

Reese Ch. 26, Part A1

(Sects. 1-5 = pp. 1206-1216)

- Discovery of the Electron (1897)
- Discovery of X-Rays (1895)
- Discovery of Radioactivity (1896)
- Planck's Introduction of h (1900)
- Photoelectric Effect
 - Experiments of Hertz, Hallwachs, Lenard (1887-1899)
 - Explanation by Einstein using "photon" concept (1905)
 - Definitive experiment → same value for h (Millikan, 1916)

Discovery of the Electron: I

Crookes tube experiments:

- Rectilinear propagation (Hittorf, 1869)
- Rays named "cathode rays" (Goldstein, 1870's)
- Rays are deflected by a magnetic field (Crookes)
- If an isolated conductor is struck by the rays, that conductor acquires a negative charge. (Perrin)
- Debate: rays as waves (Hittorf, Goldstein) versus rays as beam of particles (Crookes, Perrin)

Technological connection: Crookes or "cathode-ray" tube (CRT) was at the heart of oscilloscope and TV displays throughout the 20th Century. In addition, X-ray tubes are based on the CRT.

Discovery of the Electron: II

Findings (1895-1897) of J. J. Thomson (1856-1940):

- **Deflected** rays also carry negative charge
- Rays are deflected by a transverse electric field
- Beam particles from all cathode materials had the same ratio of charge to mass, and it was MUCH greater than the greatest charge-to-mass ratio previously known. Present-day values:

$$\left| \frac{q}{m} \right|_{\text{hydrogen ion}} = 9.58 \times 10^7 \text{ Coul} / \text{kg}$$

$$\left| \frac{q}{m} \right|_{\text{electron}} = 1.76 \times 10^{11} \text{ Coul} / \text{kg} \approx 1840 \left| \frac{q}{m} \right|_{\text{hydrogen ion}}$$

Finding q and m separately

- Thomson won the 1906 Nobel Prize in Physics for his work on "the conduction of electricity in gases," but the **elementary charge** was not known until the American physicist Robert Millikan performed his "oil-drop experiment" in 1911. Present-day values:

$$e = |q|_{\text{electron}} = 1.60 \times 10^{-19} \text{ Coulomb}$$

$$\Rightarrow m = \frac{e}{(e/m)} = 9.11 \times 10^{-31} \text{ kg}$$

- Millikan won the 1923 Nobel Prize for his work on the elementary charge of electricity and on the photoelectric effect.

Discovery of X-Rays

In 1895, Wilhelm Roentgen (1845-1923) noticed the glow of a fluorescent screen when it was placed near a working cathode-ray tube. He was able to show several things about "x" rays:

- They are produced when high-energy cathode rays strike a solid material. Dense targets $\Rightarrow$ more X-rays.
- Matter is somewhat transparent to X-rays. The denser the matter, the more absorption of X-rays.
- Photographic film is exposed by X-rays.
- X-rays are **NOT** deflected by electric or magnetic fields.

In 1901, Roentgen was awarded the first Nobel Prize in Physics for his discovery of X-rays.

Technological connection: X-rays have been used (sometimes overused) for medical imaging and for other diagnostic purposes.

Discovery of Radioactivity

In 1896, Henri Becquerel (1852-1908) accidentally discovered that photographic plates in a light-tight container were exposed by nearby crystals of a uranium compound. He soon established that . . .

- . . . the amount of photographic exposure was proportional to the amount of uranium
- . . . temperature had no effect on the process, which convinced him that the effect is NOT a chemical process.

In 1898, the Polish physicist Marie Skłodowska-Curie isolated two new elements (polonium and radium) more powerful than uranium; she introduced the term **radioactivity**.

The 1903 Nobel Prize in Physics was awarded to Becquerel for discovering radioactivity and to Marie and Pierre Curie for their researches.

Blackbody Radiation: I

As discussed in Ch. 13 (pp. 612-615), any object radiates energy at a rate proportional to the fourth power of its absolute temperature. For a perfect absorber ("blackbody"):

$$\text{Radiated power} = (\sigma T^4) A$$

Here A is the surface area and σ is the Stefan-Boltzmann constant.

$$\sigma = 5.670 \times 10^{-8} \text{ W } / (\text{m}^2 \cdot \text{K}^4)$$

Blackbody Radiation: II

The radiation from a blackbody has a characteristic spectral shape describing the relative amounts of radiation emitted at various wavelengths. One basic measure of the spectrum is the peak wavelength, where the radiated power per unit wavelength interval is the greatest. In 1893, Wilhelm Wien predicted that λ_{max} should be inversely proportional to T , and this was experimentally confirmed a few years later. The experiments reveal that

$$\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m} \cdot \text{K}$$

Blackbody Radiation: III

- Combining Maxwell's description of light as electromagnetic radiation with the idea of energy equipartition (cf. Chapter 14), Lord Rayleigh (J. W. Strutt) and James Jeans derived a theoretical formula for the spectrum of a blackbody which is **obviously wrong!** It predicts that the spectrum should not have a peak but should increase at short wavelengths, varying as the inverse fourth power of the wavelength. This is called the ultraviolet catastrophe and would mean that any object at a nonzero temperature would exhibit **INFINITE** radiated power!

Blackbody Radiation: IV

In 1900, Max Planck proposed a theory of blackbody radiation according to which the possible energy values (of any one of the "oscillators" in the walls of an oven) are NOT continuous, but discrete, with the possible energy values separated by an amount $h\nu$. Here ν is the natural frequency of the oscillator (and also the frequency of the radiation that it can emit or absorb), and h is a new physical constant, whose value Planck determined by comparing his theory with measured blackbody spectra.

Blackbody Radiation: V

The constant that Planck introduced in implementing his "quantum hypothesis" has come to be known as Planck's constant. Its dimensions are "energy times time" so its SI units are joule-seconds. In these units, Planck's constant is extraordinarily tiny:

$$h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$$

Planck won the 1918 Nobel Prize for his "discovery" of the quantization of energy.

The Photoelectric Effect: I

In the very experiment that confirmed Maxwell's interpretation of "light" (actually radio) as electromagnetic waves, Heinrich Hertz noticed that shining ultraviolet light on an electrode encouraged the production of sparks. This is the first recorded observation of the **photoelectric effect**.

Subsequent studies of this effect led to Einstein's suggestion that light energy comes in bundles of energy (photons).

⇒ Truth really **can** be stranger than fiction!

The Photoelectric Effect: II

In 1888, Wilhelm Hallwachs (1859-1922) showed that if a polished metal object is exposed to ultraviolet light, the object becomes positively charged.

Subsequent experiments by Philipp Lenard (1862-1947) and others have established a number of important features of the photoelectric effect, which are summarized on the next slide.

The experiments are typically performed using a circuit in which the illuminated surface (the cathode) and an anode are kept in an evacuated tube. When the light is shown onto the cathode, a small steady "photoelectric" current is produced. (This differs from a typical cathode-ray tube, in which the electron beam is produced by thermionic emission: the cathode is heated and "boils off" electrons.)

Technological connection: Photoelectric sensors are used very widely these days.

The Photoelectric Effect: III

Features of the photoelectric effect:

- Cutoff frequency (cutoff wavelength)
- Current proportional to light intensity
- Current not increased by increased accelerating voltage, but if reverse the polarity, can suppress or even zero the current (stopping potential)
- Stopping potential increases linearly with frequency of light
- Photoelectric effect is "instantly on." (no minimum time lag)

The Photoelectric Effect: IV

In 1905, Albert Einstein published a paper which accounts for all of these features by assuming that electromagnetic energy is delivered to the photoelectrons in packets of light (photons) whose energy is related to the frequency of the light by

$$E = h\nu$$

Einstein won the 1921 Nobel Prize for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect.

The Photoelectric Effect: V

In 1916, Millikan did precise experiments on the photoelectric effect that demonstrated quantitatively that the value of h implied by Einstein's interpretation of the photoelectric effect agrees with the value of h needed for Planck's interpretation of the blackbody spectrum.