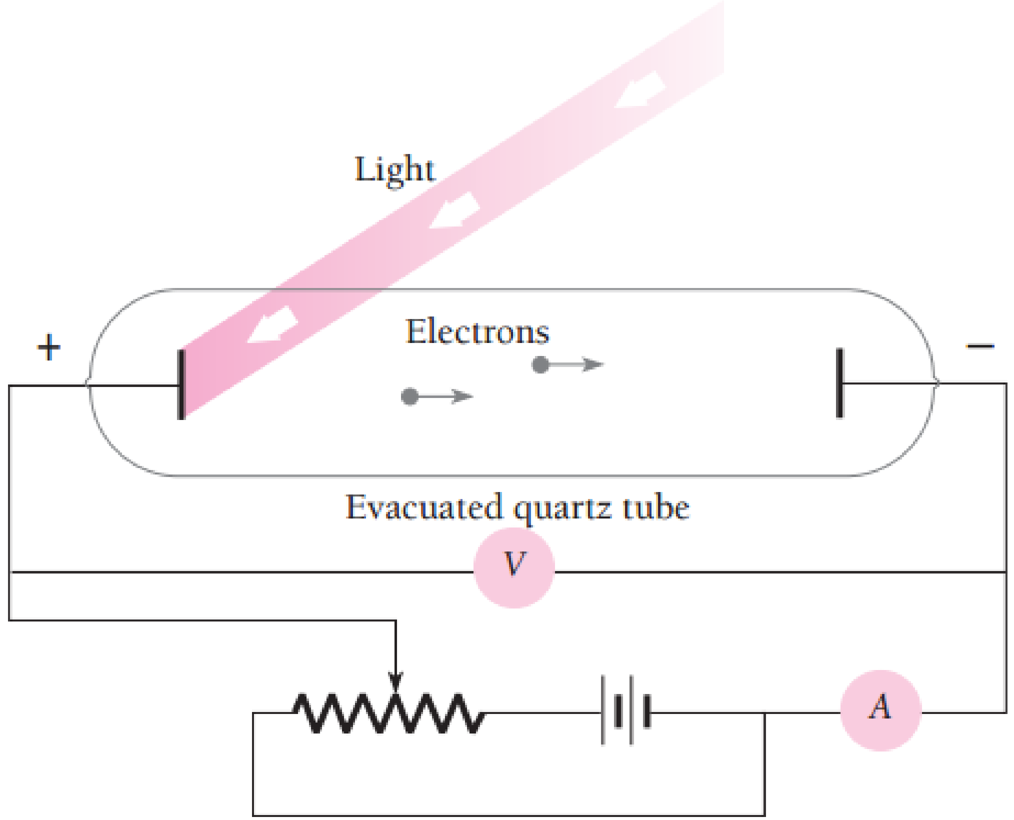
Maximum photoelectron Energy, eV
3
2
1
0
2
4
6
8
10
12 X 10^14
Frequency, Hz
Cesium
Sodium
Calcium
v_0
v_0
v_0

Experimental observation of the photoelectric effect

1. The effect is instantaneous.

2. Bright light yields more photo-electrons than a dim light.

3. Higher frequency light produce more energetic photoelectron.



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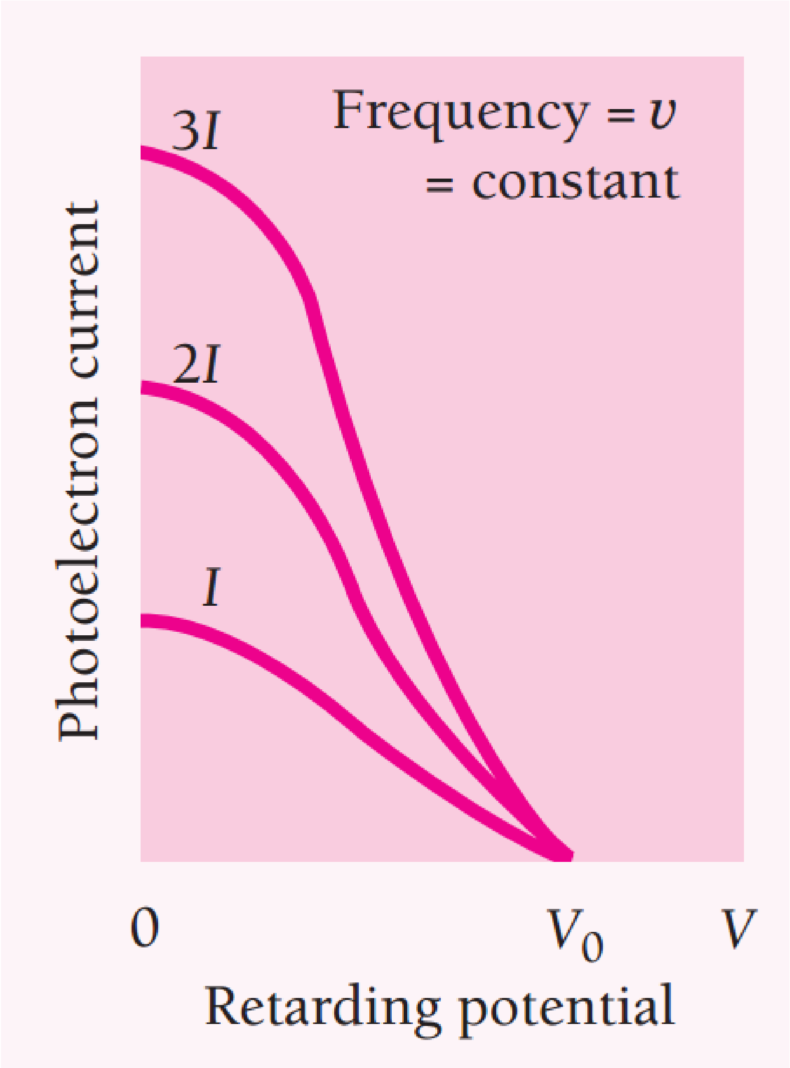

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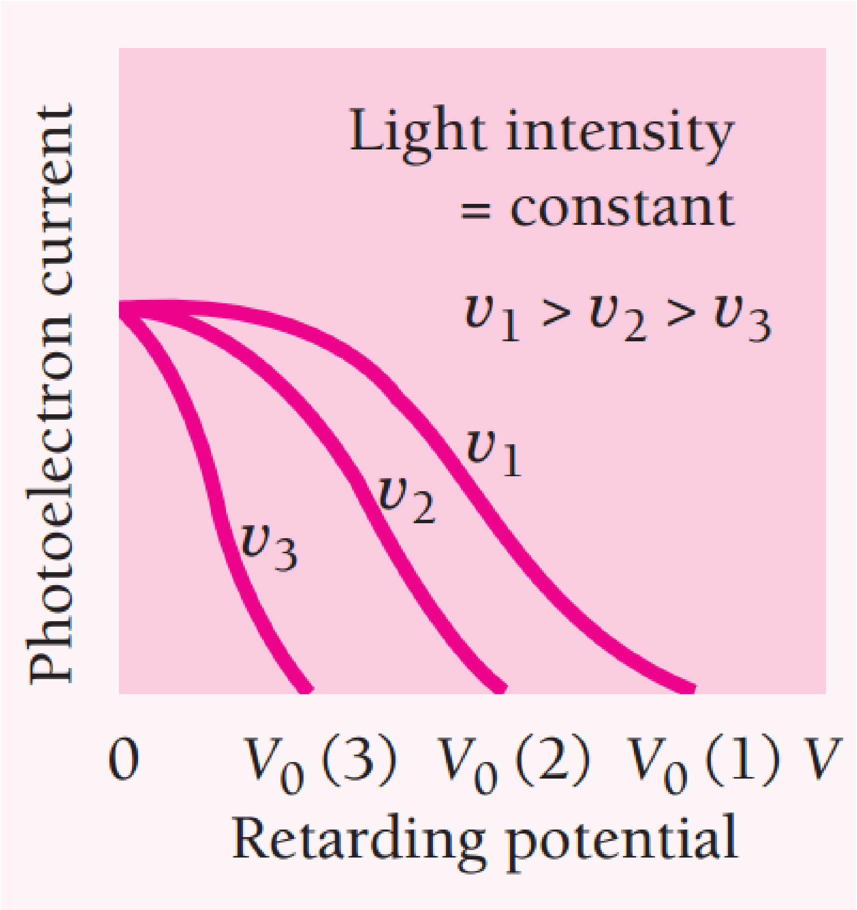


Quantum Theory of Light

In 1905, Einstein realized that the photoelectric effect could be understood if the energy in light is not spread out over wavefronts but is concentrated in small packets, or photons.

Each photon of light of frequency ν has the energy $h\nu$, the same as Planck's quantum energy.

Quantum Theory of Light

Planck had thought that, although energy from an electric oscillator apparently had to be given to em waves in separate quanta of hν each, the waves themselves behaved exactly as in conventional wave theory. Einstein’s break with classical physics was more drastic: Energy was not only given to em waves in separate quanta but was also car-ried by the waves in separate quanta.

Explanation of the photoelectric effect

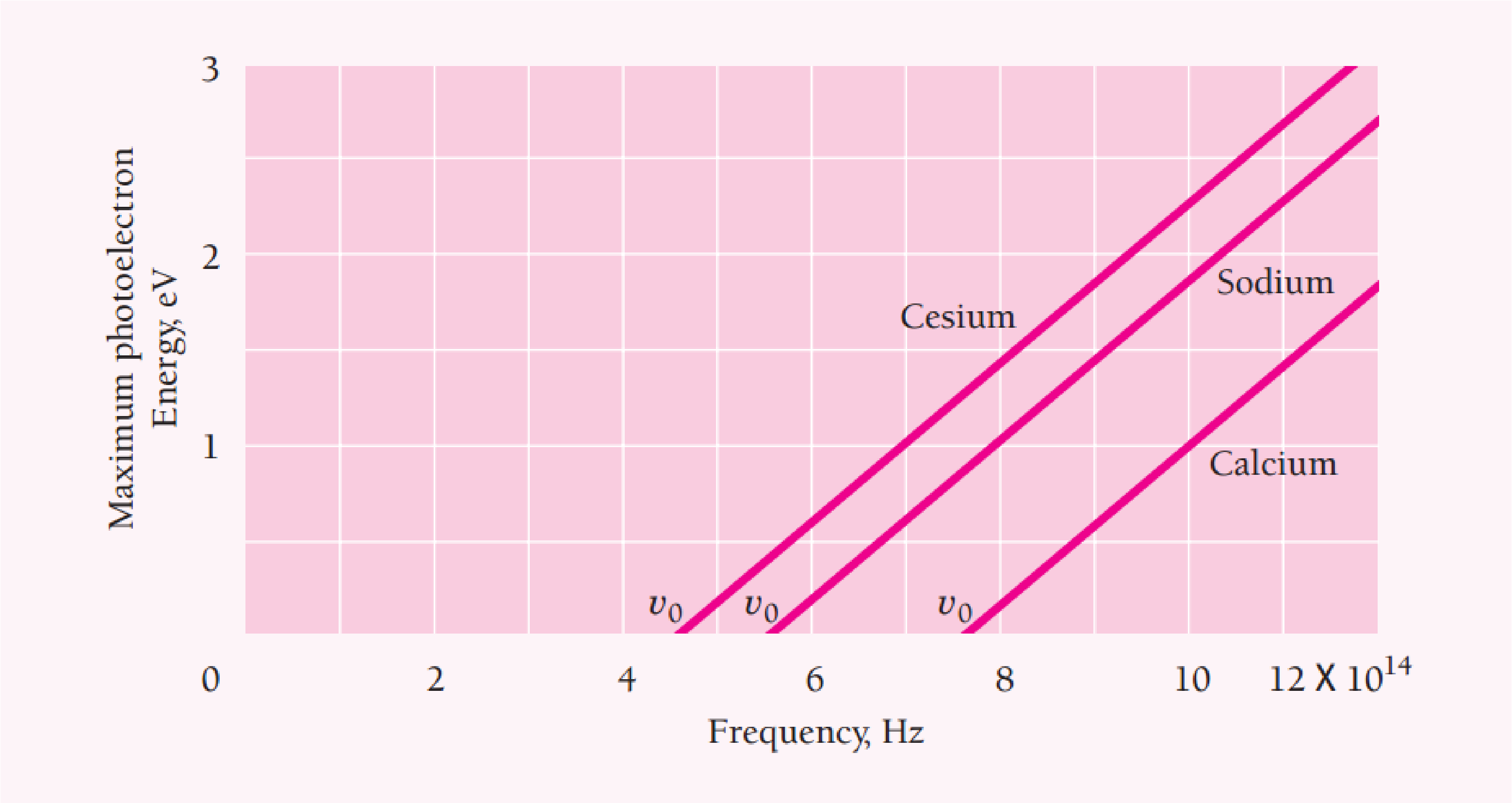
Photoelectric effect $$h\nu = \mathrm{KE}_{\mathrm{max}} + \phi$$

$h\nu$ is the photon energy

$\mathrm{KE}_{\mathrm{max}}$ is the maximum photoelectron energy

$\phi = h\nu_0$ is the work function

$$\boxed{\mathrm{KE}_{\mathrm{max}} = h\nu - h\nu_0 = h(\nu - \nu_0)}$$

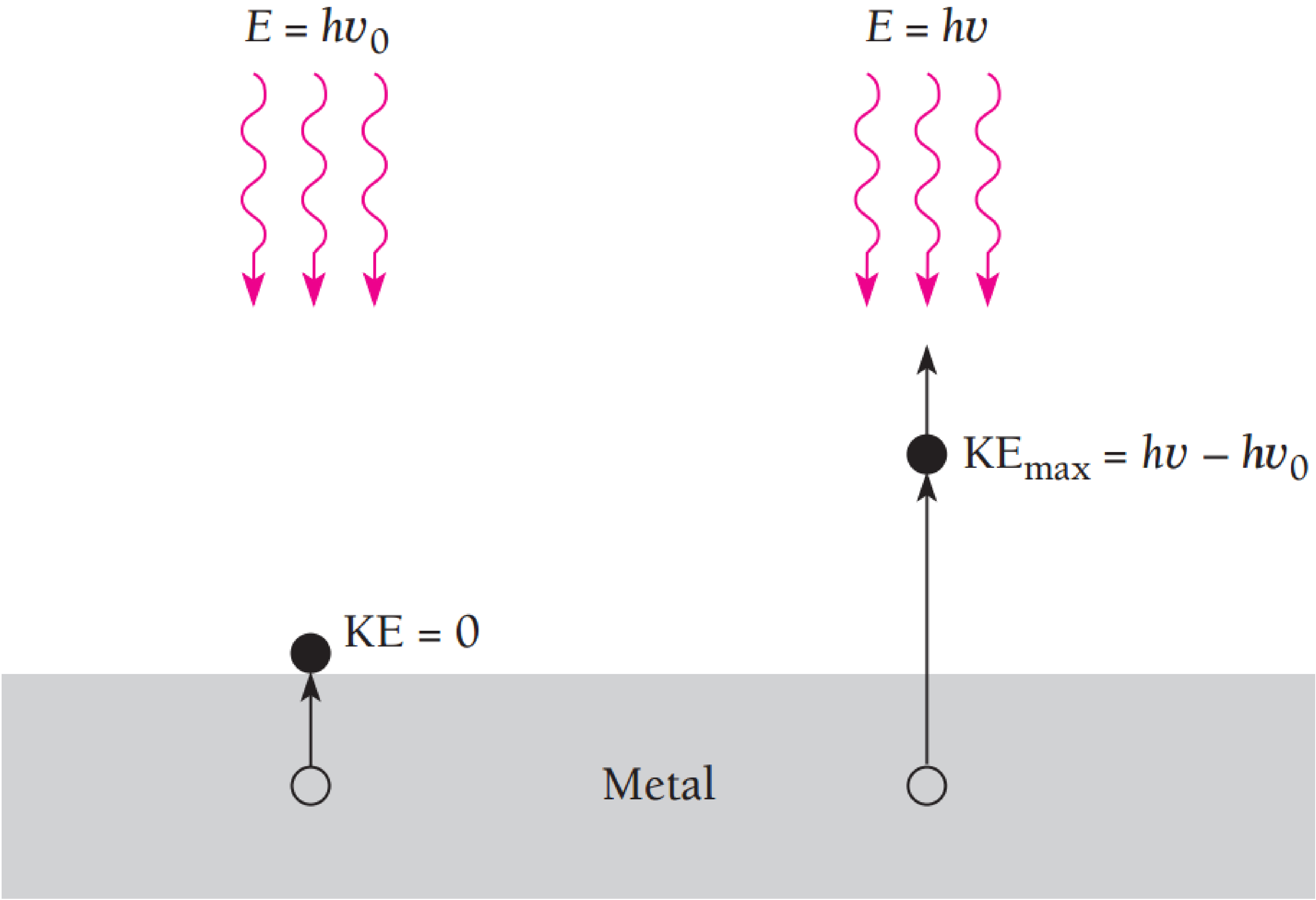


Work function $\phi = h\nu_0$

Planck's constant $h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$

Photoelectric Work Function

Metal	Symbol	Work Function, eV
Cesium	Cs	1.9
Potassium	K	2.2
Sodium	Na	2.3
Lithium	Li	2.5
Calcium	Ca	3.2
Copper	Cu	4.7
Silver	Ag	4.7
Platinum	Pt	6.4


$E = h\upsilon_0$
$E = h\upsilon$
$KE_{max} = h\upsilon - h\upsilon_0$
$KE = 0$
Metal

Explanation of the photoelectric effect

Photoelectric effect $$h\nu = KE_{max} + \phi$$

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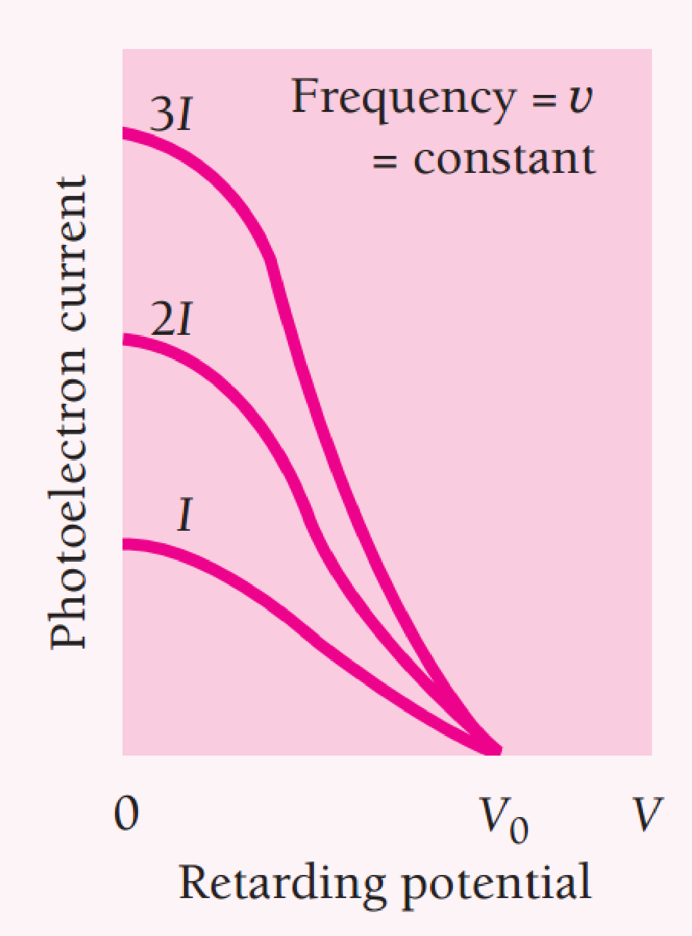
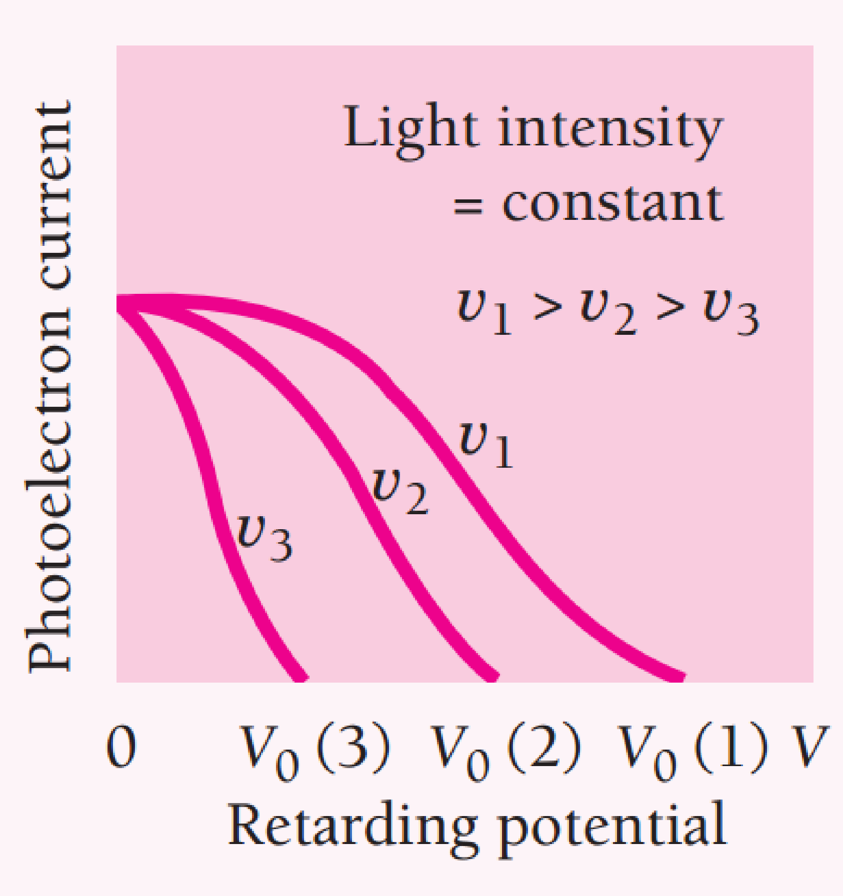
Photoelectric effect $h\nu = \mathrm{KE}_{max} + \phi$





Explanation of the photoelectric effect

- Because em wave energy is concentrated in photons and not spread out, there should be no delay in the emission of photoelectrons.

- All photons of frequency ν have the same energy, so changing the intensity of a monochromatic light beam will change the number of photoelectrons but not their energies.

- The higher the frequency ν, the greater the photon energy $h\nu$ and so the more energy the photo-electrons have.

Photoelectric effect $h\nu = KE_{max} + \phi$

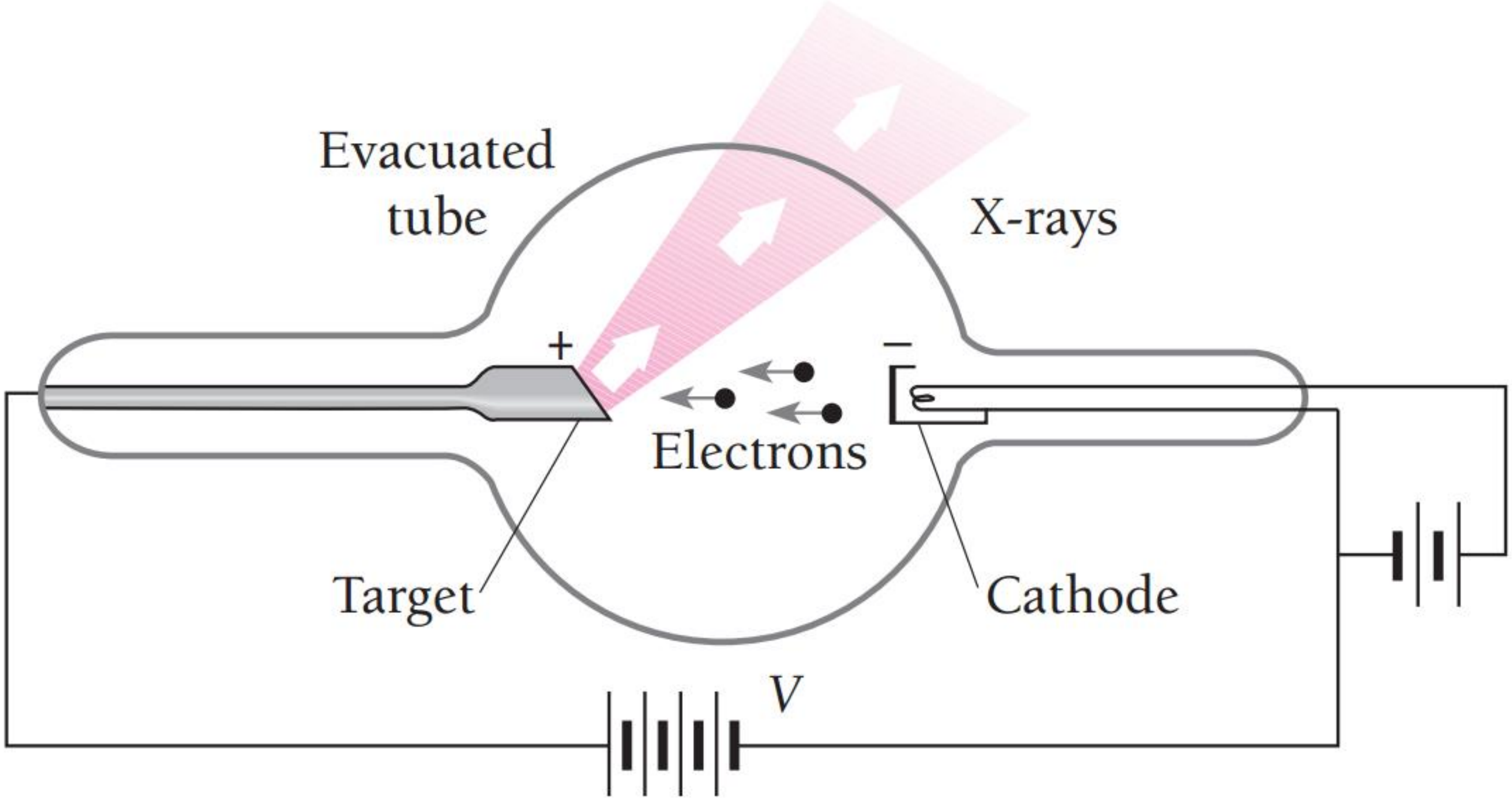
Which of the following substances, given is the metal work function, will be suitable for photocell operable with light of wave length 300 nm?

(a) Silver (4.7 eV)
(b) Cesium (1.9 eV)
(c) Calcium (3.2 eV)
(d) Platinum (6.4 eV)

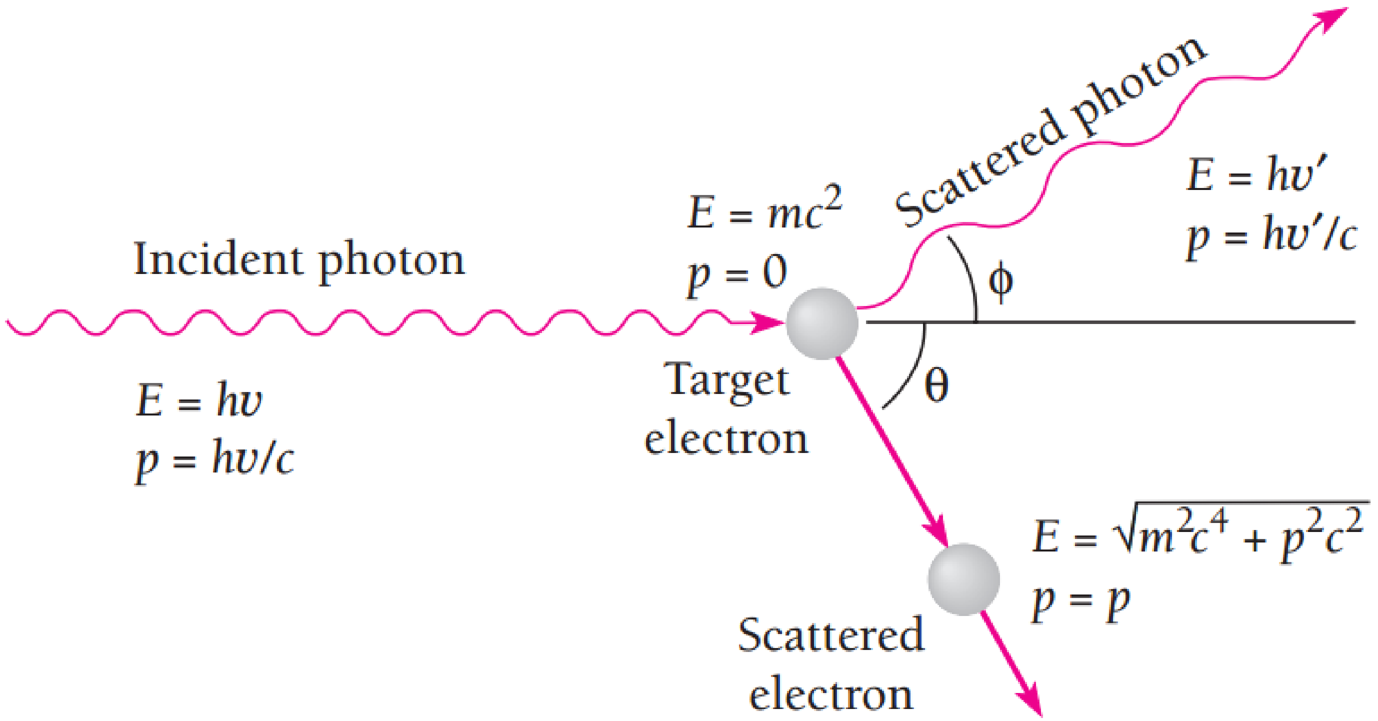
Which of the following substances, given is the metal work function, will be suitable for photocell operable with light of wave length 500 nm?

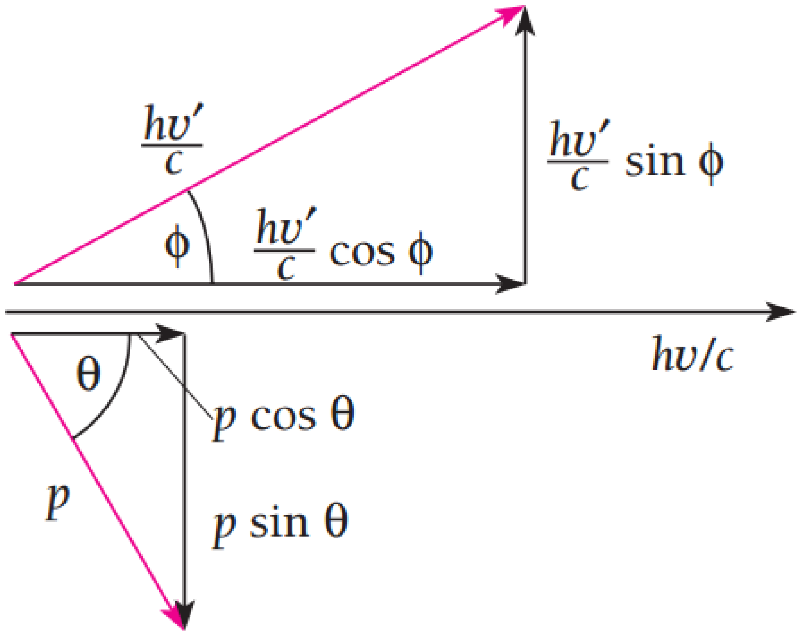
(a) Silver (4.7 eV)
(b) Potassium (2.2 eV)
(c) Cesium (1.9 eV)
(d) Calcium (3.2 eV)

An x-ray tube



The Compton effect

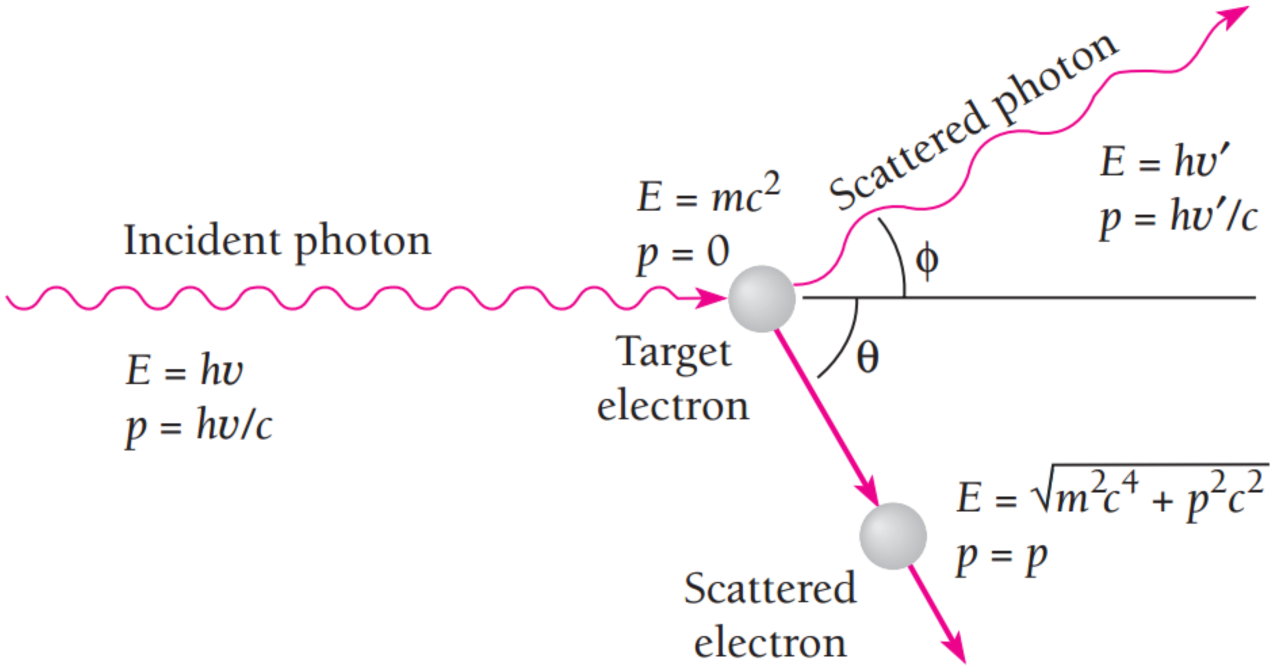




$$\frac{h\nu}{c} + 0 = \frac{h\nu'}{c}\cos\phi + p\cos\theta$$

$$0 = \frac{h\nu'}{c}\sin\phi - p\sin\theta$$

The Compton effect



$$\lambda' - \lambda = \frac{h}{mc}(1 - \cos\phi)$$

Compton wavelength

$$\lambda_C = \frac{h}{mc}$$

Example

X-rays of wavelength 10.0 pm are scattered from a target. (*a*) Find the wavelength of the x-rays scattered through 45°. (*b*) Find the maximum wavelength present in the scattered x-rays. (*c*) Find the maximum kinetic energy of the recoil electrons.

(*a*) From Eq. (2.23), $\lambda' - \lambda = \lambda_C(1 - \cos\phi)$, and so

$$\begin{aligned}\lambda' &= \lambda + \lambda_C(1 - \cos 45°)\\ &= 10.0\ \text{pm} + 0.293\lambda_C\\ &= 10.7\ \text{pm}\end{aligned}$$

(*b*) $\lambda' - \lambda$ is a maximum when $(1 - \cos\phi) = 2$, in which case

$$\lambda' = \lambda + 2\lambda_C = 10.0\ \text{pm} + 4.9\ \text{pm} = 14.9\ \text{pm}$$

Example

X-rays of wavelength 10.0 pm are scattered from a target. (*a*) Find the wavelength of the x-rays scattered through 45°. (*b*) Find the maximum wavelength present in the scattered x-rays. (*c*) Find the maximum kinetic energy of the recoil electrons.

(*c*) The maximum recoil kinetic energy is equal to the difference between the energies of the incident and scattered photons, so

$$KE_{max} = h(\nu - \nu') = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right)$$

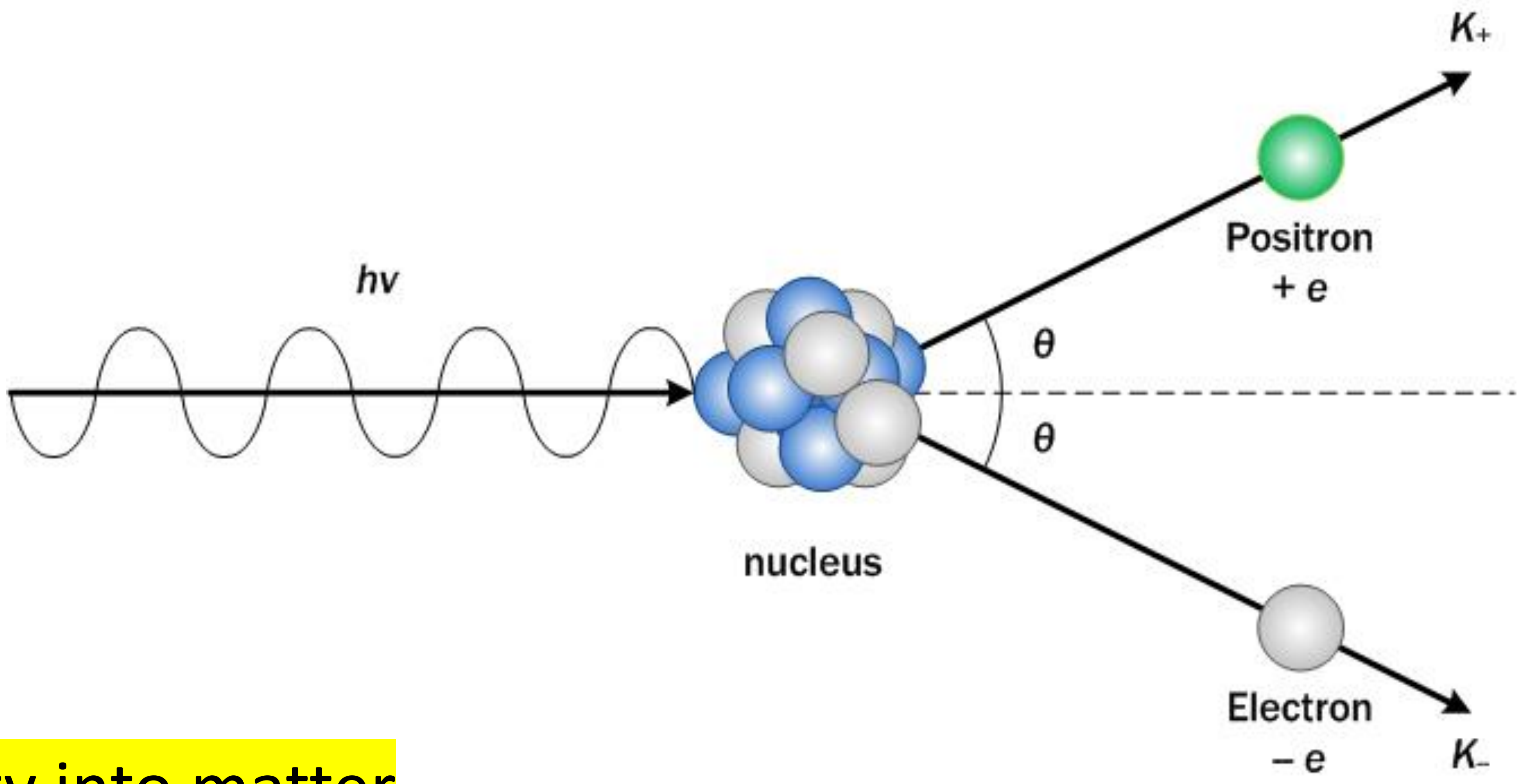
where λ' is given in (*b*). Hence

$$KE_{max} = \frac{(6.626 \times 10^{-34}\ \mathrm{J \cdot s})(3.00 \times 10^{8}\ \mathrm{m/s})}{10^{-12}\ \mathrm{m/pm}}\left(\frac{1}{10.0\ \mathrm{pm}} - \frac{1}{14.9\ \mathrm{pm}}\right)$$

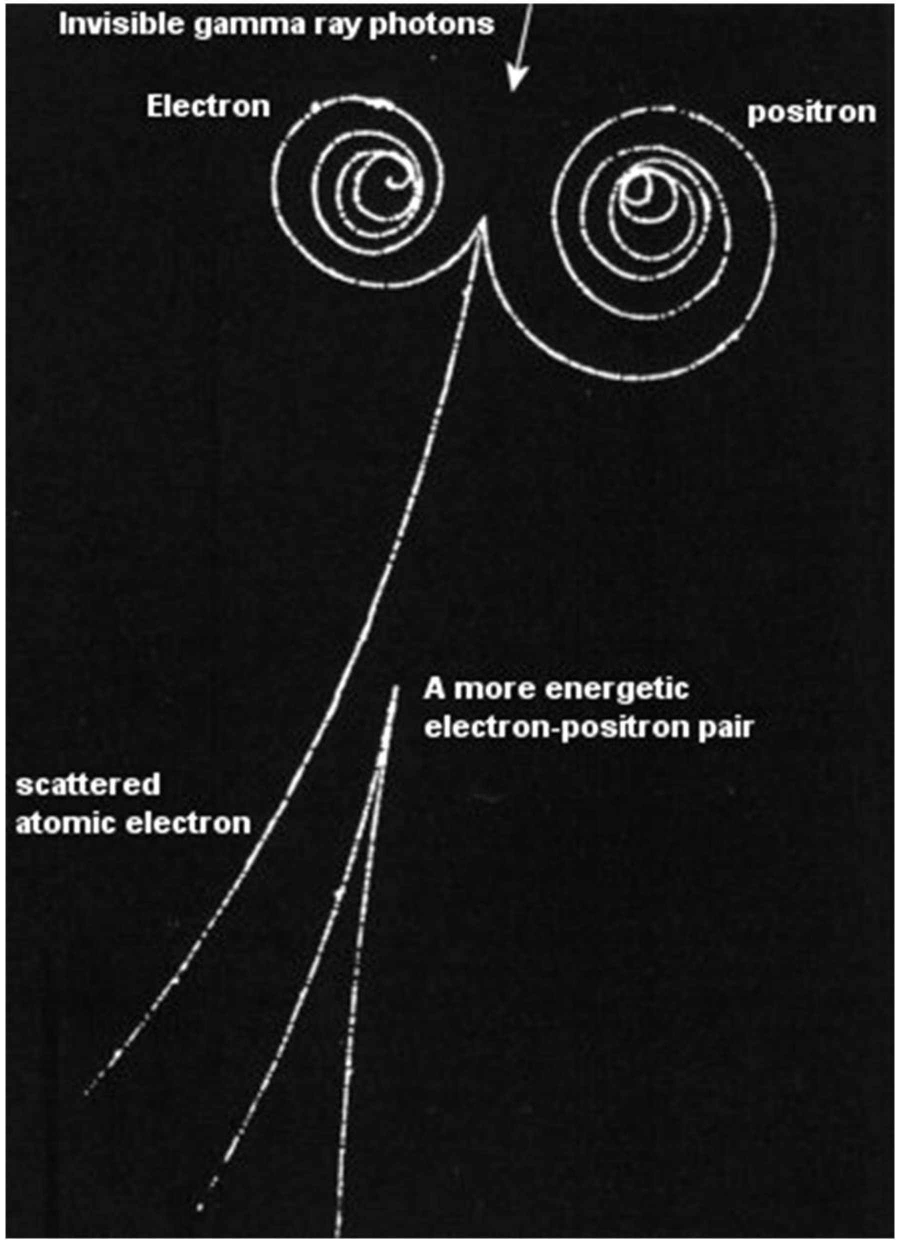
$$= 6.54 \times 10^{-15}\ \mathrm{J}$$

which is equal to 40.8 keV.

Pair Production



Energy into matter



Pair Production

Pair Annihilation

WHAT IS LIGHT?

Both wave and particle

De Broglie Wavelength

Photon wavelength $\lambda = \dfrac{h}{p}$

De Broglie wavelength $\lambda = \dfrac{h}{\gamma m v}$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

Example

Find the de Broglie wavelengths of (*a*) a 46-g golf ball with a velocity of 30 m/s, and (*b*) an electron with a velocity of 10^7 m/s.

Solution

(*a*) Since $v \ll c$, we can let $\gamma = 1$. Hence

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}}{(0.046\ \text{kg})(30\ \text{m/s})} = 4.8 \times 10^{-34}\ \text{m}$$

The wavelength of the golf ball is so small compared with its dimensions that we would not expect to find any wave aspects in its behavior.

Example

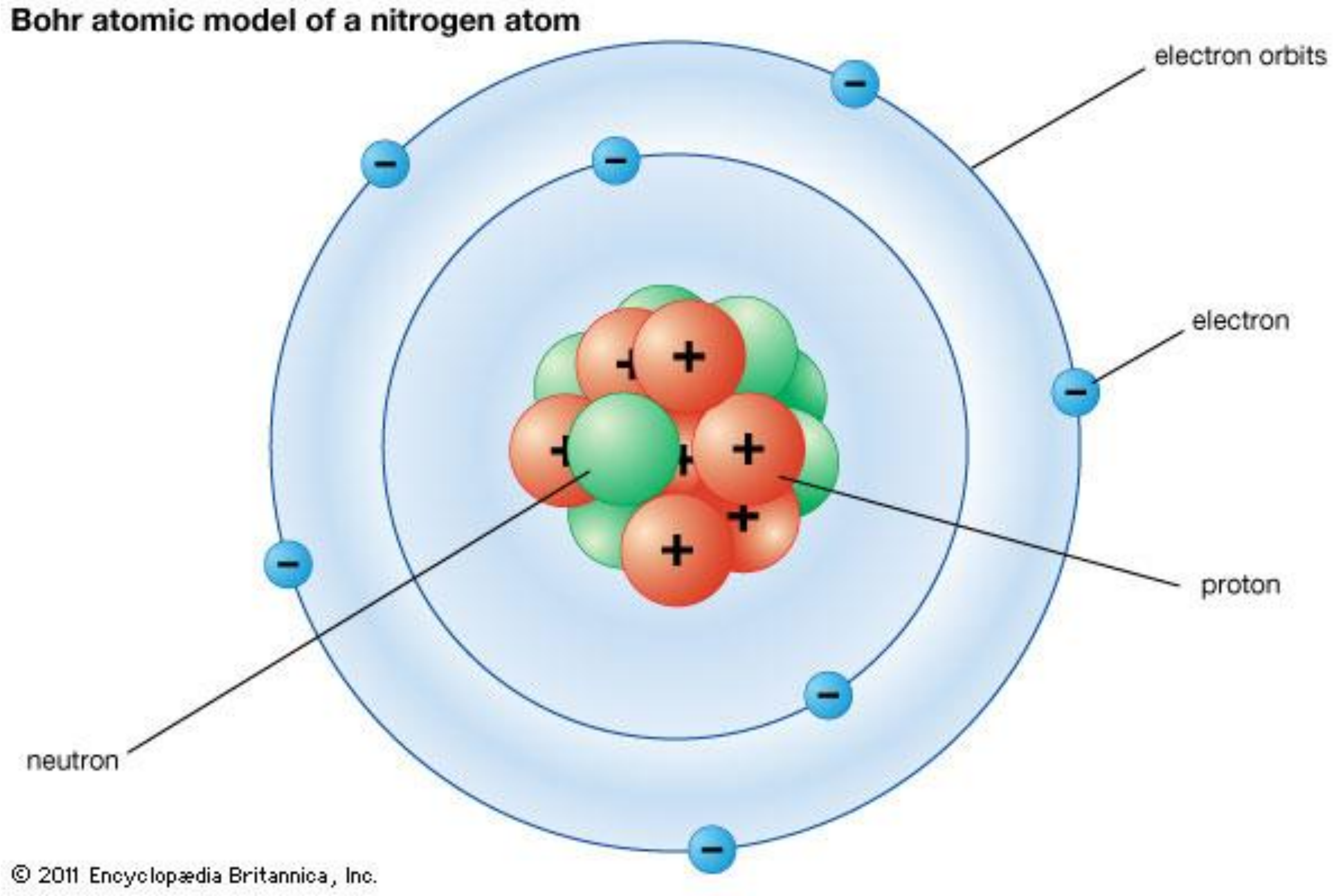
Find the de Broglie wavelengths of (*a*) a 46-g golf ball with a velocity of 30 m/s, and (*b*) an electron with a velocity of 10^7 m/s.

Solution

(*b*) Again $\boldsymbol{v} \ll c$, so with $m = 9.1 \times 10^{-31}$ kg, we have

$$\lambda = \frac{h}{m\boldsymbol{v}} = \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{(9.1 \times 10^{-31}\ \text{kg})(10^7\ \text{m/s})} = 7.3 \times 10^{-11}\ \text{m}$$

The dimensions of atoms are comparable with this figure—the radius of the hydrogen atom, for instance, is 5.3×10^{-11} m. It is therefore not surprising that the wave character of moving electrons is the key to understanding atomic structure and behavior.


Bohr atomic model of a nitrogen atom
electron orbits
electron
proton
neutron
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Bohr Atom Model

In 1913 Niels Bohr presented a new model of the hydrogen atom that circumvented the difficulties of Rutherford’s planetary model.

Bohr’s theory was historically important to the development of quantum physics, and it appeared to explain the spectral line series.

Bohr combined ideas from Planck’s original quantum theory, Einstein’s concept of the photon, Rutherford’s planetary model of the atom, and Newtonian mechanics to arrive at a semiclassical structural model based on some revolutionary ideas.

Postulates of Bohr Atom Model

In an atom, electrons (negatively charged) revolve around the positively charged nucleus in a definite circular path called as orbits or shells without emission of radiant energy.

Each orbit or shell has a fixed energy and these circular orbits are known as orbital shells.

Condition for orbital stability

$$mvr = \frac{nh}{2\pi} \qquad n = 1, 2, 3, \ldots$$

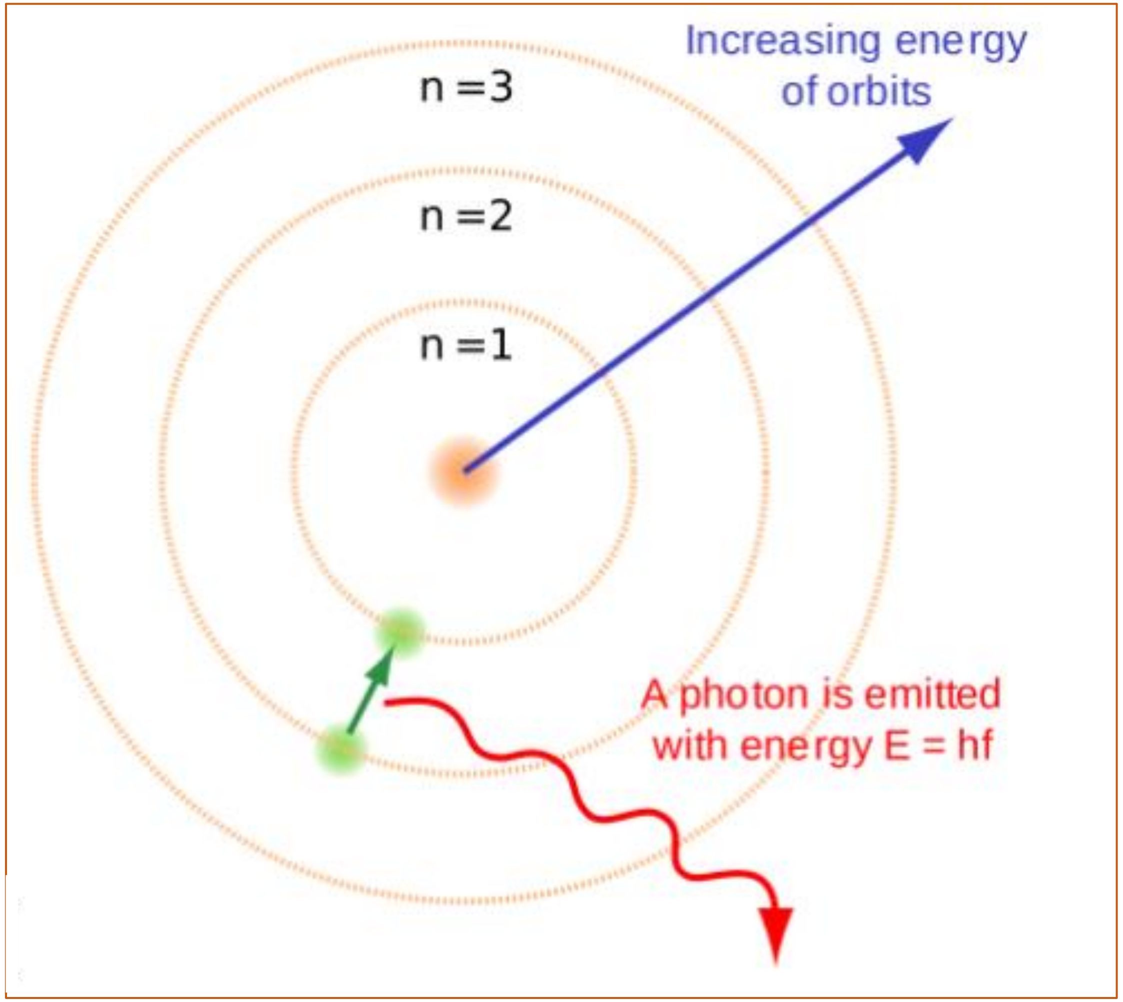
Postulates of Bohr Atom Model

The electrons in an atom move from lower energy level to higher energy level by gaining the required energy and an electron moves from higher energy level to lower energy level by losing energy.

$$\text{Initial energy} - \text{final energy} = \text{photon energy}$$

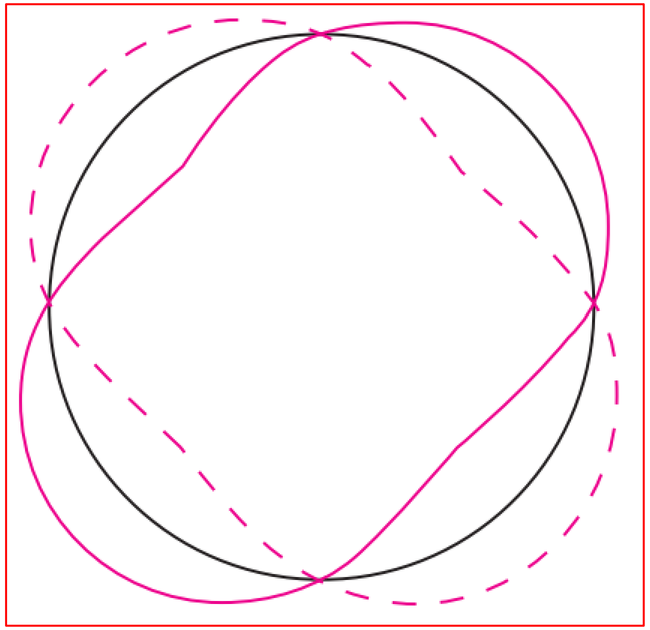
$$E_i - E_f = h\nu$$

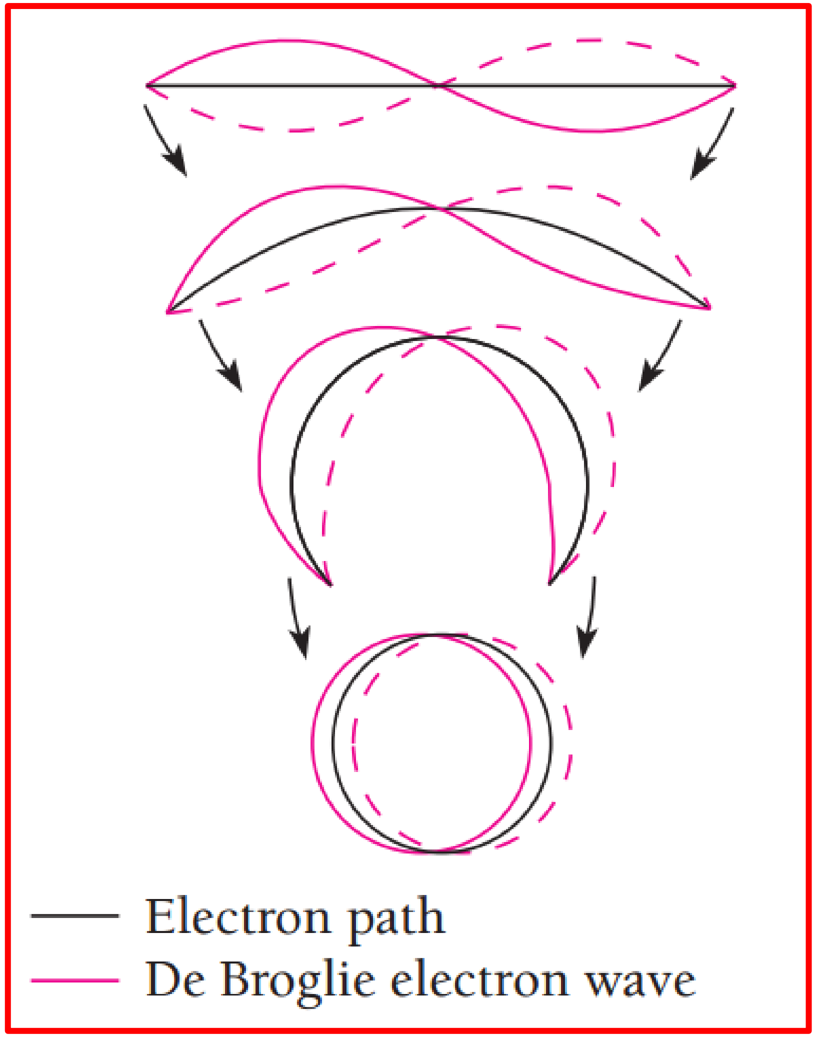
Postulates of Bohr Atom Model



Condition for stable orbit

An electron can circle a nucleus only if its orbit contains an integral number of de Broglie wavelengths.





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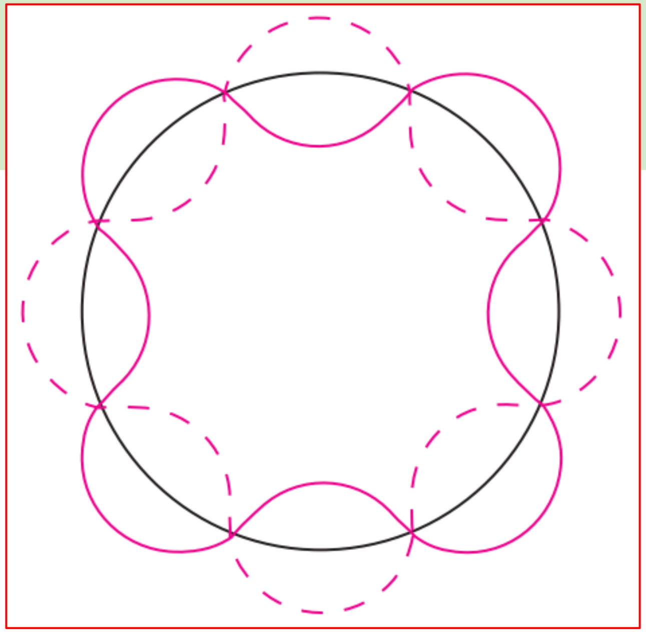

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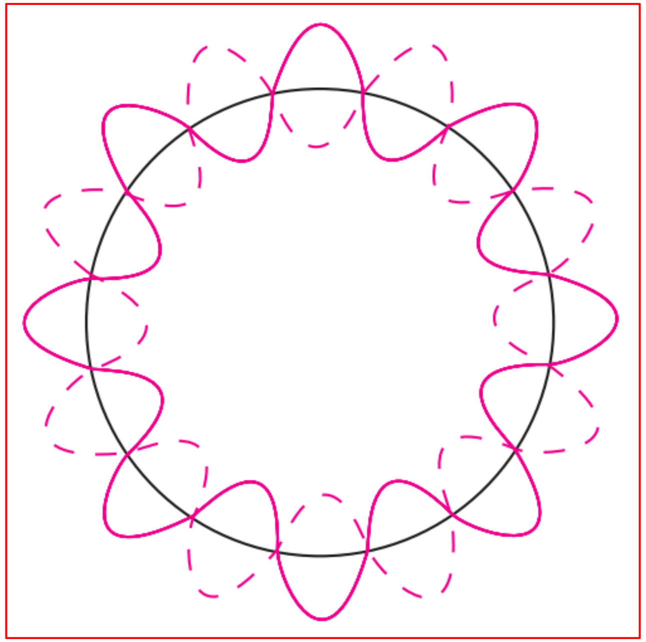
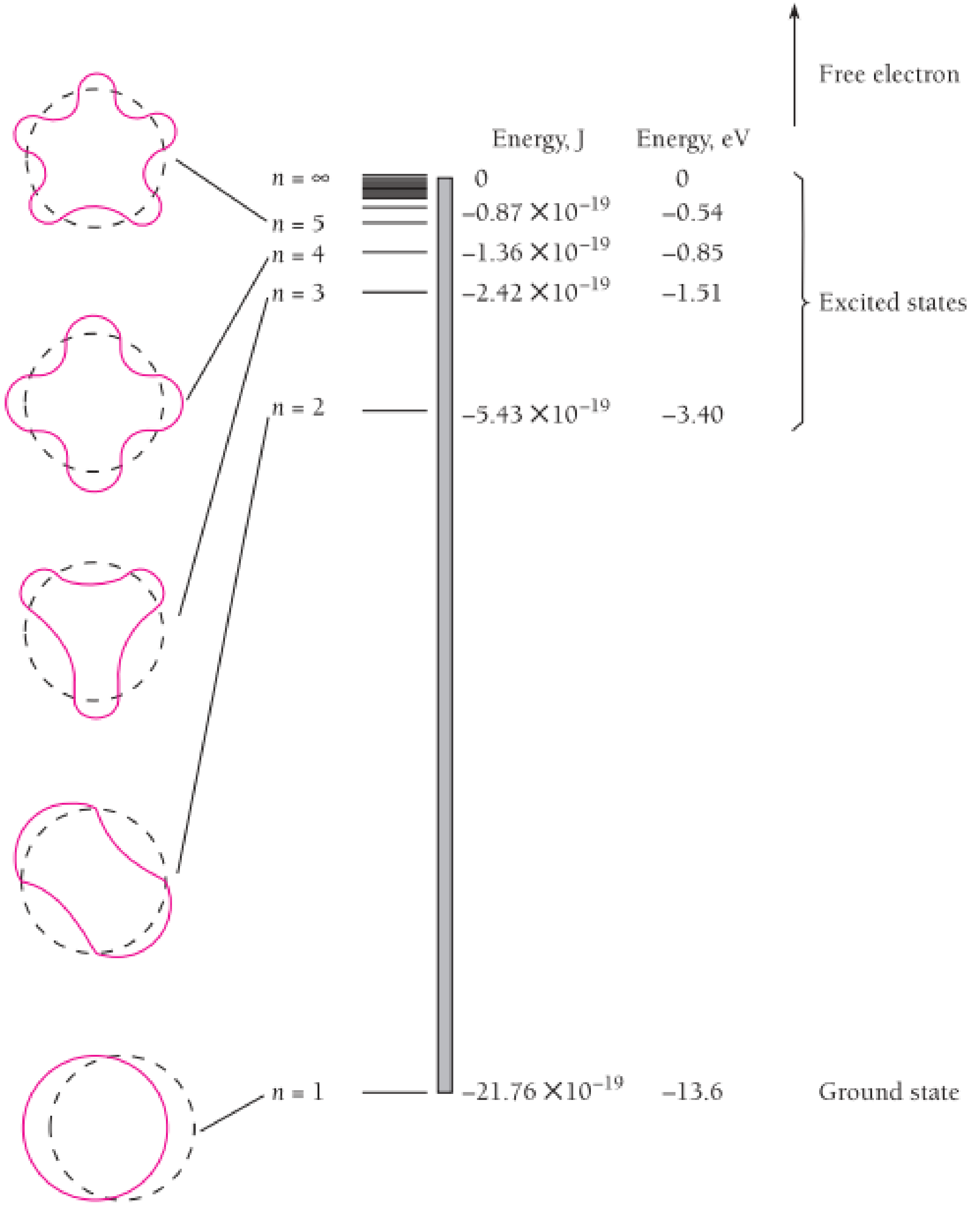
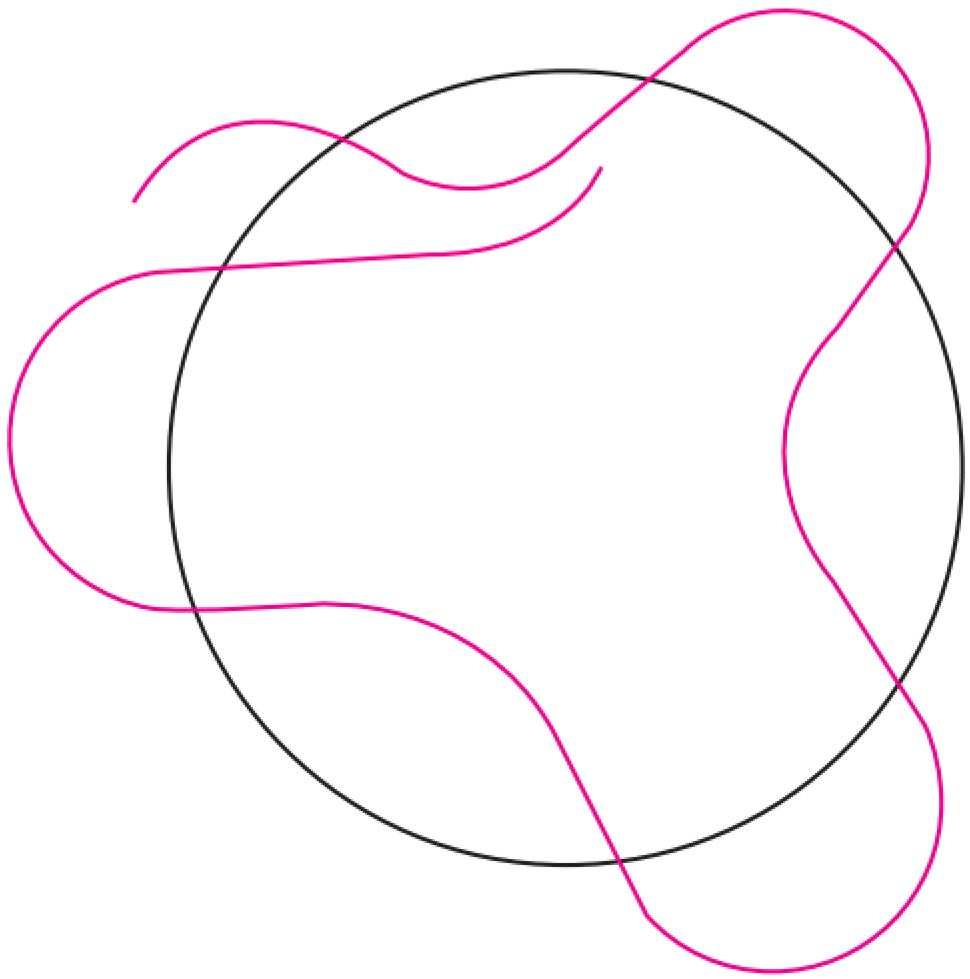


Condition for orbit stability $$n\lambda = 2\pi r_n \qquad n = 1, 2, 3, \ldots$$

Energy levels of hydrogen atom



A fractional number of wavelengths cannot persist because destructive interference will occur



Orbital radii in Bohr atom

The centripetal force $$F_c = \frac{mv^2}{r}$$

The electric force $$F_e = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2}$$

Electron velocity

$$v = \frac{e}{\sqrt{4\pi\epsilon_0 mr}}$$

According to Bohr's first postulate $$mvr = \frac{nh}{2\pi} \qquad n = 1, 2, 3, \ldots$$

Orbital radii in Bohr atom $$r_n = \frac{n^2h^2\epsilon_0}{\pi me^2}$$

Electron waves in the atom

De Broglie wavelength

$$\lambda = \frac{h}{\gamma m v}$$

Electron velocity

$$v = \frac{e}{\sqrt{4\pi\epsilon_0 m r}}$$

Orbital electron wavelength

$$\lambda = \frac{h}{e}\sqrt{\frac{4\pi\epsilon_0 r}{m}}$$

Electron waves in the atom

$$\lambda = \frac{6.63 \times 10^{-34}\ \mathrm{J \cdot s}}{1.6 \times 10^{-19}\mathrm{C}} \sqrt{\frac{(4\pi)(8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2})(5.3 \times 10^{-11}\mathrm{m})}{9.1 \times 10^{-31}\ \mathrm{kg}}}$$

$$= 33 \times 10^{-11}\ \mathrm{m}$$

This wavelength is exactly the same as the circumference of the electron orbit,

$$2\pi r = 33 \times 10^{-11}\ \mathrm{m}$$

The orbit of the electron in a hydrogen atom corresponds to one complete electron wave joined on itself