

PHYS 3313 – Section 001

Lecture #6

Monday, Sept. 17, 2012

Dr. Jaehoon Yu

- Discovery of the X-ray and the Electron
- Determination of Electron Charge
- Line Spectra
- Quantization
- Blackbody Radiation
- Photoelectric Effect
- Compton Effect
- Pair production/Pair annihilation



Announcements

- Reading assignments: CH 3.3 (special topic – the discovery of Helium) and CH3.7
- Quiz results
 - Class average: 17.7/65
 - Equivalent to: 27.2/100
 - Top score: 53/65
- Conference volunteer application
 - LCWS12 international conference : Oct. 21 – 26, 2012
 - Send e-mail to Dr. Jackson (cbjackson@uta.edu)
 - Subject must have: LCWS12 Volunteer Application
- Colloquium this week: Physics Faculty Expo - II



INTERNATIONAL WORKSHOP
ON FUTURE LINEAR COLLIDERS

<http://www.lcws12.org>

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Special Project #2

1. Derive the three Lorentz velocity transformation equations. (10 points)
 2. Derive the three reverse Lorentz velocity transformation equations. (10 points)
 3. Prove that the spacetime invariant quantity $s^2 = x^2 - (ct)^2$ is indeed invariant, i.e. $s^2 = s'^2$, in Lorentz Transformation. (5 points)
 4. You must derive each one separately starting from the Lorentz spatial coordinate transformation equations to obtain any credit.
 - Just switching the signs and primes will not cut!
 - Must take the simplest form of the equations, using β and γ .
 5. You MUST have your own, independent answers to the above three questions even if you worked together with others. All those who share the answers will get 0 credit if copied.
- Due for the submission is this Wednesday, Sept. 19!



What does the word “Quantize” mean?

- Dictionary: To restrict to discrete values
- To consist of indivisible discrete quantities instead of continuous quantities
 - Integer is a quantized set with respect to real numbers
- Some examples of quantization?
 - Digital photos
 - Lego blocks
 - Electric charge
 - Photon (a quanta of light) energy
 - Angular momentum
 - Etc...



Discovery of the X Ray and the Electron

- X rays were discovered by Wilhelm Röntgen in 1895.
 - Observed x rays emitted by cathode rays bombarding glass
- Electrons were discovered by J. J. Thomson.
 - Observed that cathode rays were charged particles



Cathode Ray Experiments

- In the 1890s scientists and engineers were familiar with cathode rays, generated from one of the metal plates in an evacuated tube across a large electric potential
- People thought cathode rays had something to do with atoms.
- It was known that cathode rays could penetrate matter and their properties were under intense investigation during the 1890s.



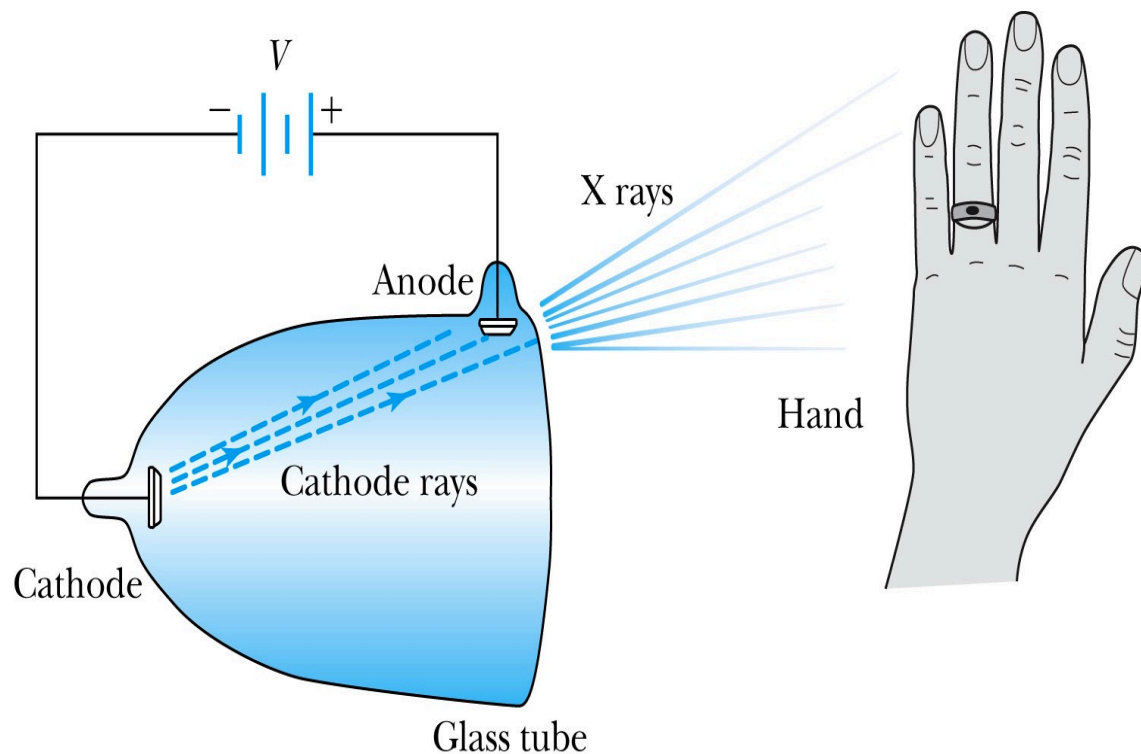
Observation of X Rays

- Wilhelm Röntgen studied the effects of cathode rays passing through various materials.
- He noticed that a phosphorescent screen near the tube glowed during some of these experiments.
- These rays were unaffected by magnetic fields and penetrated materials more than cathode rays.
- He called them **x rays** and deduced that they were produced by the cathode rays bombarding the glass walls of his vacuum tube



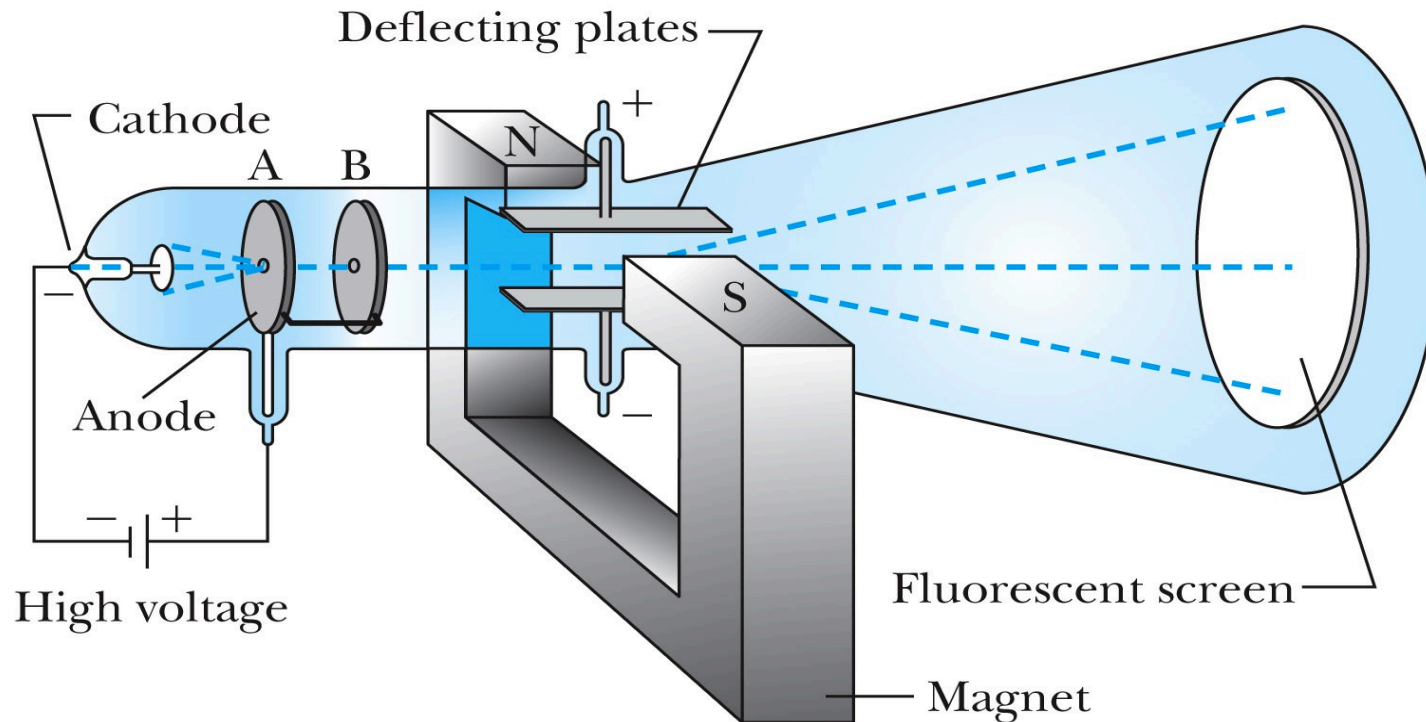
Röntgen's X Ray Tube

- Röntgen produced x-ray by allowing cathode rays to impact the glass wall of the tube.
- Took image the bones of a hand on a phosphorescent screen.



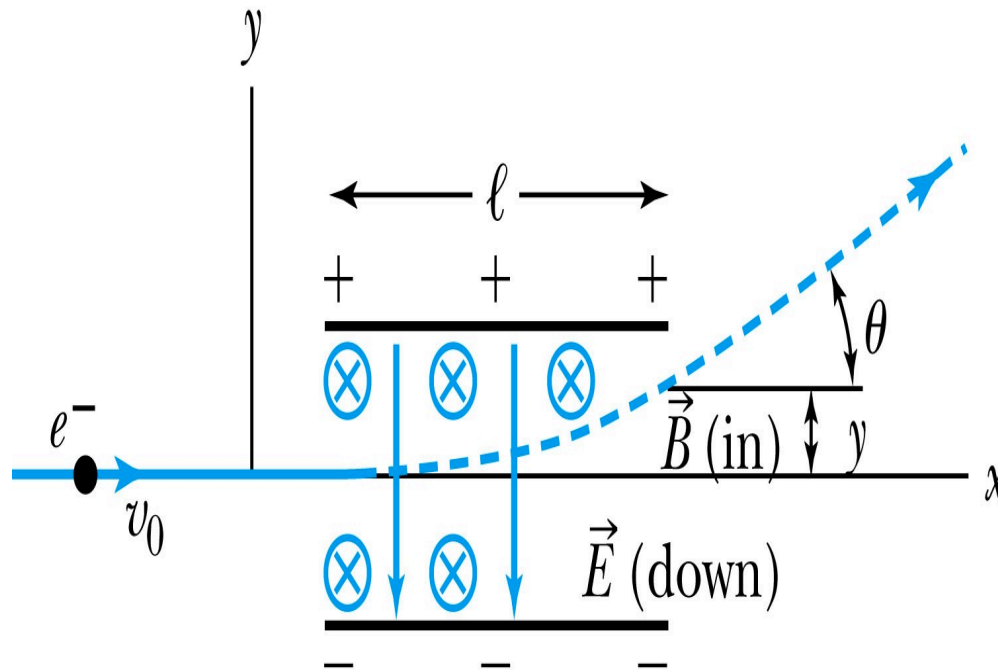
J.J. Thomson's Cathode-Ray Experiment

- Thomson showed that the cathode rays were negatively charged particles (electrons)! How?
 - By deflecting them in electric and magnetic fields.



Thomson's Experiment

- Thomson measured the ratio of the electron's charge to mass by sending electrons through a region containing a magnetic field perpendicular to an electric field.



- Measure the deflection angle with only E !
- Turn on and adjust B field till no deflection!
- What do we know?
 - ℓ , B , E and θ
- What do we not know?
 - v_0 , q and m

Calculation of q/m

- An electron moving through the electric field w/o magnetic field is accelerated by a force: $F_y = ma_y = qE$
- Electron angle of deflection: $\tan \theta = \frac{v_y}{v_x} = \frac{a_y t}{v_0} = \frac{qE}{m} \frac{l/v_0}{v_0} = \frac{qE}{m} \frac{l}{v_0^2}$
- Adjust the perpendicular magnetic field till it balances E and keeps electrons from deflecting in y-direction

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

$$F_y = -qE + qv_x B = 0 \Rightarrow qE = qv_x B \Rightarrow v_x = \frac{E}{B} = v_0$$

- Charge to mass ratio:

$$\tan \theta = \frac{qE}{m} \frac{l}{v_0^2} \Rightarrow \frac{q}{m} = \frac{v_0^2 \tan \theta}{El} = \frac{(E/B)^2 \tan \theta}{El} = \frac{E \tan \theta}{B^2 l}$$

Ex 3.1: Thomson's experiment

- In an experiment similar to Thomson's, we use deflecting plates 5.0cm in length with an electric field of $1.2 \times 10^4 \text{ V/m}$. Without the magnetic field, we find an angular deflection of 30° , and with a magnetic field of $8.8 \times 10^{-4} \text{ T}$ we find no deflection. What is the initial velocity of the electron and its q/m ?
- First v_0 using E and B , we obtain:

$$v_0 = v_x = \frac{E}{B} = \frac{1.2 \times 10^4}{8.8 \times 10^{-4}} = 1.4 \times 10^7 \text{ m/s}$$

- q/m is then

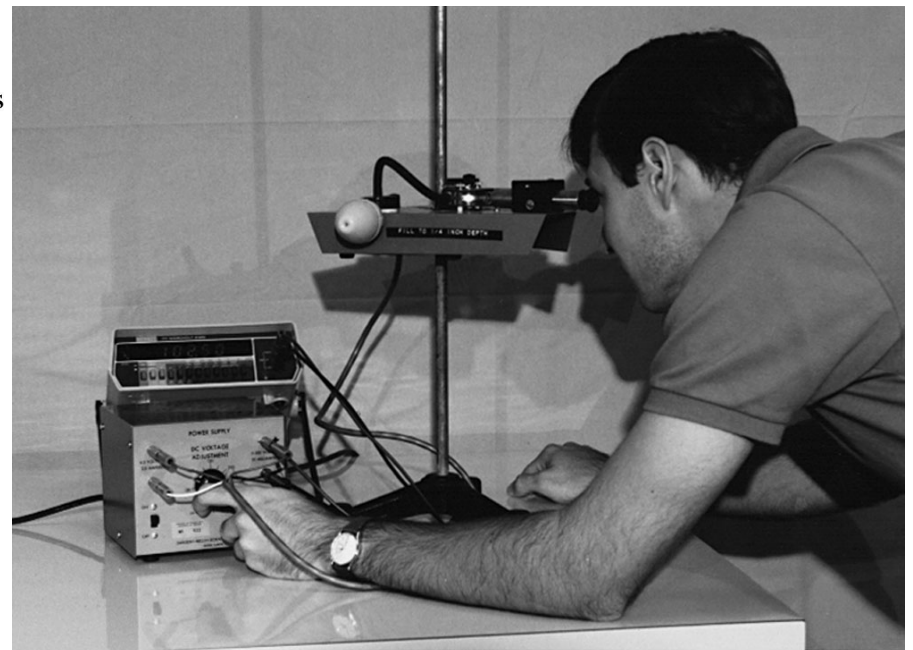
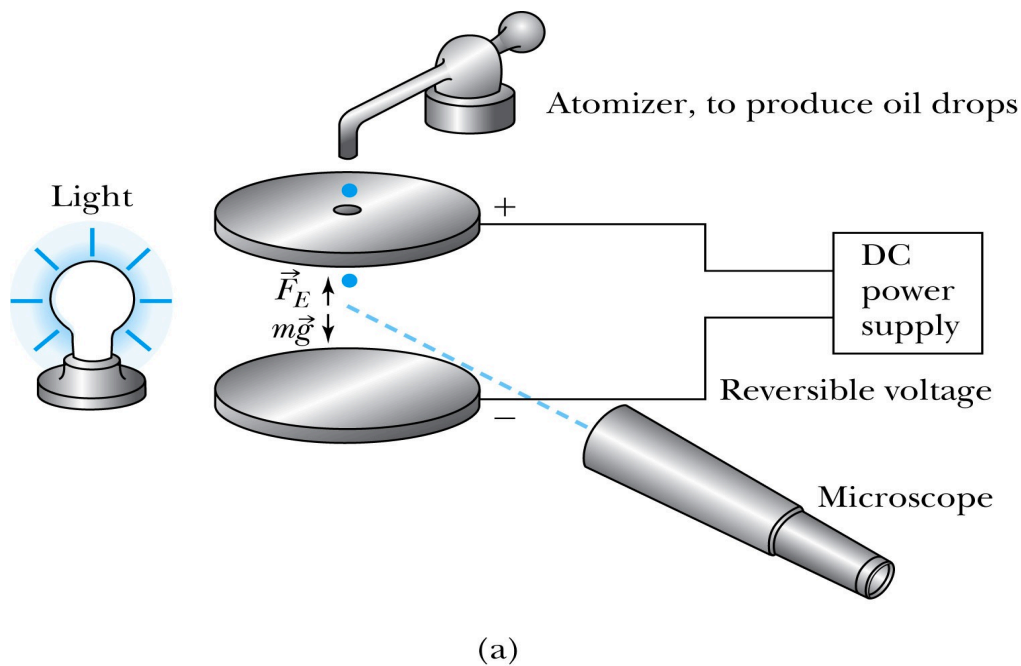
$$\frac{q}{m} = \frac{E \tan \theta}{B^2 l} = \frac{1.2 \times 10^4 \tan 30^\circ}{(8.8 \times 10^{-4})^2 \cdot 0.5} = 1.8 \times 10^{11} \text{ C/kg}$$

- What is the actual value of q/m using the known quantities?

$$\frac{q}{m} = \frac{1.6022 \times 10^{-19}}{9.1094 \times 10^{-31}} = 1.759 \times 10^{-11} \text{ C/kg}$$

Determination of Electron Charge

- Millikan (and Fletcher) in 1909 measured charge of electron, showed that free electric charge is in multiples of the basic charge of an electron



Calculation of the oil drop charge

- Used an electric field and gravity to suspend a charged oil drop

$$\vec{F}_E = q\vec{E} = -m\vec{g} \Rightarrow qV/d = mg$$

- So the magnitude of the charge on the oil drop

$$q = \frac{mgd}{V}$$

- Mass is determined from Stokes' relationship of the terminal velocity to the radius and density

$$m = \frac{4}{3}\pi r^3 \rho$$

- Thousands of experiments showed that there is a basic quantized electron charge

$$q = 1.602 \times 10^{-19} \text{ C}$$



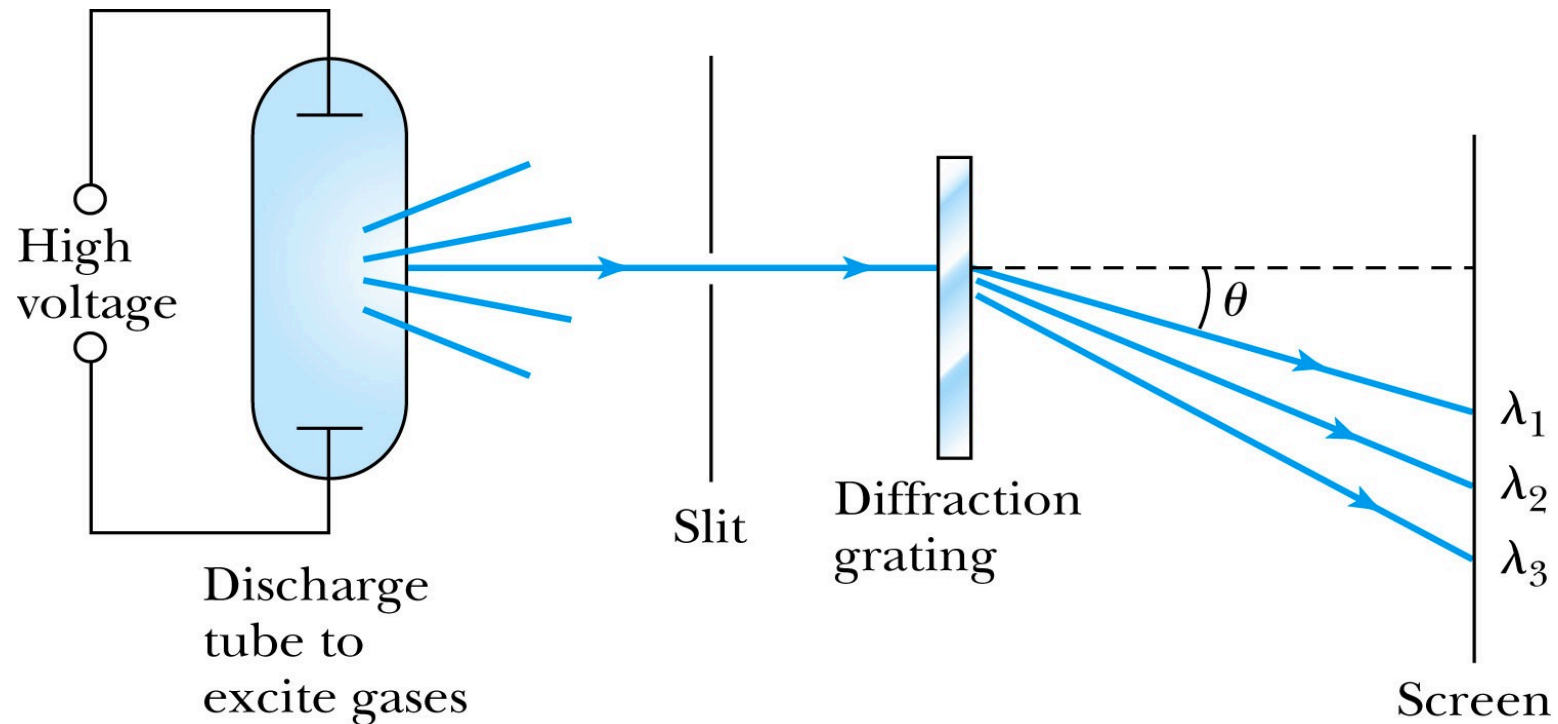
Line Spectra

- Chemical elements produce unique wavelengths of light when burned or excited in an electrical discharge.
- Collimated light is passed through a diffraction grating with thousands of ruling lines per centimeter.
 - The diffracted light is separated at an angle θ according to its wavelength λ by the equation:

$$d \sin \theta = n\lambda$$

where d is the distance between rulings and n is an integer called the order number

Optical Spectrometer

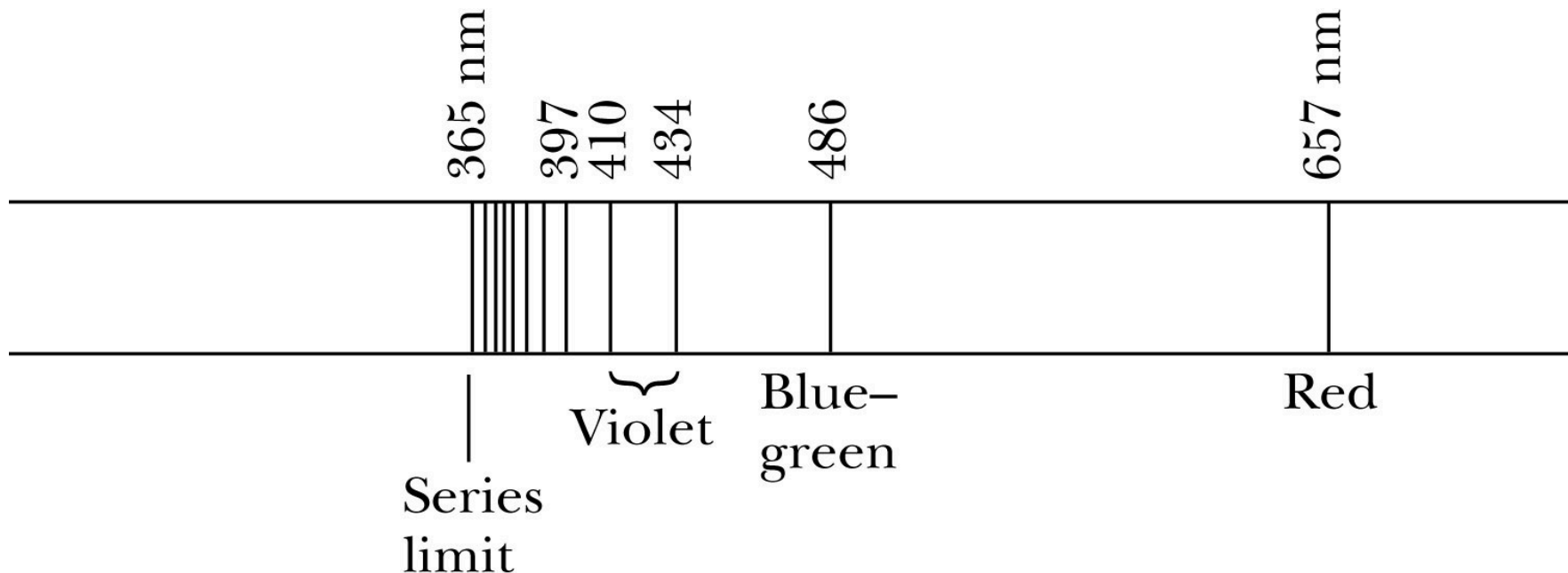


- Diffraction creates a *line spectrum* pattern of light bands and dark areas on the screen.
- Chemical elements and the composition of materials can be identified through the wavelengths of these line spectra

Balmer Series

- In 1885, Johann Balmer found an empirical formula for wavelength of the visible hydrogen line spectra in nm:

$$\lambda = 364.56 \frac{k^2}{k^2 - 4} \text{ nm} \quad (\text{where } k = 3, 4, 5 \dots \text{ and } k > 2)$$



Rydberg Equation

- Several more series of emission lines at infrared and ultraviolet wavelengths were discovered, the Balmer series equation was extended to the Rydberg equation:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n^2} - \frac{1}{k^2} \right) \quad R_H = 1.096776 \times 10^7 \text{ m}^{-1} \quad (n = 2)$$

Table 3.2 Hydrogen Series of Spectral Lines

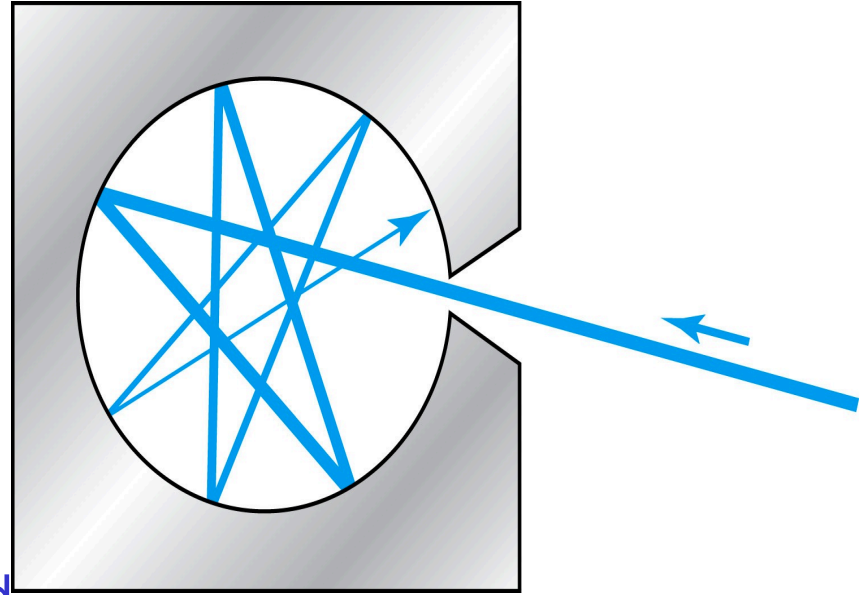
Discoverer (year)	Wavelength	n	k
Lyman (1916)	Ultraviolet	1	>1
Balmer (1885)	Visible, ultraviolet	2	>2
Paschen (1908)	Infrared	3	>3
Brackett (1922)	Infrared	4	>4
Pfund (1924)	Infrared	5	>5

Quantization

- Current theories predict that charges are quantized in units (**quarks**) of $\pm e/3$ and $\pm 2e/3$, but quarks are not directly observed experimentally.
- The charges of particles that have been directly observed are always quantized in units of $\pm e$.
- The measured atomic weights are not continuous—they have only discrete values, which are close to integral multiples of a unit mass.

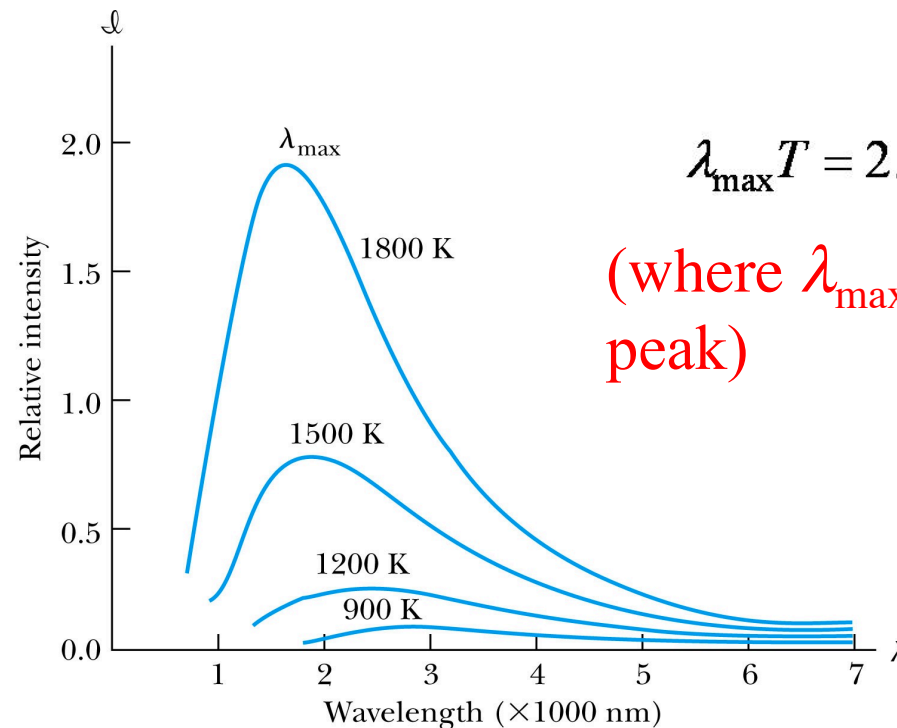
Blackbody Radiation

- When matter is heated, it emits radiation.
- A blackbody is an ideal object that has 100% absorption and 100% emission without a loss of energy
- A cavity in a material that only emits thermal radiation can be considered as a black-body. Incoming radiation is fully absorbed in the cavity.
- Blackbody radiation is theoretically interesting because
 - Radiation properties are independent of the particular material.
 - Properties of intensity versus wavelength at fixed temperatures can be studied



Wien's Displacement Law

- The intensity $\mathcal{I}(\lambda, T)$ is the total power radiated per unit area per unit wavelength at a given temperature.
- **Wien's displacement law:** The maximum of the distribution shifts to smaller wavelengths as the temperature increases.



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

(where λ_{\max} = wavelength of the peak)

Stefan-Boltzmann Law

- The total power radiated increases with the temperature:

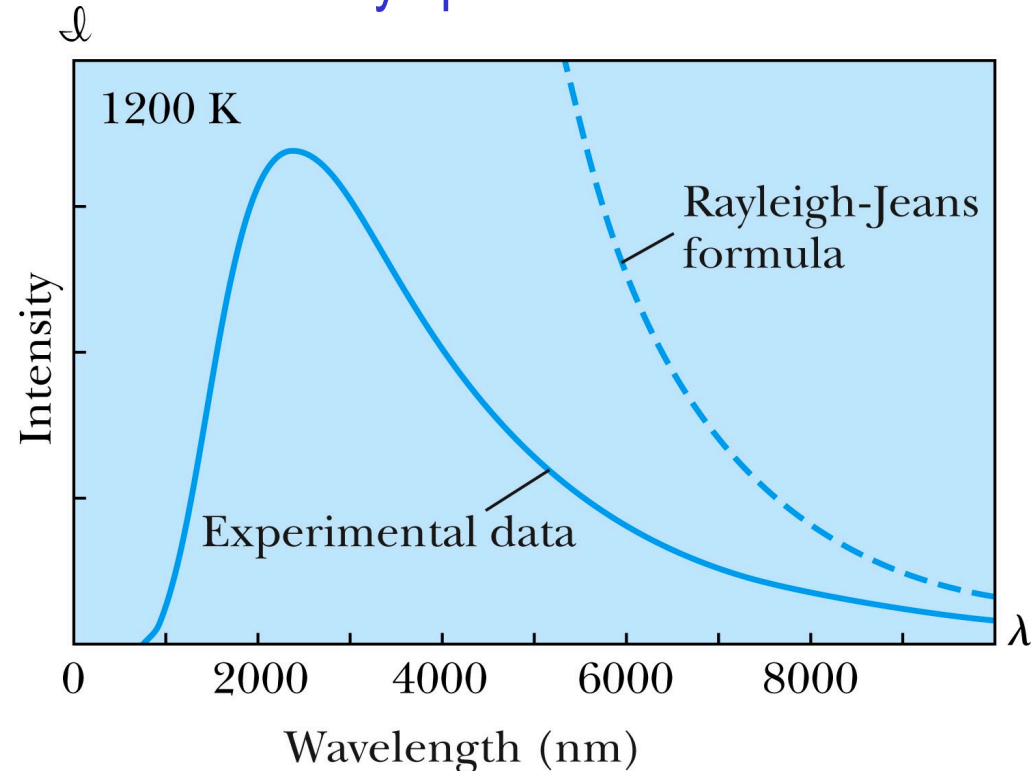
$$R(T) = \int_0^{\infty} \mathcal{I}(\lambda, T) d\lambda = \epsilon \sigma T^4$$

- This is known as the **Stefan-Boltzmann law**, with the constant σ experimentally measured to be $5.6705 \times 10^{-8} \text{ W} / (\text{m}^2 \cdot \text{K}^4)$.
- The **emissivity** ϵ ($\epsilon = 1$ for an idealized blackbody) is the ratio of the emissive power of an object to that of an ideal blackbody and is always less than 1.

Rayleigh-Jeans Formula

- Lord Rayleigh used the classical theories of electromagnetism and thermodynamics to show that the blackbody spectral distribution should be

$$\mathcal{I}(\lambda, T) = \frac{2\pi ckT}{\lambda^4}$$



- Worked reasonably at longer wavelengths
- it deviates badly at short wavelengths.
- ➔ “the ultraviolet catastrophe” a serious issue that couldn’t be explained

Planck's Radiation Law

- Planck assumed that the radiation in the cavity was emitted (and absorbed) by some sort of “oscillators” that were contained in the walls. He used Boltzman's statistical methods to arrive at the following formula that fit the blackbody radiation data.

$$\mathcal{I}(\lambda, T) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad \text{Planck's radiation law}$$

- Planck made two modifications to the classical theory:
 - 1) The oscillators (of electromagnetic origin) can only have certain discrete energies determined by $E_n = nhf$, where n is an integer, f is the frequency, and h is called Planck's constant. $h = 6.6261 \times 10^{-34}$ J·s.
 - 2) **The oscillators can absorb or emit energy ONLY in discrete multiples of the fundamental quantum of energy** given by

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

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Photoelectric Effect

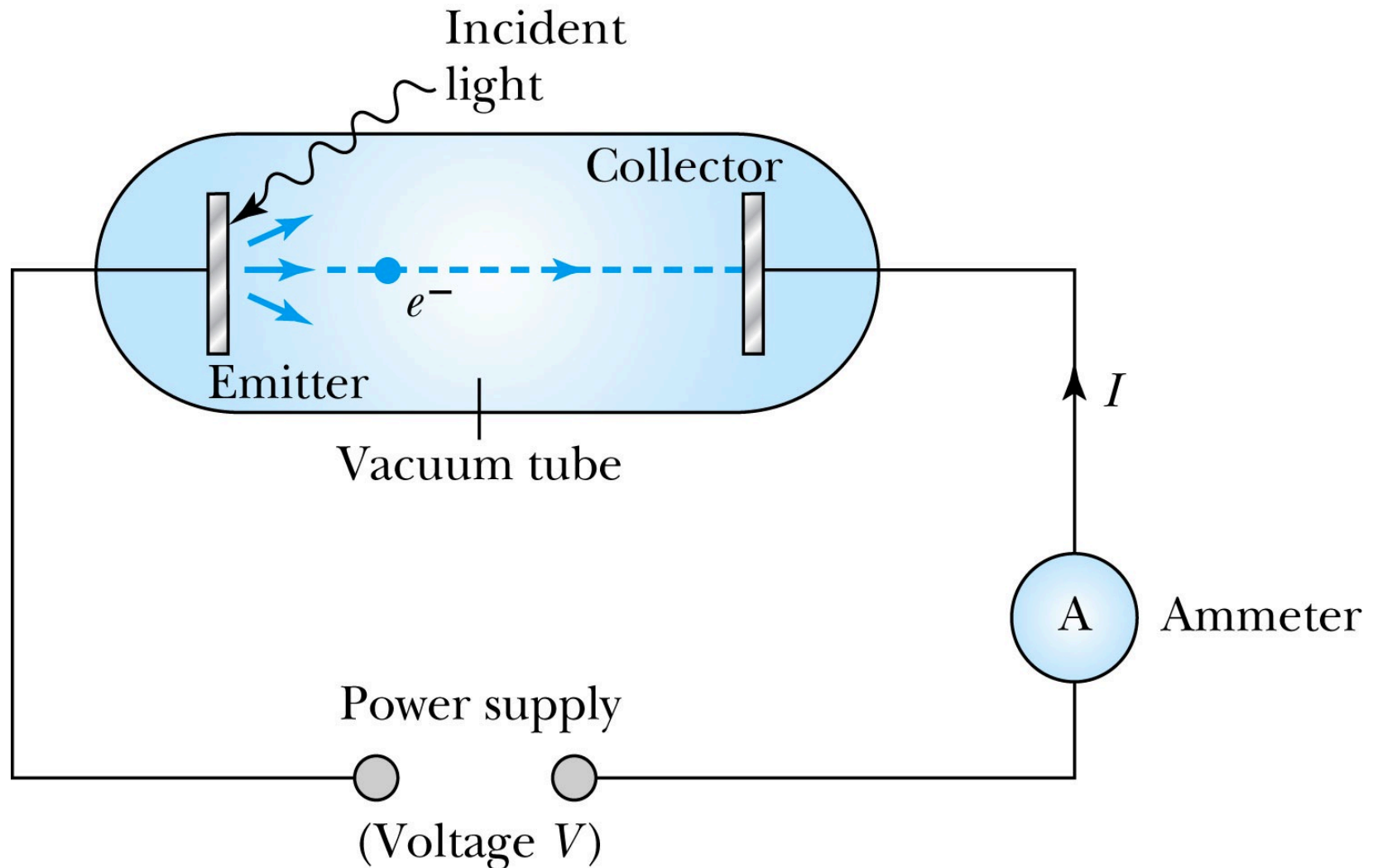
Methods of electron emission:

- Thermionic emission: Application of heat allows electrons to gain enough energy to escape.
- Secondary emission: The electron gains enough energy by transfer from another high-speed particle that strikes the material from outside.
- Field emission: A strong external electric field pulls the electron out of the material.
- Photoelectric effect: Incident light (electromagnetic radiation) shining on the material transfers energy to the electrons, allowing them to escape.

Electromagnetic radiation interacts with electrons within metals and gives the electrons increased kinetic energy. Light can give electrons enough extra kinetic energy to allow them to escape. We call the ejected electrons **photoelectrons**.



Photoelectric Effect Experimental Setup



Experimental Results

- Light intensity does not affect the KE of the photoelectrons
- The max KE of the photoelectrons, for a given emitting material, depends only on the frequency of the light
- The smaller the work function ϕ of the emitter material, the smaller is the threshold frequency of the light that can eject photoelectrons.
- When the photoelectrons are produced, their number is proportional to the intensity of light.
- The photoelectrons are emitted almost instantly following illumination of the photocathode, independent of the intensity of the light. → Totally unexplained by classical physics