Wilhelm Röntgen’s discovery of the x ray: Nobel Prize for Physics in 1901.

1895: Röntgen realized he was observing a new kind of ray, one that, unlike cathode rays, was unaffected by magnetic fields and was far more penetrating than cathode rays.

Figure 3.1 In Röntgen’s experiment, “x rays” were produced by cathode rays (electrons) hitting the glass near the anode. He studied the penetration of the x rays through several substances and even noted that if the hand was held between the glass tube and a screen, the darker shadow of the bones could be discriminated from the shadow of the hand.
For several years before the discovery of x rays, J. J. Thomson (1856–1940), professor of experimental physics at Cambridge University, had been studying the properties of electrical discharges in gases: cathode rays acted as negatively charged particles (electrons); Nobel Prize for Physics in 1906.

**Figure 3.2** Apparatus of Thomson’s cathode-ray experiment. Thomson proved that the rays emitted from the cathode were negatively charged particles (electrons) by deflecting them in electric and magnetic fields. The key to the experiment was to evacuate the glass tube.
Figure 3.3 Thomson’s method of measuring the ratio of the electron’s charge to mass was to send electrons through a region containing a magnetic field ($\vec{B}$ into page) perpendicular to an electric field ($\vec{E}$ down). The electrons having $v = E/B$ go through undevected. Then, using electrons of the same energy, the magnetic field is turned off and the electric field deflects the electrons, which exit at angle $\theta$. The ratio of $e/m$ can be determined from $\vec{B}, \vec{E}, \theta$, and $\ell$, where $\ell$ is the length of the field distance and $\theta$ is the emerging angle. See Equation (3.5).

$$F_y = ma_y = qE$$

$$t \approx \ell / v_0.$$ 

$$\tan \theta = \frac{v_y}{v_x} = \frac{a_y t}{v_0} = \frac{qE \ell}{m v_0^2}$$

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} = 0$$

$$\vec{E} = -\vec{v} \times \vec{B}$$

$$|\vec{E}| = |v_x| \ell$$

$$\frac{q}{m} = \frac{v_0^2 \tan \theta}{E \ell} = \frac{E \tan \theta}{B^2 \ell}$$

$$v_x = \frac{E}{B} = v_0$$
In 1911 the American physicist Robert A. Millikan (1868–1953) reported convincing evidence for an accurate determination of the electron’s charge.

\[ \vec{F}_E = q\vec{E} = -mg \quad \text{(when } v = 0) \]

\[ m = \frac{4}{3} \pi r^3 \rho \quad q = \frac{mgd}{V} \]
5 WAYS YOU USE QUANTUM TECHNOLOGY EVERY DAY

COMPUTERS

LIGHT EMITTING DIODES

PHOTODETECTORS

LASERS

G.P.S.

OTHER QUANTUM TECH

TRANSPARENT SCANNING TUNNELLING MICROSCOPE

SOLAR PANELS

HELIUM, NEON, CAESIUM

DRUG DEVELOPMENT OR OTHERS
Scanning Tunneling Microscopy

STM tip

Adsorbate

Surface

Control voltages for piezotube

Piezoelectric tube with electrodes

Tunneling current amplifier

Distance control and scanning unit

Tip

Sample

Tunneling voltage

Data processing and display
Transmission Electron Microscopy
**Electromagnetic WAVE**

\[ \nabla \times \nabla \times \mathbf{E} = -\nabla^2 \mathbf{E} = \]

\[ = -\mu \frac{\partial}{\partial t} (\nabla \times \mathbf{H}) \quad \text{(substitute in Ampere's Law)} \]

\[ = -\mu \frac{\partial}{\partial t} \left( \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \right) \quad \text{(J is zero because source free region)} \]

\[ = -\mu_0 \epsilon \frac{\partial}{\partial t} \left( \frac{\partial \mathbf{E}}{\partial t} \right) \]

\[ \Rightarrow \nabla^2 \mathbf{E} = \mu_0 \epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad \text{[The Vector Wave Equation]} \]

\[ \mathbf{E} = \mathbf{E}_0 \sin(kz - \omega t), \quad \mathbf{B} = \mathbf{B}_0 \sin(kz - \omega t) \]

\[ B_0 = \frac{E_0}{c} \quad \mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \]
Superposition and interference

Assumption of infinite source distance gives plane wave at slit so that all amplitude elements are in phase.

\[
\tan \theta = \frac{y}{D}
\]

For distant screen assumption

\[
\tan \theta \sim \sin \theta \sim \theta \sim \frac{y}{D}
\]

Condition for maximum

\[
d \sin \theta = m \lambda
\]

\[
y = \frac{m \lambda D}{d}
\]

\[
X_1^2 = D^2 + \left(\frac{d}{2} + y_n\right)^2 \quad \text{and} \quad X_2^2 = D^2 + \left(\frac{d}{2} - y_n\right)^2
\]

\[
X_1 + X_2 \approx 2D, \quad |X_1 - X_2| = n\lambda \quad n = 0, 1, 2, \ldots
\]

\[
y_n = n \frac{\lambda D}{d}
\]
All of the examples we have discussed in this section depend on the wave properties of electromagnetic radiation. However, as we now begin to discuss, there are other experiments that cannot be explained if we regard electromagnetic radiation as waves.
Photoelectric effect: Evidence for the quantization of radiation energy

- Discovered by Heinrich Hertz in 1887
- By the early 1900s it was known that electrons are bound to matter. The valence electrons in metals are “free”. They are able to move easily from atom to atom but are not able to leave the surface of the material.

1. **Thermionic emission**: Application of heat allows electrons to gain enough energy to escape.

2. **Secondary emission**: The electron gains enough energy by transfer from a high-speed particle that strikes the material from outside.

3. **Field emission**: A strong external electric field pulls the electron out of the material.

4. **Photoelectric effect**: Incident light (electromagnetic radiation) shining on the material transfers energy to the electrons, allowing them to escape.

The minimum extra kinetic energy that allows electrons to escape the material is called the work function $\phi$. The work function is the minimum binding energy of the electron to the material.
### Table 3.3 Work Functions

<table>
<thead>
<tr>
<th>Element</th>
<th>$\phi$ (eV)</th>
<th>Element</th>
<th>$\phi$ (eV)</th>
<th>Element</th>
<th>$\phi$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>4.64</td>
<td>K</td>
<td>2.29</td>
<td>Pd</td>
<td>5.22</td>
</tr>
<tr>
<td>Al</td>
<td>4.20</td>
<td>Li</td>
<td>2.93</td>
<td>Pt</td>
<td>5.64</td>
</tr>
<tr>
<td>C</td>
<td>5.0</td>
<td>Na</td>
<td>2.36</td>
<td>W</td>
<td>4.63</td>
</tr>
<tr>
<td>Cs</td>
<td>1.95</td>
<td>Nd</td>
<td>3.2</td>
<td>Zr</td>
<td>4.05</td>
</tr>
<tr>
<td>Cu</td>
<td>4.48</td>
<td>Ni</td>
<td>5.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>4.67</td>
<td>Pb</td>
<td>4.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Photoelectric effect

Clean Metal Surface

Vacuum tube

Power supply

Voltage V

I

A Ammeter
The kinetic energies of the photoelectrons are independent of the light intensity. In other words, a stopping potential (applied voltage) of $V_0$ is sufficient to stop all photoelectrons, **no matter what the light intensity**. For a given light intensity there is a maximum photocurrent, which is reached as the applied voltage increases from negative to positive values.
The maximum kinetic energy of the photoelectrons, for a given emitting material, depends only on the frequency of the light. In other words, for light of different frequency, a different retarding potential $V_0$ is required to stop the most energetic photoelectrons. The value of $V_0$ depends on the frequency but not on the intensity.
The smaller the work function $\phi$ of the emitter material, the lower is the threshold frequency of the light that can eject photoelectrons. No photoelectrons are produced for frequencies below this threshold frequency, no matter what the intensity.
When the photoelectrons are produced, however, their number is proportional to the intensity of light. That is, the maximum photocurrent is proportional to the light intensity.
The photoelectrons are emitted almost instantly.
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The smaller the work function $\phi$ of the emitter material, the lower is the threshold frequency of the light that can eject photoelectrons. No photoelectrons are produced for frequencies below this threshold frequency, no matter what the intensity.

The existence of a threshold frequency is completely inexplicable in classical theory.
When the photoelectrons are produced, however, their number is proportional to the intensity of light. That is, the maximum photocurrent is proportional to the light intensity.
Classical theory would predict that for extremely low light intensities, a long time would elapse before any one electron could obtain sufficient energy to escape.

Photoelectrons may be emitted from sodium even for light intensities as low as $10^{-8}$ W/m². Calculate classically how much time the light must shine to produce a photoelectron of kinetic energy 1.00 eV.

\[ \rho = 0.97 \text{ gr/cm}^3 \]
\[ M_{Na} = 23 \text{ gr/mol} \]

The photoelectrons are emitted almost instantly.
Photoelectric effect: Quantum theory

- Electromagnetic radiation field must be absorbed and emitted in **quantized amounts**
- The energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which we now call these energy **quanta of light photons**
- Einstein proposed that in addition to its well-known wavelike aspect, light should also be considered to have a **particle-like aspect**.
- Einstein suggested that the photon (quantum of light) **delivers its entire energy to a single electron** in the material.

\[ E = hf \quad \lambda f = c \]

\[ hf = \phi + \text{K.E. (electron)} \]

\[ hf = \phi + \frac{1}{2} m v_{\text{max}}^2 \]

\[ eV_0 = \frac{1}{2} m v_{\text{max}}^2 \]

\[ \frac{1}{2} m v_{\text{max}}^2 = eV_0 = hf - \phi \]

\[ eV_0 = \frac{1}{2} m v_{\text{max}}^2 = hf - h\nu_0 = h(f - f_0) \]
Photoelectric effect: Quantum theory

$hf = \phi + \text{K.E. (electron)}$

$hf = \phi + \frac{1}{2}mv^2_{\text{max}}$

$eV_0 = \frac{1}{2}mv^2_{\text{max}}$

$eV_0 = \frac{1}{2}mv^2_{\text{max}} = hf - hf_0 = h(f - f_0)$
Light of wavelength 400 nm is incident upon lithium ($\phi = 2.93$ eV). Calculate (a) the photon energy and (b) the stopping potential.

For the light intensity of $10^{-8}$ W/m$^2$, a wavelength of 350 nm is used. What is the number of photons/(m$^2$.s) in the light beam?
Photoelectric effect

Noble Prices

- Lenard, 1905, partially, behavior of photo electrons.
- Einstein, 1921, developing quantum theory for photoelectric effect.
- Millikan, 1923, precise and accurate measurements, Planck constant.
Photoelectric effect: Application
Photoelectric effect: Application

Photocell  CdS
Photoelectric effect: Our experiment
### Heat Colors

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500 F</td>
<td>1371 C</td>
</tr>
<tr>
<td>2400 F</td>
<td>1316 C</td>
</tr>
<tr>
<td>2300 F</td>
<td>1260 C</td>
</tr>
<tr>
<td>2200 F</td>
<td>1204 C</td>
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<tr>
<td>2100 F</td>
<td>1149 C</td>
</tr>
<tr>
<td>2000 F</td>
<td>1093 C</td>
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<tr>
<td>1900 F</td>
<td>1038 C</td>
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<td>1800 F</td>
<td>982 C</td>
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<tr>
<td>1700 F</td>
<td>927 C</td>
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<tr>
<td>1600 F</td>
<td>871 C</td>
</tr>
<tr>
<td>1500 F</td>
<td>816 C</td>
</tr>
<tr>
<td>1400 F</td>
<td>760 C</td>
</tr>
<tr>
<td>1300 F</td>
<td>704 C</td>
</tr>
<tr>
<td>1200 F</td>
<td>649 C</td>
</tr>
</tbody>
</table>

Object at temperature $T_1$ is analyzed using a prism and a detector.
Black body radiation: electromagnetic radiation emitted by all objects because of their temperature.

- 1800 Sir Wilhelm Herschel: Discovers IR-radiation
- 1859 Gustav Kirchhoff: Derives the law of thermal radiation
- 1893 Wilhelm Wien: Derives the displacement law
- 1897 Walther Nernst: Invents the Nernst Glower
- 1901 Max Planck: Derives Plancks Law

- Humans
- Peak value = 9.3 μm
- Almost no intensity in the visible
- Applications:
  - Motion detectors
  - Temperature measurement
  - Infrared cameras

Wien's law: $T\lambda_{\text{max}} = c$
Black body radiation

Sun (idealize BB radiation)
Max $\approx 500$ nm

Incandescent lamps
peak value $= 966$ nm
($T = 3000$ K)

peak value $= 1.1$ $\mu$m
($T = 2700$ K)
Black body radiation: a cavity as a BB

- Reflections, scattering, all phenomena depending on materials.

- For thermal radiation the simplest case is a blackbody, which has the ideal property that it absorbs all the radiation falling on it and reflects none.

- If the blackbody is in thermal equilibrium, then it must also be an excellent emitter of radiation.

- Blackbody radiation is theoretically interesting because of its universal character: the radiation properties of the blackbody are independent of the particular material of which the container is made.

- A small hole in one wall of the box allows some of the radiation to escape.

- It is the hole, and not the box itself, that is the blackbody.
Black body radiation

Wien’s displacement law

\[ \lambda_{\text{max}} T = 2.8978 \times 10^{-3} \text{ m.K} \]

“white hot” refers to an object that is hot enough to produce the mixture of all wavelengths in the visible region to make white light.

Noble prize in 1911
Black body radiation

Stefan’s law: empirically 1879

\[ I = \sigma T^4 \]
\[ \sigma = 5.67037 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4 \]

Stefan-Boltzmann constant

The emissivity \( \varepsilon \) (1 for an idealized blackbody) is simply the ratio of the emissive power of an object to that of an ideal blackbody and is always less than 1.
Black body radiation

Lord Rayleigh  1900
Sir James Jeans  1905

\[ \mathcal{L}(\lambda, T) = \frac{2\pi \epsilon_0 c k T}{\lambda^4} \]

In 1911 Paul Ehrenfest

“ultraviolet catastrophe,”