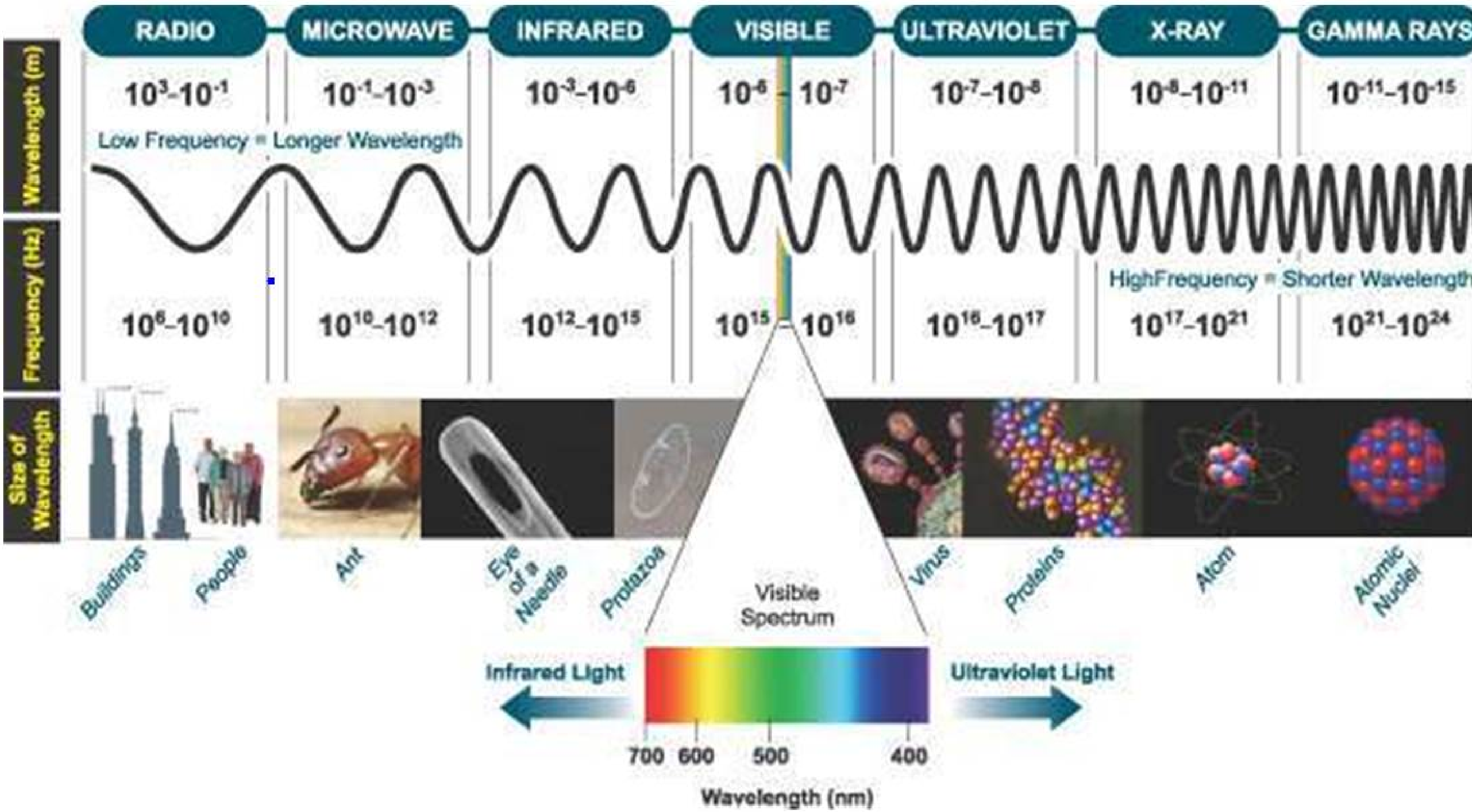

RADIO
MICROWAVE
INFRARED
VISIBLE
ULTRAVIOLET
X-RAY
GAMMA RAYS
Wavelength (m)
10³-10⁻¹
10⁻¹-10⁻³
10⁻³-10⁻⁶
10⁻⁶ - 10⁻⁷
10⁻⁷-10⁻⁸
10⁻⁸-10⁻¹¹
10⁻¹¹-10⁻¹⁵
Low Frequency = Longer Wavelength
HighFrequency = Shorter Wavelength
Frequency (Hz)
10⁶-10¹⁰
10¹⁰-10¹²
10¹²-10¹⁵
10¹⁵ - 10¹⁶
10¹⁶-10¹⁷
10¹⁷-10²¹
10²¹-10²⁴
Size of Wavelength
Buildings
People
Ant
Eye of a Needle
Protozoa
Virus
Proteins
Atom
Atomic Nuclei
Visible Spectrum
Infrared Light
Ultraviolet Light
700 600 500 400
Wavelength (nm)

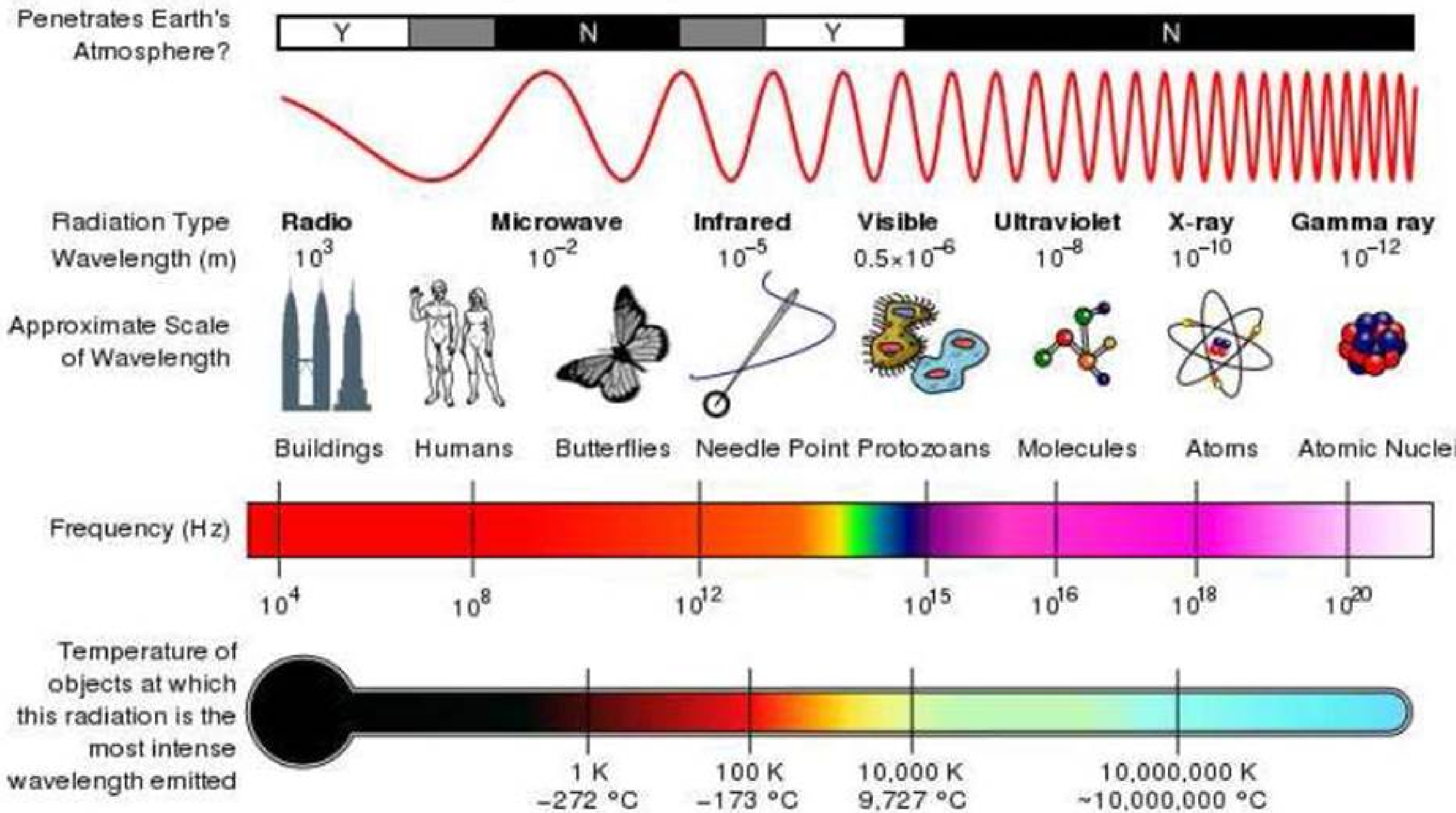

Figure 15.1: The electromagnetic spectrum as a function of frequency. The different types according to wavelength are shown as well as everyday comparisons.

Table 15.1: Electromagnetic spectrum

Category	**Range of Wavelengths (nm)**	**Range of Frequencies (Hz)**
gamma rays	<1	$> 3 \times 10^{19}$
X-rays	1-10	3×10^{17}-3×10^{19}
ultraviolet light	10-400	$7{,}5 \times 10^{14}$-3×10^{17}
visible light	400-700	$4{,}3 \times 10^{14}$-$7{,}5 \times 10^{14}$
infrared	700-10^5	3×10^{12}-$4{,}3 \times 10^{19}$
microwave	$10^5 - 10^8$	3×10^9-3×10^{12}
radio waves	$> 10^8$	$< 3 \times 10^9$

$c = f\lambda$ $c = 3 \times 10^8$ m/s

Worked Example 82: EM spectrum I

Question: Calculate the frequency of red light with a wavelength of $4{,}2 \times 10^{-7}$ m

Answer

We use the formula: $c = f\lambda$ to calculate frequency. The speed of light is a constant 3×10^8m/s.

$$
\begin{aligned}
c &= f\lambda \\
3 \times 10^8 &= f \times 4{,}2 \times 10^{-7} \\
f &= 7{,}14 \times 10^{14}\text{Hz}
\end{aligned}
$$

Worked Example 83: EM spectrum II

Question: Ultraviolet radiation has a wavelength of $200\ \mathrm{nm}$. What is the frequency of the radiation?

Answer

Step 1 : To calculate the frequency we need to identify the wavelength and the velocity of the radiation.

Recall that all radiation travels at the speed of light (c) in vacuum. Since the question does not specify through what type of material the Ultraviolet radiation is traveling, one can assume that it is traveling through a vacuum. We can identify two properties of the radiation - $wavelength$ ($200\ \mathrm{nm}$) and speed (c).

Step 2 : We can use the equation $c = f\lambda$ to find the frequency since the wavelength is given.

$$\begin{aligned} c &= f\lambda \\ 3 \times 10^8 &= f \times 200 \times 10^{-9} \\ f &= 1.5 \times 10^{15}\ \mathrm{Hz} \end{aligned}$$

Table 15.2: Uses of EM waves

Category	**Uses**
gamma rays	used to kill the bacteria in marsh-mallows and to sterilise medical equipment
X-rays	used to image bone structures
ultraviolet light	bees can see into the ultraviolet because flowers stand out more clearly at this frequency
visible light	used by humans to observe the world
infrared	night vision, heat sensors, laser metal cutting
microwave	microwave ovens, radar
radio waves	radio, television broadcasts

$$c = f \cdot \lambda$$
$$f = c/\lambda$$

15.5 The particle nature of electromagnetic radiation

When we talk of electromagnetic radiation as a particle, we refer to photons, which are packets of energy. The energy of the photon is related to the wavelength of electromagnetic radiation according to: h (called Planck's constant).

$$E = hf \Rightarrow E = \frac{hc}{\lambda}$$

Definition: Planck's constant
Planck's constant is a physical constant named after Max Planck.

$$h = 6{,}626 \times 10^{-34}\ \mathsf{J \cdot s}$$

The energy of a photon can be calculated using the formula: $E = hf$ or $E = h\frac{c}{\lambda}$. Where E is the energy of the photon in joules (J), h is planck's constant, c is the speed of light, f is the frequency in hertz (Hz) and λ is the wavelength in metres (m).

Worked Example 85: Calculating the energy of a photon II

Question: What is the energy of an ultraviolet photon with a wavelength of 200 nm?

Answer

Step 1 : Determine what is required and how to approach the problem.

We are required to calculate the energy associated with a photon of ultraviolet light with a wavelength of 200 nm.

We can use:

$$E = h\frac{c}{\lambda}$$

Step 2 : Solve the problem

$$\begin{aligned} E &= h\frac{c}{\lambda} \\ &= (6{,}626 \times 10^{-34})\frac{3 \times 10^{8}}{200 \times 10^{-9}} \\ &= 9{,}939 \times 10^{-10}\ \mathrm{J} \end{aligned}$$

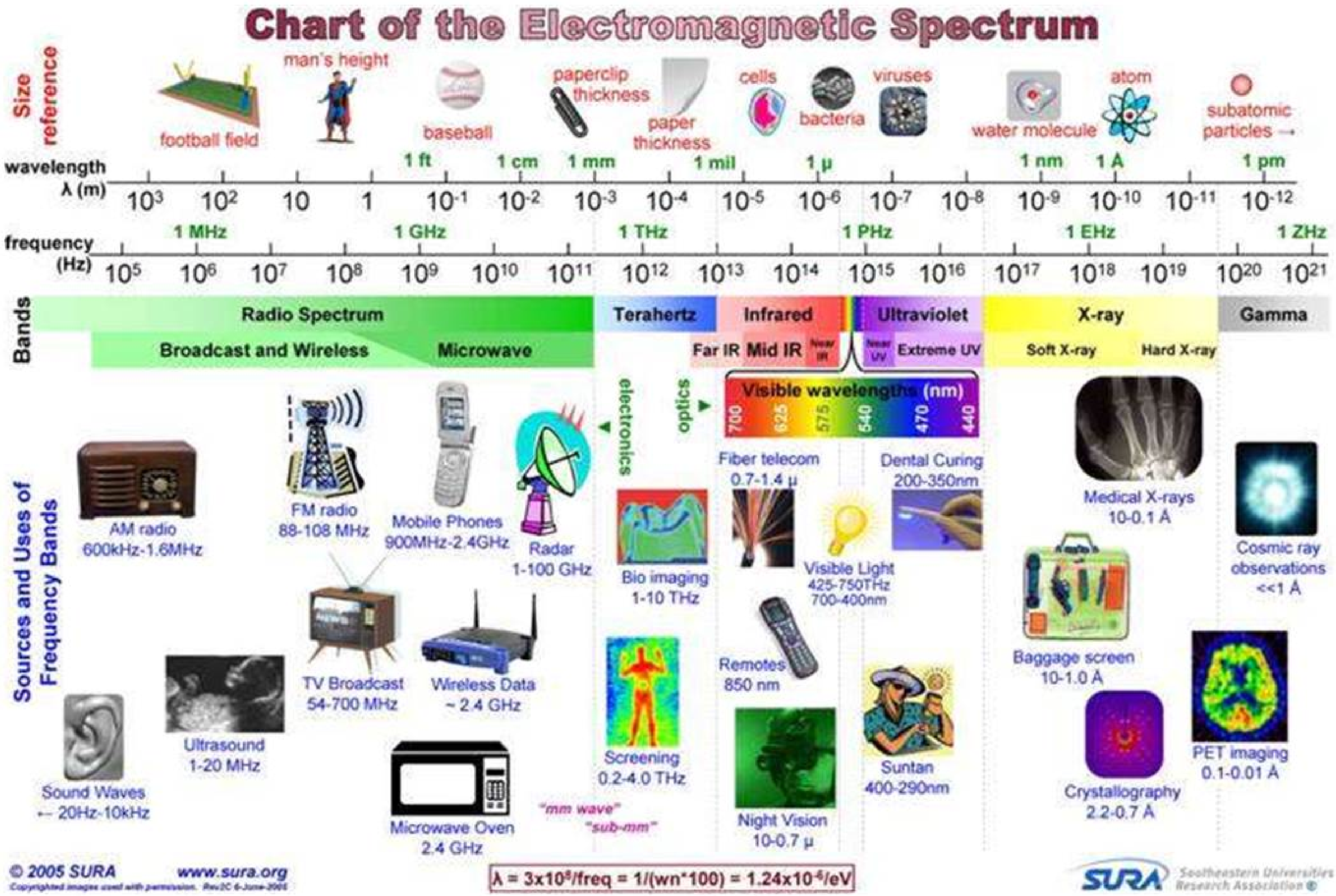

Chart of the Electromagnetic Spectrum
Size reference
football field
man's height
baseball
paperclip thickness
paper thickness
cells
bacteria
viruses
water molecule
atom
subatomic particles →
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10³ 10² 10 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹
Bands
Radio Spectrum
Broadcast and Wireless
Microwave
Terahertz
Infrared
Far IR
Mid IR
Near IR
Ultraviolet
Near UV
Extreme UV
X-ray
Soft X-ray
Hard X-ray
Gamma
electronics
optics
Visible wavelengths (nm)
700 625 575 540 470 440
Sources and Uses of Frequency Bands
AM radio 600kHz-1.6MHz
FM radio 88-108 MHz
Mobile Phones 900MHz-2.4GHz
Radar 1-100 GHz
Bio imaging 1-10 THz
Fiber telecom 0.7-1.4 μ
Dental Curing 200-350nm
Medical X-rays 10-0.1 Å
Cosmic ray observations <<1 Å
Visible Light 425-750THz 700-400nm
TV Broadcast 54-700 MHz
Wireless Data ~ 2.4 GHz
Remotes 850 nm
Baggage screen 10-1.0 Å
Ultrasound 1-20 MHz
Sound Waves ← 20Hz-10kHz
Microwave Oven 2.4 GHz
"mm wave"
"sub-mm"
Screening 0.2-4.0 THz
Night Vision 10-0.7 μ
Suntan 400-290nm
Crystallography 2.2-0.7 Å
PET imaging 0.1-0.01 Å
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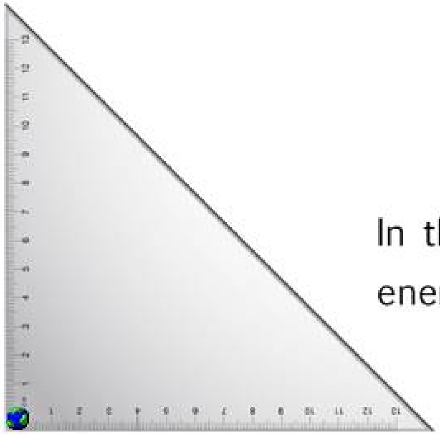
Copyrighted images used with permission. Rev2C 6-June-2005
λ = 3x10⁸/freq = 1/(wn*100) = 1.24x10⁻⁶/eV
SURA Southeastern Universities Research Association ©



The Photoelectric Effect

In the photoelectric effect, electrons are emitted from solids, liquids or gases when they absorb energy from light. Electrons emitted in this manner may be called photoelectrons

The Photoelectric Effect Sim

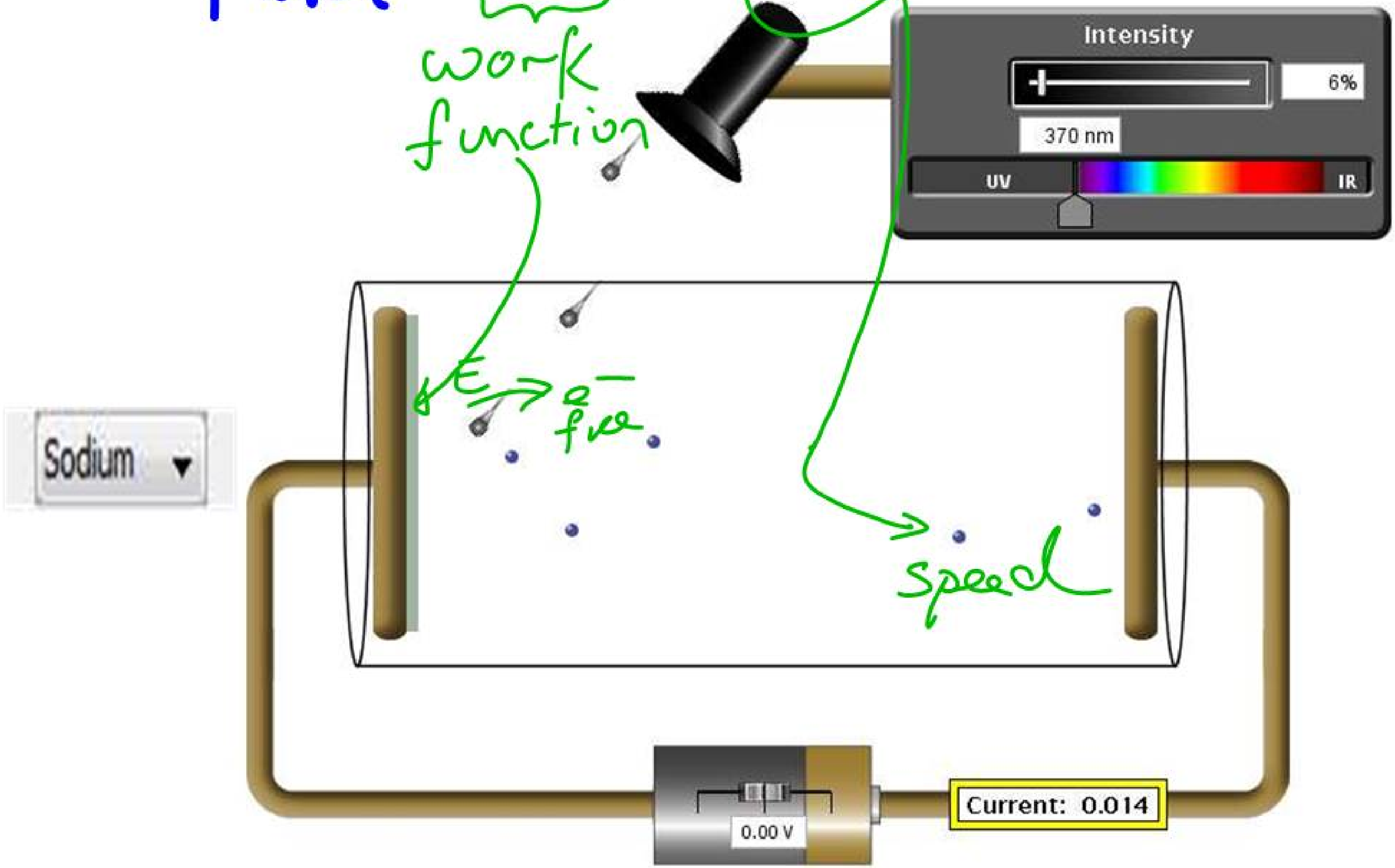
Heinrich Hertz

Born	Heinrich Rudolf Hertz 22 February 1857 Hamburg, German Confederation

In 1887, Heinrich Hertz discovered that electrodes illuminated with ultraviolet light create electric sparks more easily. In 1905 Albert Einstein published a paper that explained experimental data from the photoelectric effect as being the result of light energy being carried in discrete quantized packets. This discovery led to the quantum revolution. Einstein was awarded the Nobel Prize in 1921 for "his discovery of the law of the photoelectric effect".

The photoelectric effect requires photons with energies from a few electronvolts to over 1 MeV in high atomic number elements. Study of the photoelectric effect led to important steps in understanding the quantum nature of light and electrons and influenced the formation of the concept of wave-particle duality

$$E_{photon} = W_0 + E_K$$



Increasing the intensity of the light (i.e. making it brighter) did not change the wavelength of the light and therefore the electrons would be emitted with *the same* kinetic energy as before! This solved the paradox and showed that light has *both* a **wave nature** and a **particle nature**. Einstein won the Nobel prize for this quantum theory and his explanation of the photoelectric effect.

Increasing the intensity of the light actually means increasing the *number* of incident photons. Therefore, since each photon only gives energy to one electron, more incident photons means *more* electrons would be knocked out of the metal, but their kinetic energies would be *the same* as before.

Interesting Fact

The **electron volt** (eV) is the kinetic energy gained by an electron passing through a potential difference of one volt (1 V). A **volt** is not a measure of energy, but the **electron volt** is a unit of energy. When you connect a 1.5 V battery to a circuit, you can give 1.5 eV of energy to every electron.

1 eV = 1.602176487(40)×1019. J

Worked Example 86: The photoelectric effect - I

$E - W_0 = E_k$

Question: Ultraviolet radiation with a wavelength of 250 nm is incident on a silver foil (work function $\phi = 6{,}9 \times 10^{-19}$). What is the maximum kinetic energy of the emitted electrons?

Answer

Step 1 : Determine what is required and how to approach the problem

We need to determine the maximum kinetic energy of an electron ejected from a silver foil by ultraviolet radiation.

The photoelectric effect tells us that:

$$\begin{aligned} E_k &= E_{photon} - \phi \\ E_k &= h\frac{c}{\lambda} - \phi \end{aligned}$$

We also have:
Work function of silver: $\phi = 6{,}9 \times 10^{-19}$ J
UV radiation wavelength = 250 nm = 250×10^{-9} m
Planck's constant: $h = 6{,}63 \times 10^{-34}\ \mathrm{m^2kgs^{-1}}$
speed of light: $c = 3 \times 10^8\ \mathrm{ms^{-1}}$

Step 2 : Solve the problem

$$\begin{aligned} E_k &= \frac{hc}{\lambda} - \phi \\ &= [6{,}63 \times 10^{-34} \times \frac{3 \times 10^8}{250 \times 10^{-9}}] - 6{,}9 \times 10^{-19} \\ &= 1{,}06 \times 10^{-19}\ \mathrm{J} \end{aligned}$$

The maximum kinetic energy of the emitted electron will be $1{,}06 \times 10^{-19}$ J.

Worked Example 87: The photoelectric effect - II

Question: If we were to shine the same ultraviolet radiation ($f = 1{,}2 \times 10^{15}$ Hz), on a gold foil (work function = $8{,}2 \times 10^{-19}$ J), would any electrons be emitted from the surface of the gold foil?

Answer

For the electrons to be emitted from the surface, the energy of each photon needs to be *greater* than the work function of the material.

Step 1 : Calculate the energy of the incident photons

$$\begin{aligned} E_{photon} &= hf \\ &= 6{,}63 \times 10^{-34} \times 1{,}2 \times 10^{15} \\ &= 7{,}96 \times 10^{-19} \text{ J} \end{aligned}$$

Therefore each photon of ultraviolet light has an energy of $7{,}96 \times 10^{-19}$ J.

Step 2 : Write down the work function for gold.

$$\phi_{gold} = 8{,}2 \times 10^{-19} \text{ J}$$

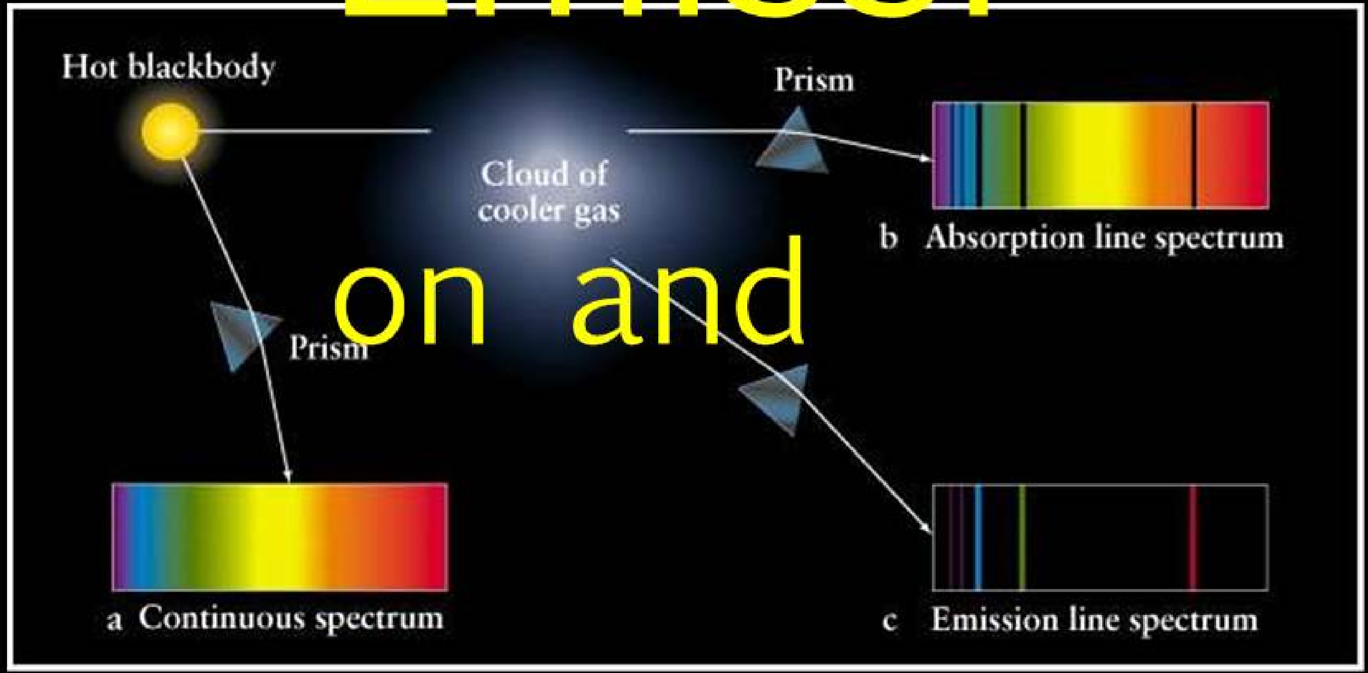
Step 3 : Is the energy of the photons greater or smaller than the work function?

$$\begin{aligned} 7{,}96 \times 10^{-19} \text{ J} &< 8{,}2 \times 10^{-19} \text{ J} \\ E_{photons} &< \phi_{gold} \end{aligned}$$

The energy of each photon is less than the work function of gold, therefore,

Emissi

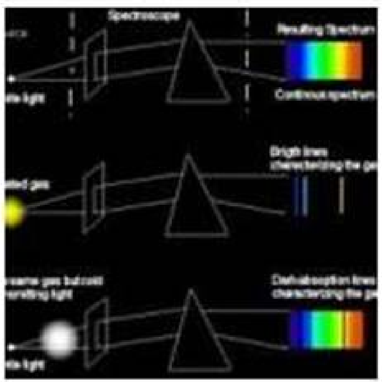
on and

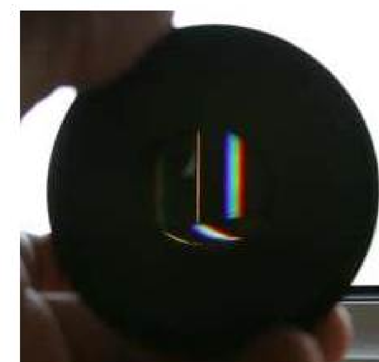


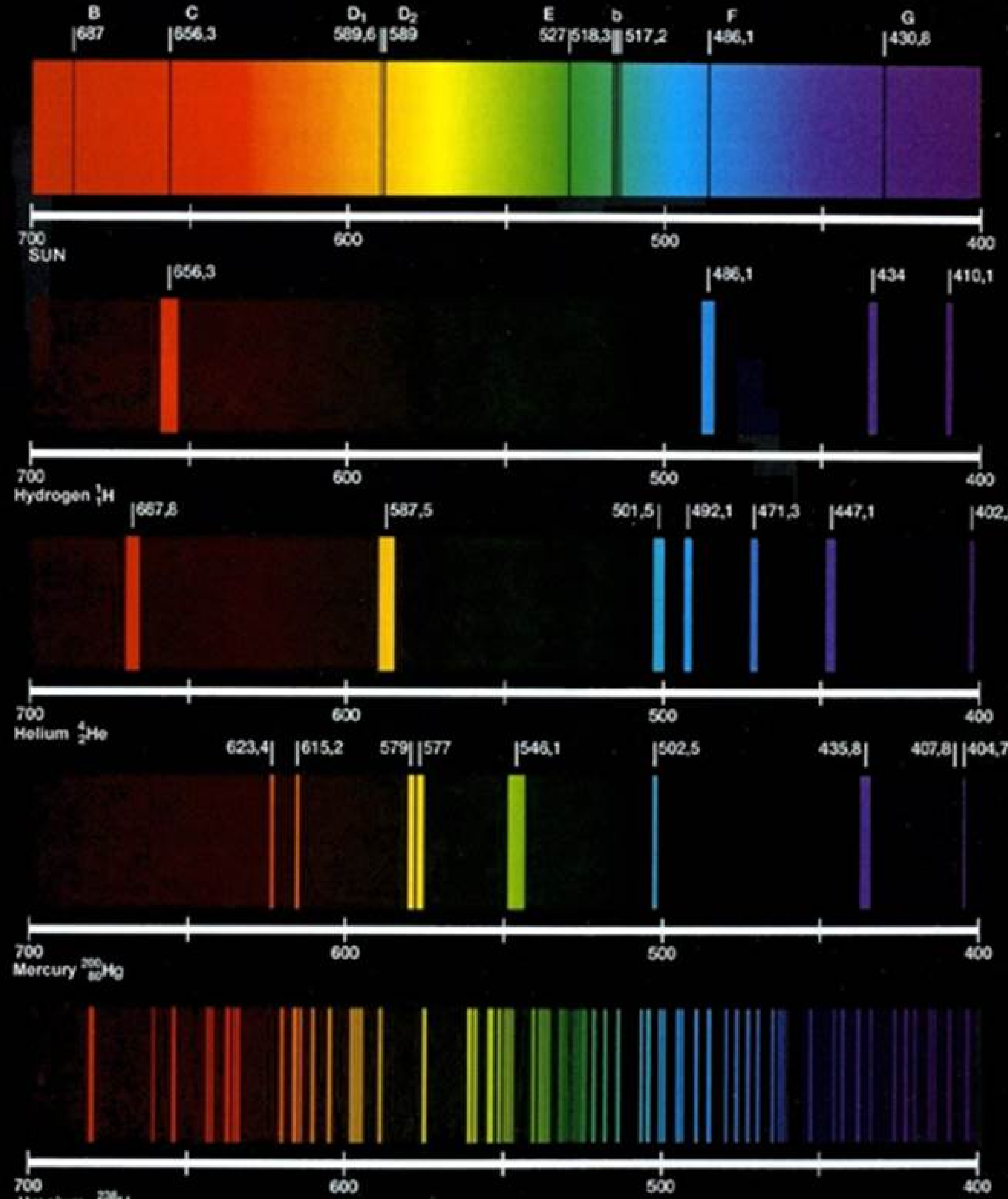
Line

Spectroscope

A spectroscope is an optical device for producing and observing a spectrum of light or radiation from any source. The device is usually made up of slit through which light or radiation passes, a collimating lens and a prism. A spectroscope works by breaking light into the wavelengths (or spectra) that make it up. When light hits the lines, it bends. Different wavelengths (colors) of light bend by different amounts, so it splits the light into its colors. Other spectroscopes are made of prisms- as light passes through the glass, the different wavelengths slow down by different amounts and are bent into their colors. Scientists can tell the elements present in a star by looking at its light through a spectroscope. Each element will have its own unique spectral lines of color, just as people each have a unique fingerprint. This field of study is used to study atoms because as electrons gain or lose energy they release their own spectra lines. We looked at the wall of the spectroscope because that is where the light was shined and where the spectrum was being showed.






B
C
D1
D2
E
b
F
G
687
656,3
589,6
589
527
518,3
517,2
486,1
430,8
700
600
500
400
SUN
656,3
486,1
434
410,1
700
600
500
400
Hydrogen ¹₁H
667,8
587,5
501,5
492,1
471,3
447,1
402,6
700
600
500
400
Helium ⁴₂He
623,4
615,2
579
577
546,1
502,5
435,8
407,8
404,7
700
600
500
400
Mercury ²⁰⁰₈₀Hg
700
600
500
400