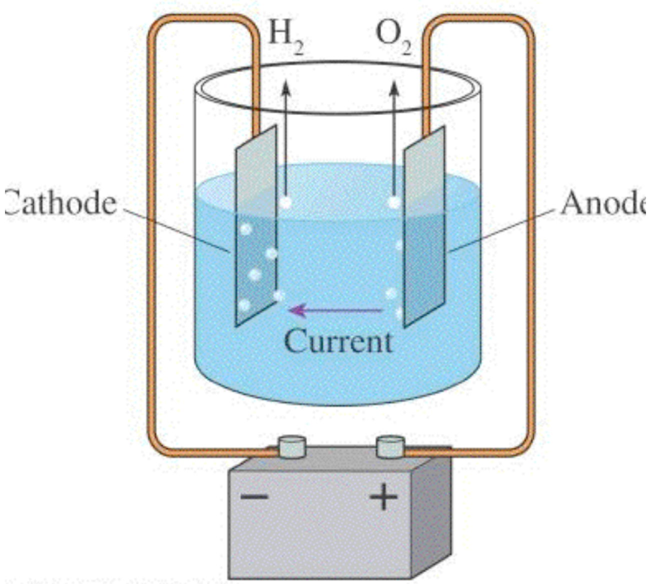
Chapter 38. The End of Classical Physics

Studies of the light emitted by gas discharge tubes helped bring classical physics to an end.

Chapter Goal: To understand how scientists discovered the properties of atoms and how these discoveries led to the need for a new theory of light and matter.

How did we come to know that the phenomena of electrical charge and current is associated with discrete particles of matter? - electrons

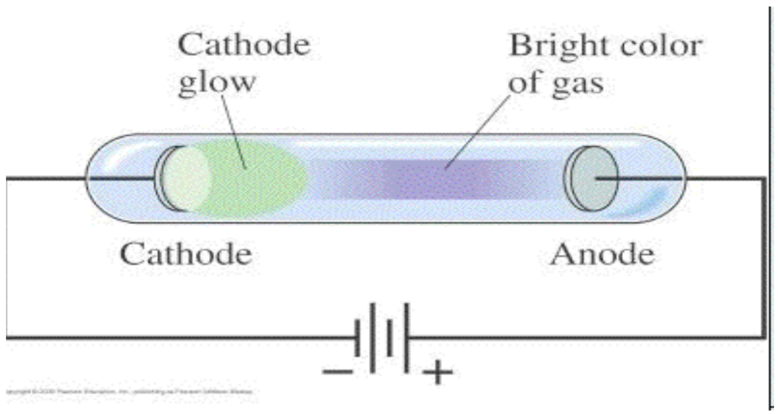
Current through the water decomposes it to Hydrogen and Oxygen –Bubbles of them come out near electrodes



Faraday: Electrolysis can be understood on the basis of atomic theory of matter- Charge associated with each atom or molecule in the solution. Positive and negative ions.

1. Confirmed existence of atoms
2. Electric charges are associated with atoms
3. There are two different kinds of charge
4. Electricity is made up of discrete charges. It is not a continuous fluid.

More Faraday - Gaseous Discharges



1. Electrical current flows through a low pressure gas. Called an electrical discharge.
2. Discharge color depends on gas (N_2, Neon)
3. Cathode glow – Independent of gas

Connection between color of light and type of atoms in the discharge

Unification of matter-electricity-light

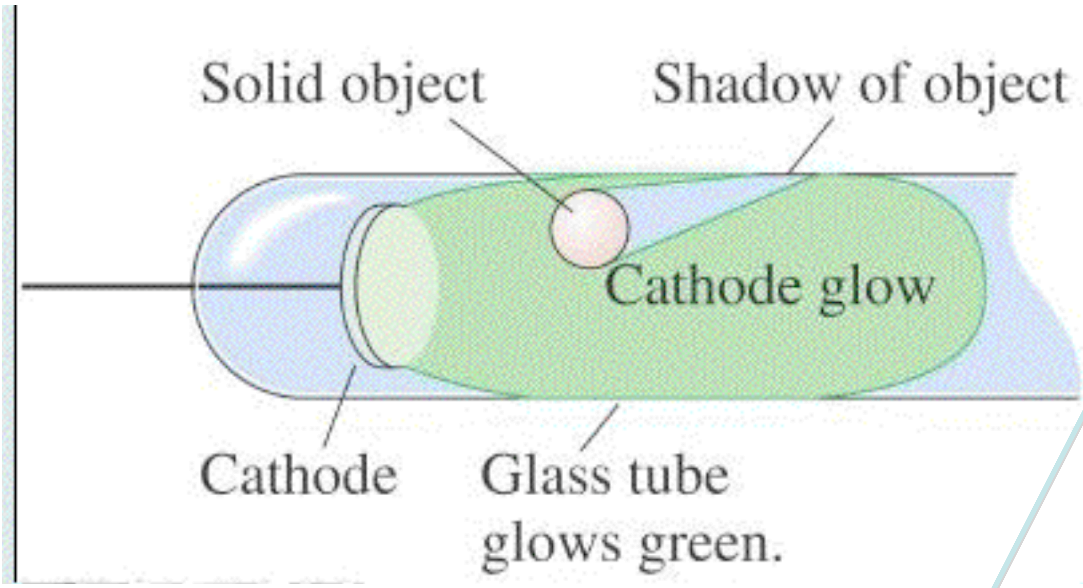
SPECTROSCOPY

Faraday is also known for his law of induced electric fields.

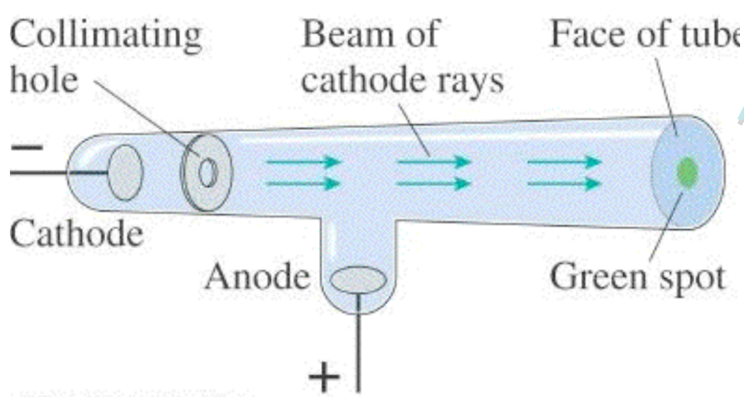
HELIUM EXAMPLE

Cathode Rays

IMPROVED PUMPS->LOW PRESSURE-> CATODE GLOW DOMINATES+GLASS EMITS GREENISH GLOW (FLUORESCENCE)



SOMETHING BLOCKING FLOW



Crooke’s Tubes led to

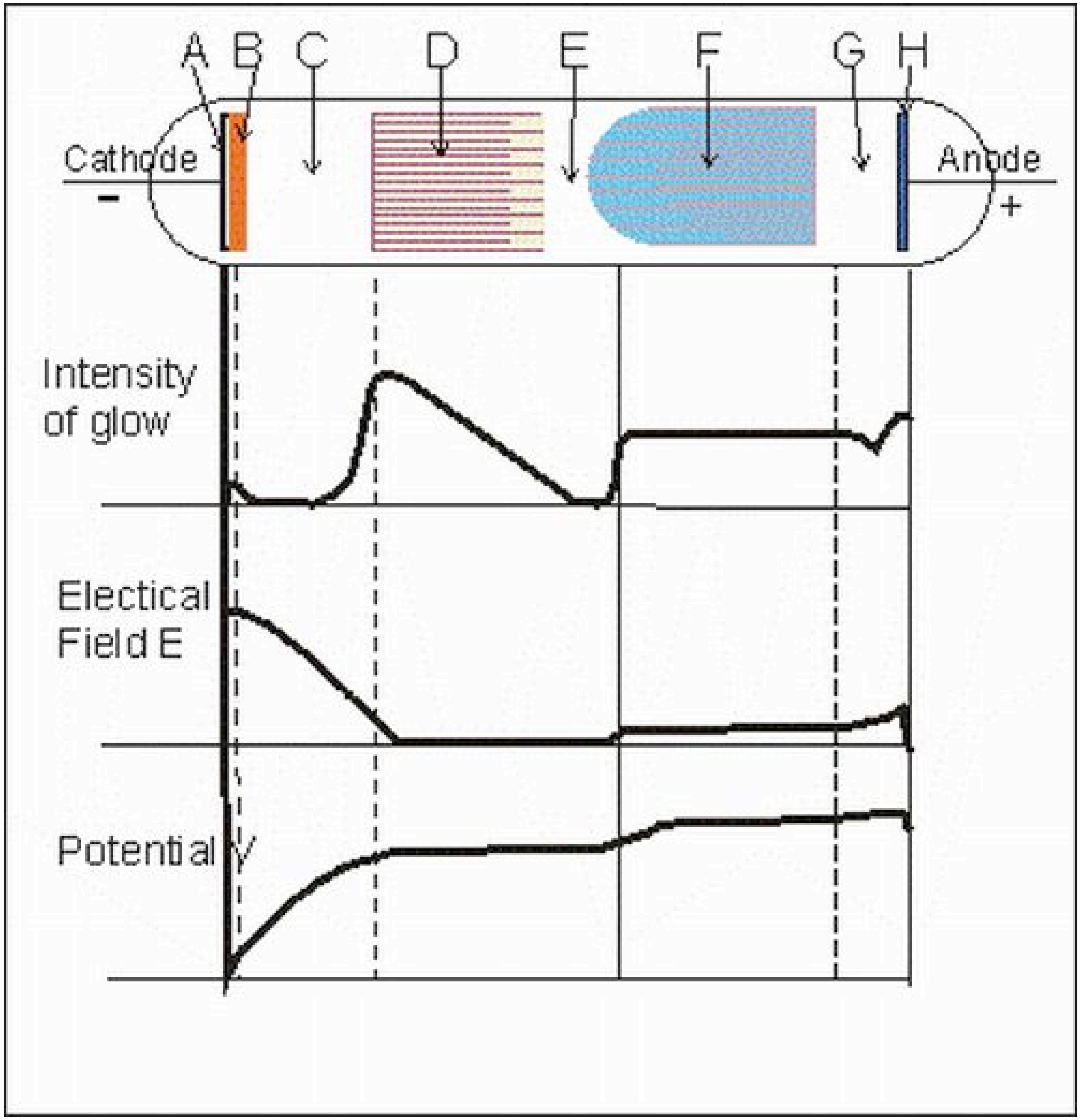
1.Electric current associated with cathode rays

2.The rays are deflected by a magnetic field like a negative charge

3.Cathodes of any metal produce cathode rays. Ray properties independent of metal type.

4.Rays can exert forces on objects. Thin foil gets hot and glows red.

Gas Discharge Tubes - its complicated



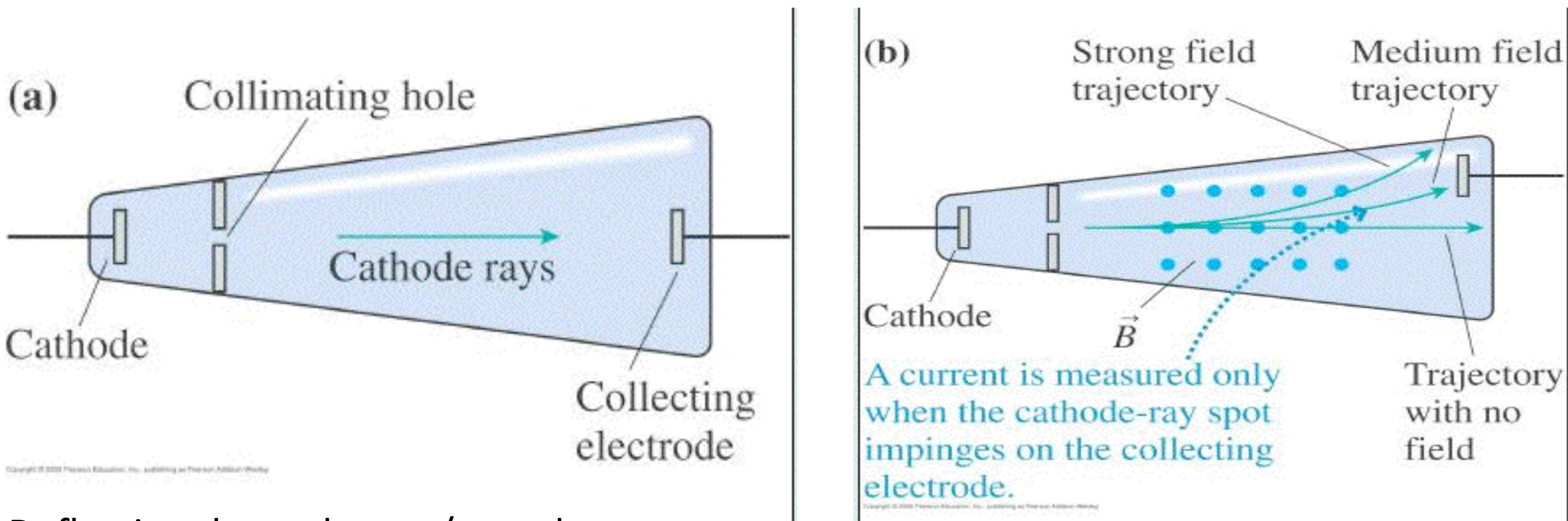
Aston Dark Space (A)
Cathodic Glow, (B)
Cathode (Crooks, Hittorf)
dark space (C)
Negative Glow NG (D)
Faraday dark space (E)
Positive Column (F)
Anodic glow (G)
Anode dark space (H)

http://www.glow-discharge.com/Index.php?Physical_background:Glow_Discharges

Authors: Lydie Salsac & Thomas Nelis

Are Cathode Rays Charged Particles ?

Atoms should be composed of positive and negative parts



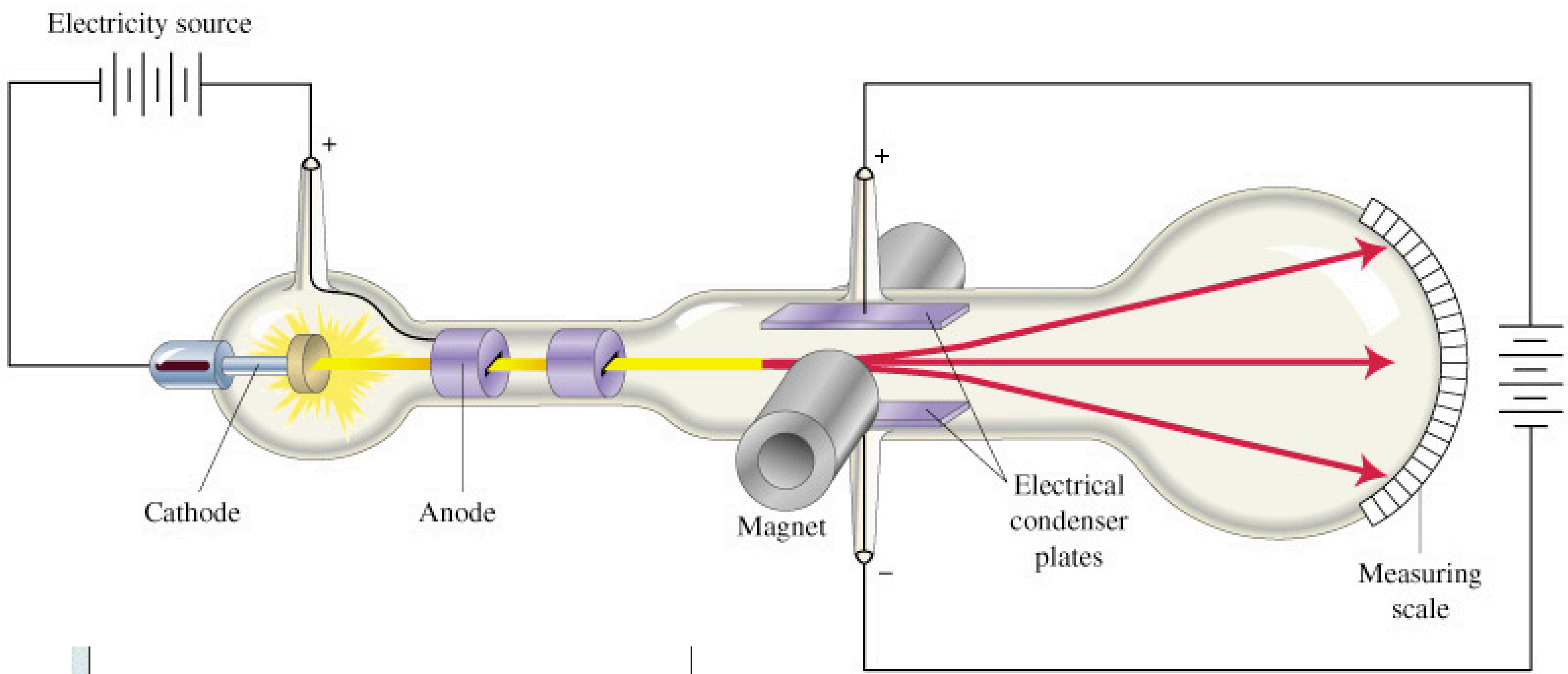
Deflection depends on q/m and v

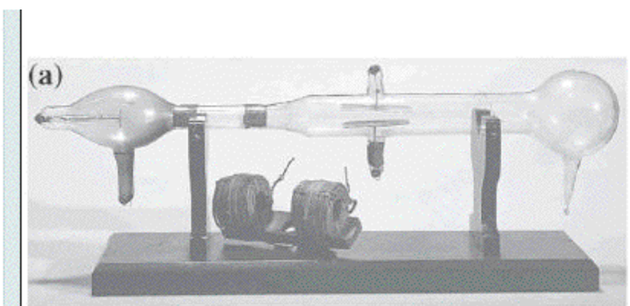
$$\frac{d\vec{v}}{dt} = \frac{q}{m}(\vec{v} \times \vec{B})$$

$$r = mv/qB$$

Confirmed that cathode rays were negatively charged particles but could not measure the q/m

Thomson's Cathode Ray Tube



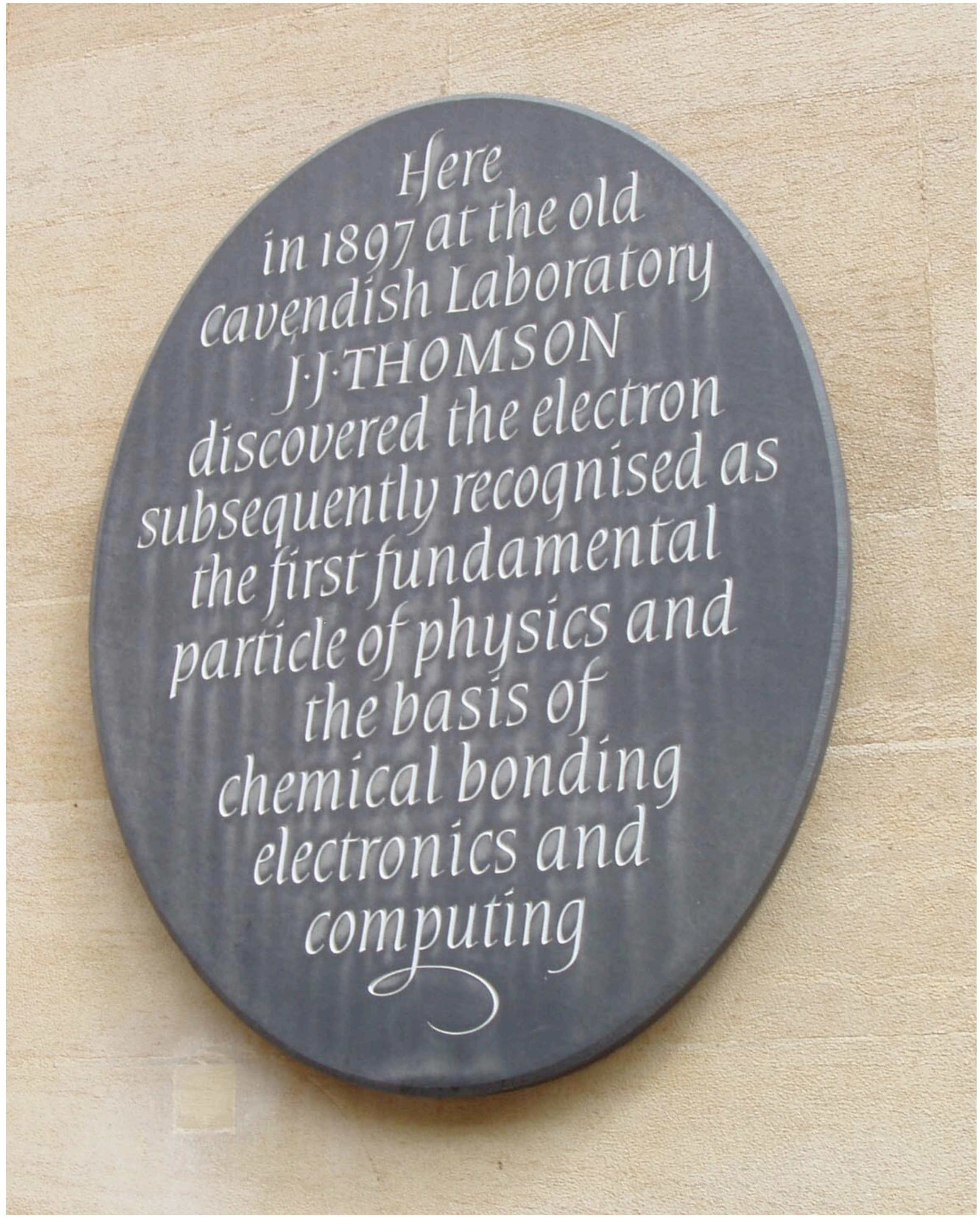


FOUND THAT NEGATIVE PARTICLES EMITTED FROM METALS HAVE THE SAME q/m.

-> ELECTRONS ARE CONSTITUENT OF ALL MATTER

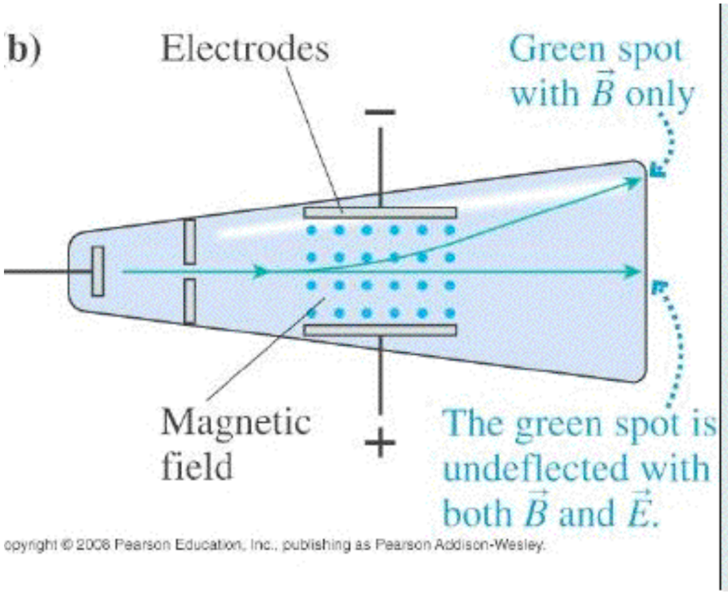

CAVENDISH LABORATORY
1874-1974
Established by the Duke of Devonshire
and extended by Lord Rayleigh (1908) and
Lord Austin (1940), the Cavendish Laboratory
housed the Department of Physics
from the time of the first Cavendish Professor,
James Clerk Maxwell, until its move to
new laboratories in West Cambridge

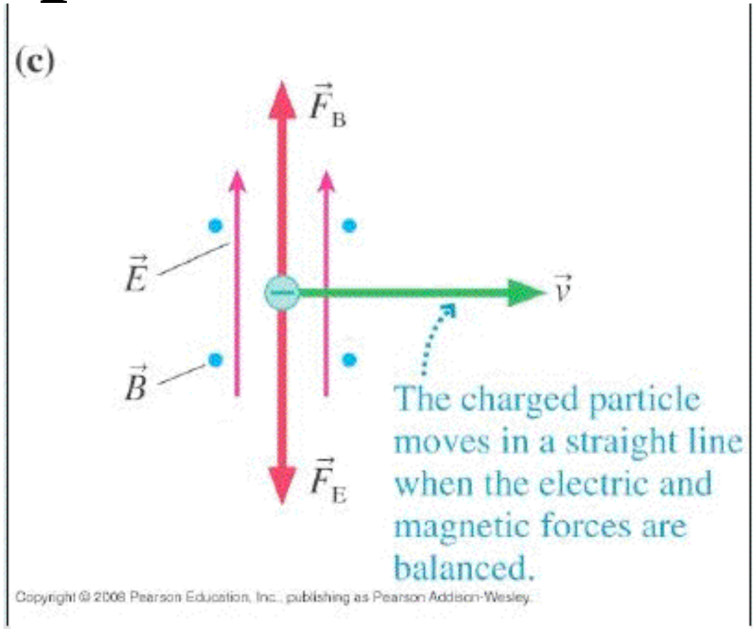
Old Cavendish Laboratory



Punting on the Cam

Cross – Field Experiment





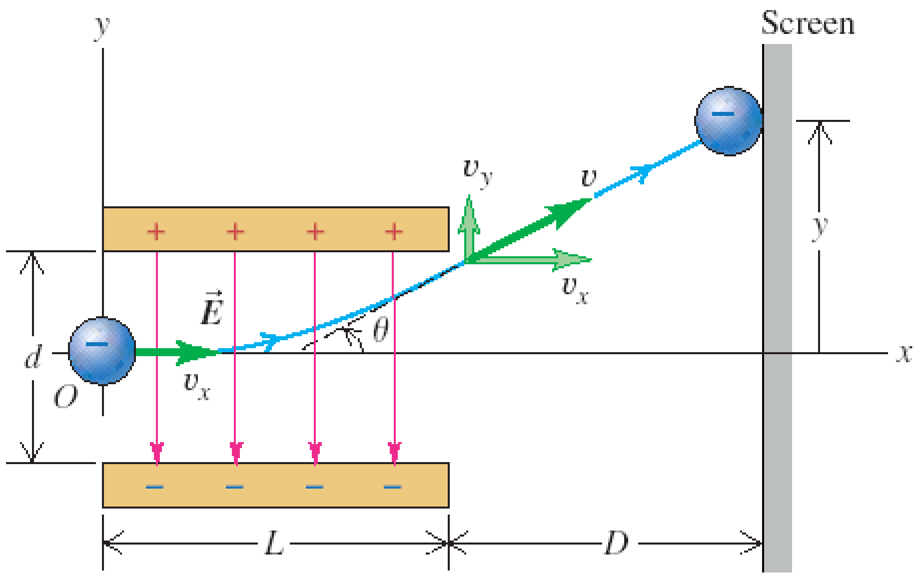
$$\frac{d\vec{v}}{dt} = \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B})$$

$$\frac{d\vec{v}}{dt} = 0$$

$$v_x = E / B$$

$$r = mv / qB = (m / q)(E / B^2)$$

Thomson found $q/m = 10^{11}$ Cb/kg
For Hydrogen $q/m = 10^{8}$ Cb/kg
Cathode ray particle has either much larger charge or much smaller mass.



Two Steps: 1. deflection due to E with B=0

$$v_y = a_y t, \quad F = m_e a_y, \quad F = Ee$$

$$E = V / d$$

$$a_y = Ve / m_e d, \quad t = L / v_x$$

$$v_y = \frac{VLe}{m_e v_x d}$$

beam deflection θ :

$$\tan\theta = \frac{v_y}{v_x} = \frac{VL}{v_x^2 d}\left(\frac{e}{m_e}\right) \approx \theta \;\; \textit{for small angles}$$

V, L, and d are all measurable characteristics of the apparatus

If you can measure v_x, then you can determine e/m.

2. A magnetic field can be used to just cancel the deflection and determine v_x.

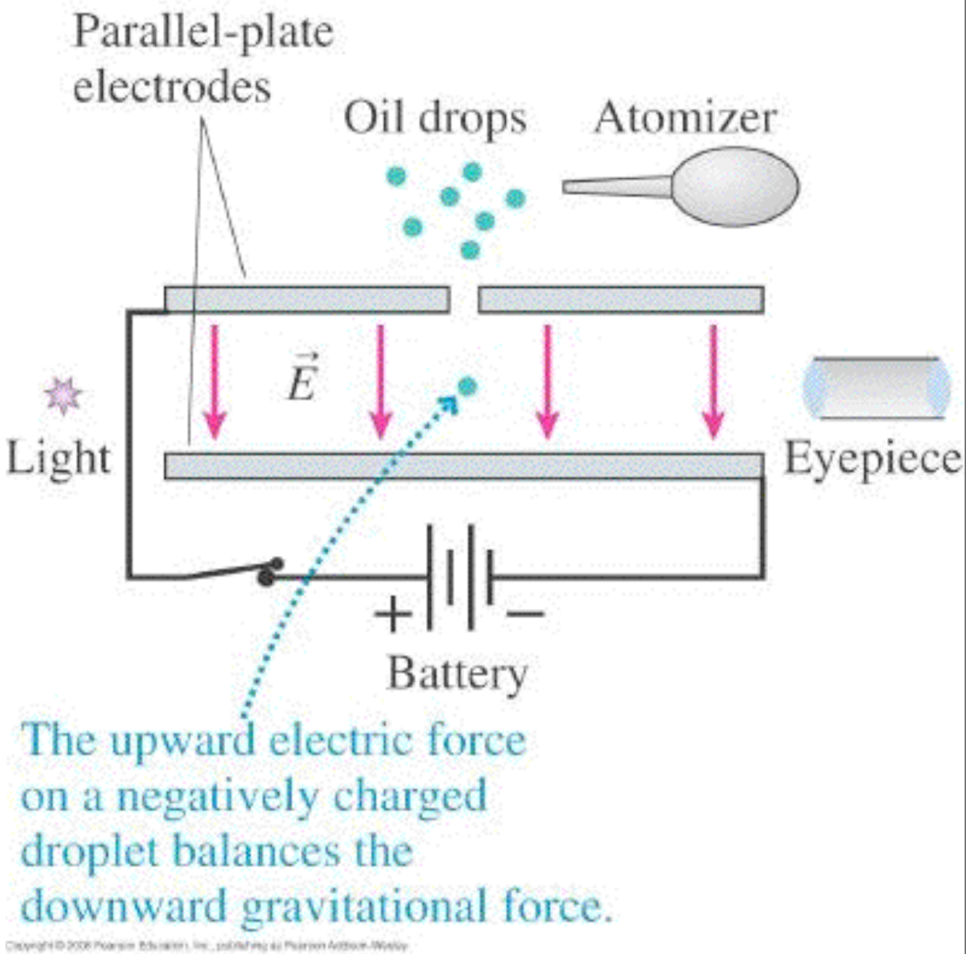
$$qE = qv_x B \quad \Rightarrow \quad v_x = \frac{E}{B} = \frac{V}{Bd}$$

$$\boxed{\frac{e}{m_e} = \frac{V\theta}{B^2 L d}}$$

J. J. Thomson's conclusion that cathode ray particles are *fundamental* constituents of atoms was based primarily on which observation?

A. They have a negative charge.
B. Their mass is much less than hydrogen.
C. They are the same from all cathode materials.
D. They penetrate very thin metal foils.

Measuring the charge- Millikan's Experiment



$$m_{dr} g = q_{dr} E$$

$$q_{dr} = m_{dr} g / E$$

Problem: how to measure the mass of a droplet?

Terminal velocity of drop depends on radius

$$m_e = 9.11 \times 10^{-30} kg$$

$$e = 1.6 \times 10^{-19} Cb$$

$$e / m_e = 1.76 \times 10^{11} Cb / kg$$

Suspending an oil drop

QUESTION:

EXAMPLE 38.2 Suspending an oil drop

Oil has a density of 860 kg/m^3. A 1.0-μm-diameter oil droplet acquires 10 extra electrons as it is sprayed. What potential difference between two parallel plates 1.0 cm apart will cause the droplet to be suspended in air?

MODEL Assume a uniform electric field $E = \Delta V/d$ between the plates.

Suspending an oil drop

SOLVE The magnitude of the charge on the drop is $q_{\text{drop}} = 10e$. The mass of the charge is related to its density ρ and volume V by

$$m_{\text{drop}} = \rho V = \frac{4}{3}\pi R^3 \rho = 4.50 \times 10^{-16}\ \text{kg}$$

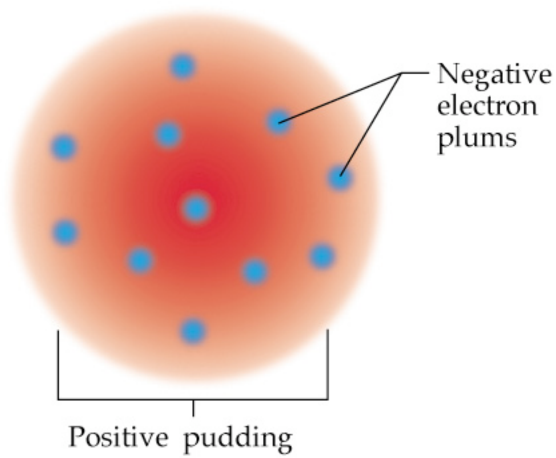
where the droplet's radius is $R = 5.0 \times 10^{-7}$ m. The electric field that will suspend this droplet against the force of gravity is

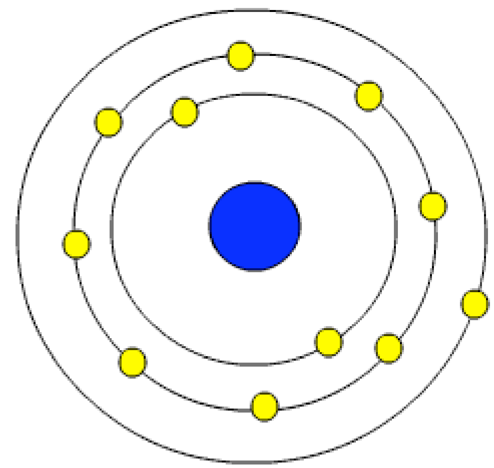
$$E = \frac{m_{\text{drop}} g}{q_{\text{drop}}} = 2760\ \text{V/m}$$

Establishing this electric field between two plates spaced by $d = 0.010$ m requires a potential difference

$$\Delta V = Ed = 27.6\ \text{V}$$

What is inside an atom? Two Models of the Atom

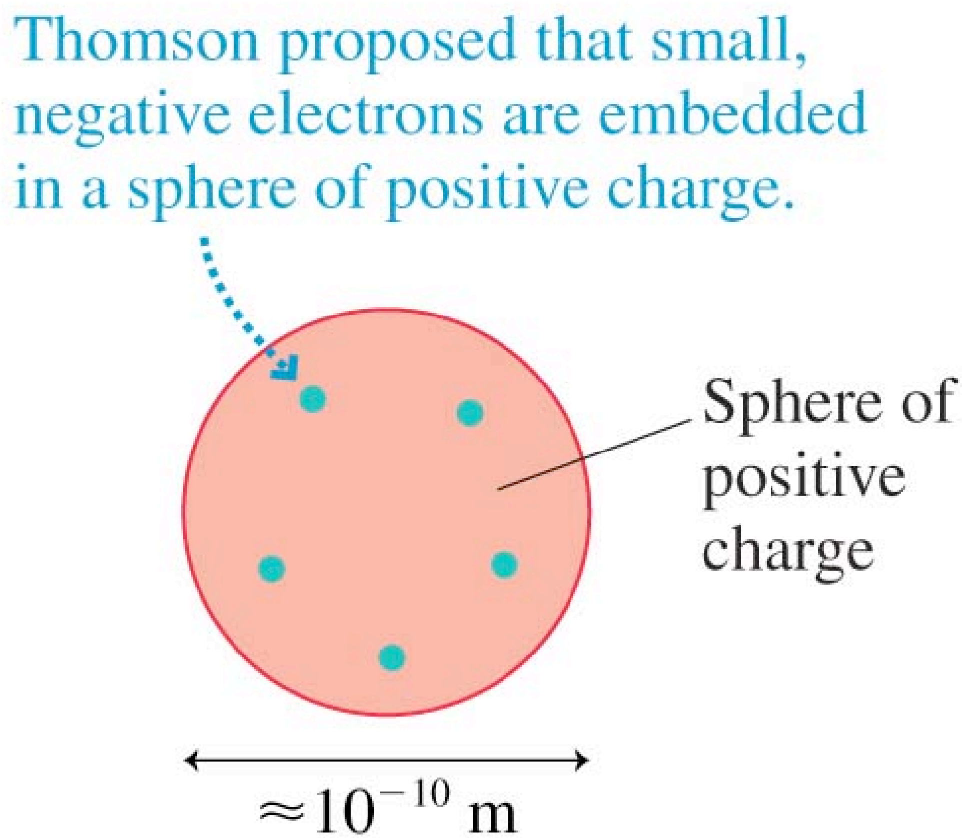




IF MATTER COMPOSED OF ATOMS WHAT ATOMS ARE COMPOSED OF?

- **FARADAY –ELECTROLYSIS**
- **THOMSON – ELECTRONS q/m**
- **MILLIKAN – ELECTRONIC q**
- **RUTHERFORD – NUCLEAR MODEL**

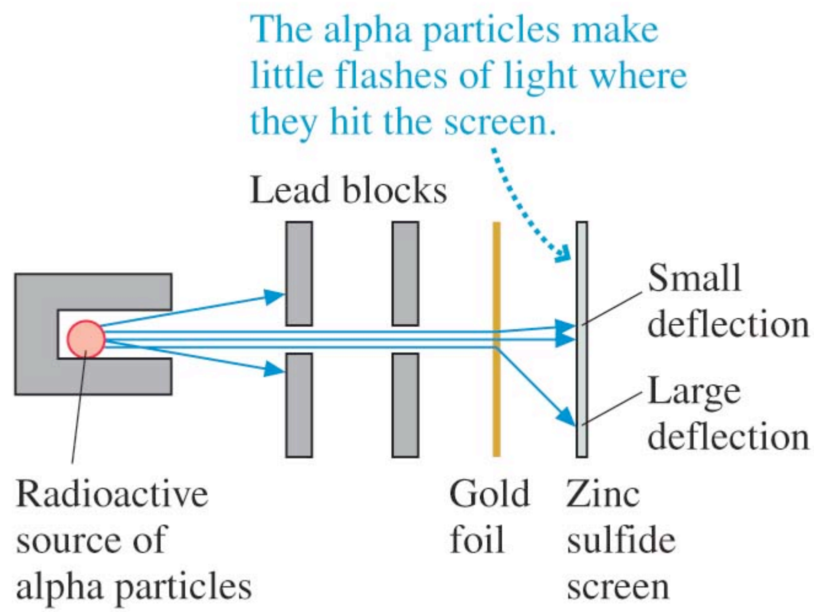
FIGURE 38.10 Thomson's raisin-cake model of the atom.



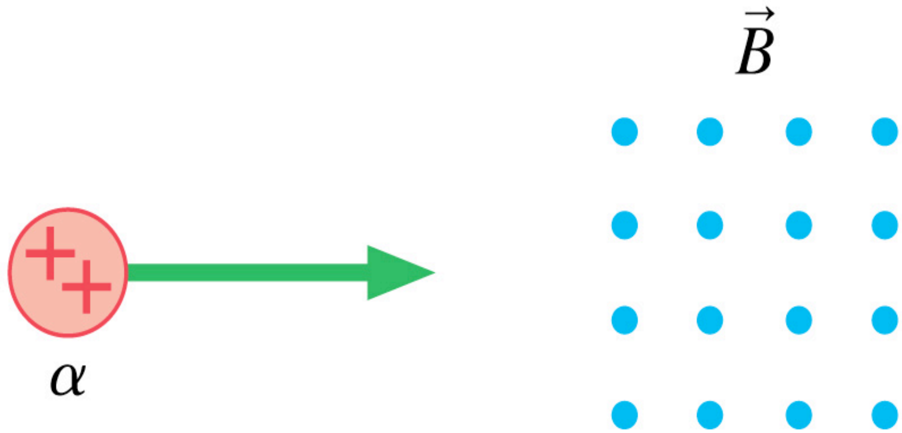
Rutherford and the Discovery of the Nucleus

- In 1896 Rutherford's experiment was set up to see if any alpha particles were deflected from gold foil at *large* angles.
- Not only were alpha particles deflected at large angles, but a very few were reflected almost straight backward toward the source!

FIGURE 38.11 Rutherford's experiment to shoot high-speed alpha particles through a thin gold foil.

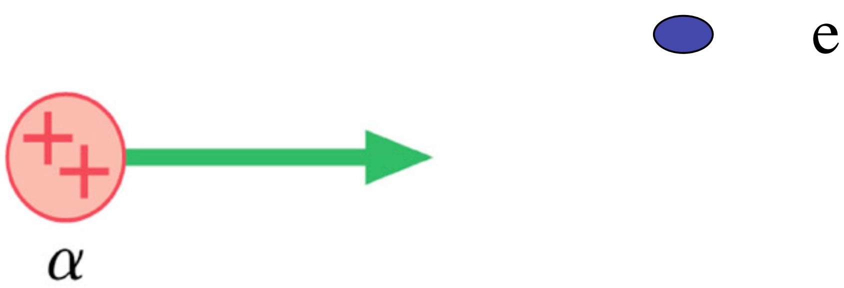


If the alpha particle has a positive charge, which way will it be deflected in the magnetic field?



A. Into the page
B. Out of the page
C. Up
D. Down

If the alpha particle has a positive charge, and atomic mass 4. which way will it be deflected in by the electron?



A. Into the page
B. Out of the page
C. Up
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If the alpha particle has a positive charge, and atomic mass 4. Which way will it be deflected in by the proton?

A. Into the page
B. Out of the page
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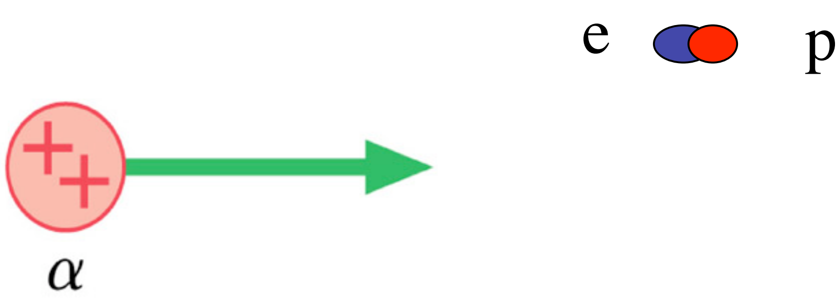
D. Down

If the alpha particle has a positive charge, and atomic mass 4. Which way will it be deflected in by the electron and proton?



A. Into the page
B. Out of the page
C. Up
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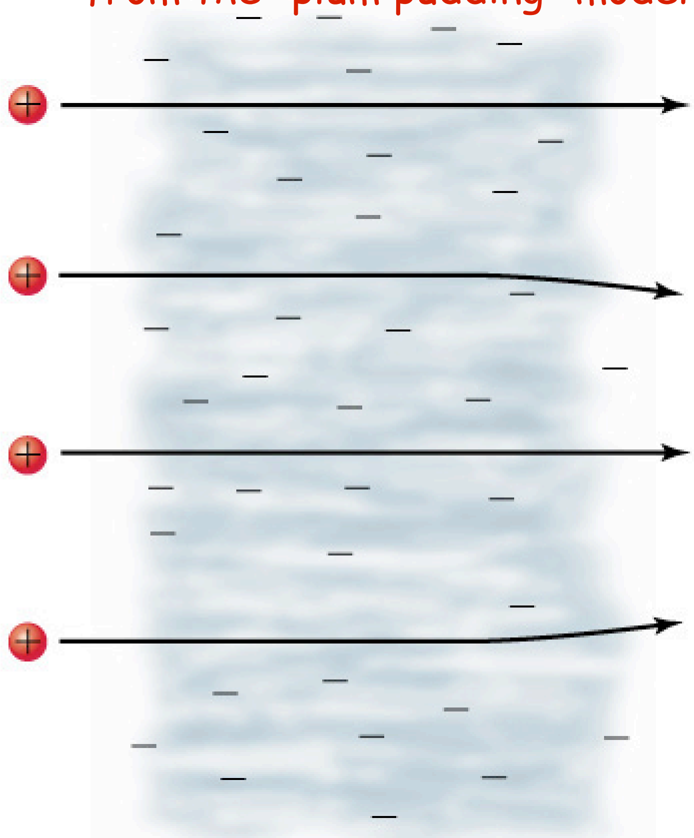
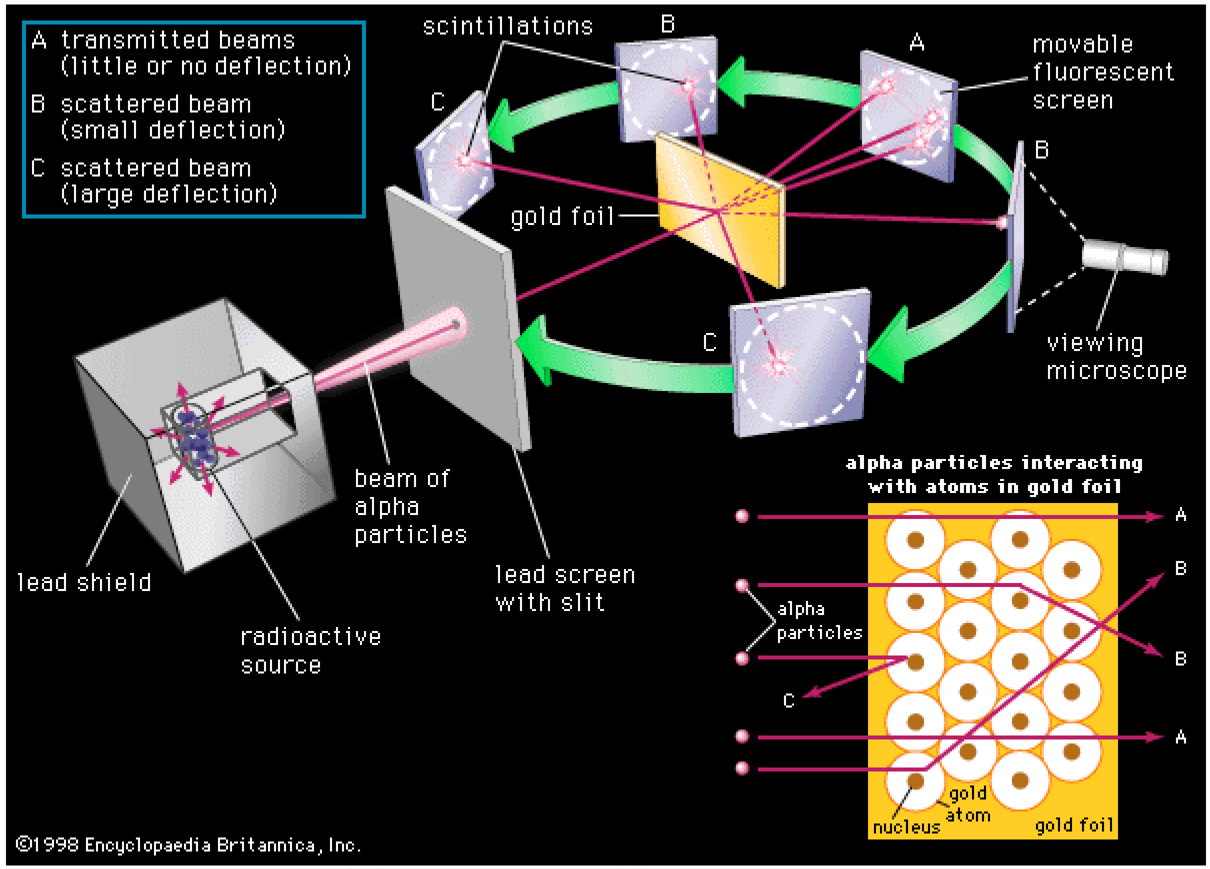
The discovery of the atomic nucleus: Rutherford Back Scattering

what Rutherford expected from the "plum pudding" model



the clever experiment

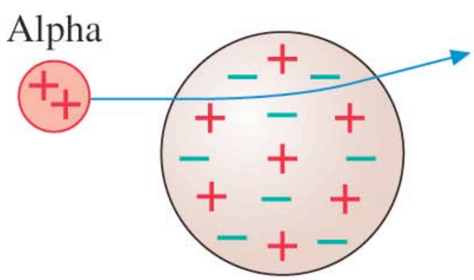


the (surprise!) result

"It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

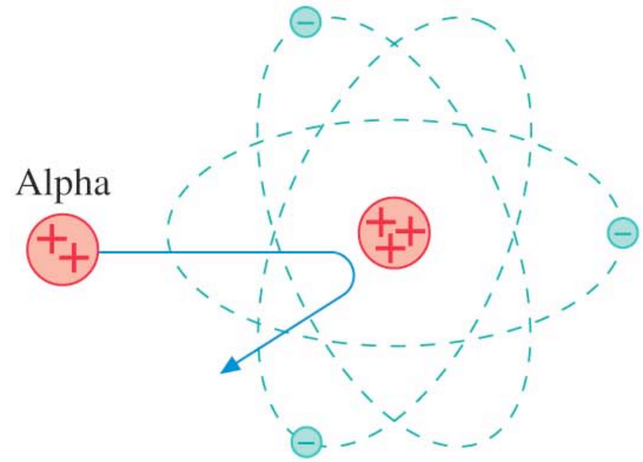
FIGURE 38.12 Alpha particles interact differently with a concentrated positive nucleus than they would with the spread-out charge in Thomson's model.

(a)



The alpha particle is only slightly deflected by a Thomson atom because forces from the spread-out positive and negative charges nearly cancel.

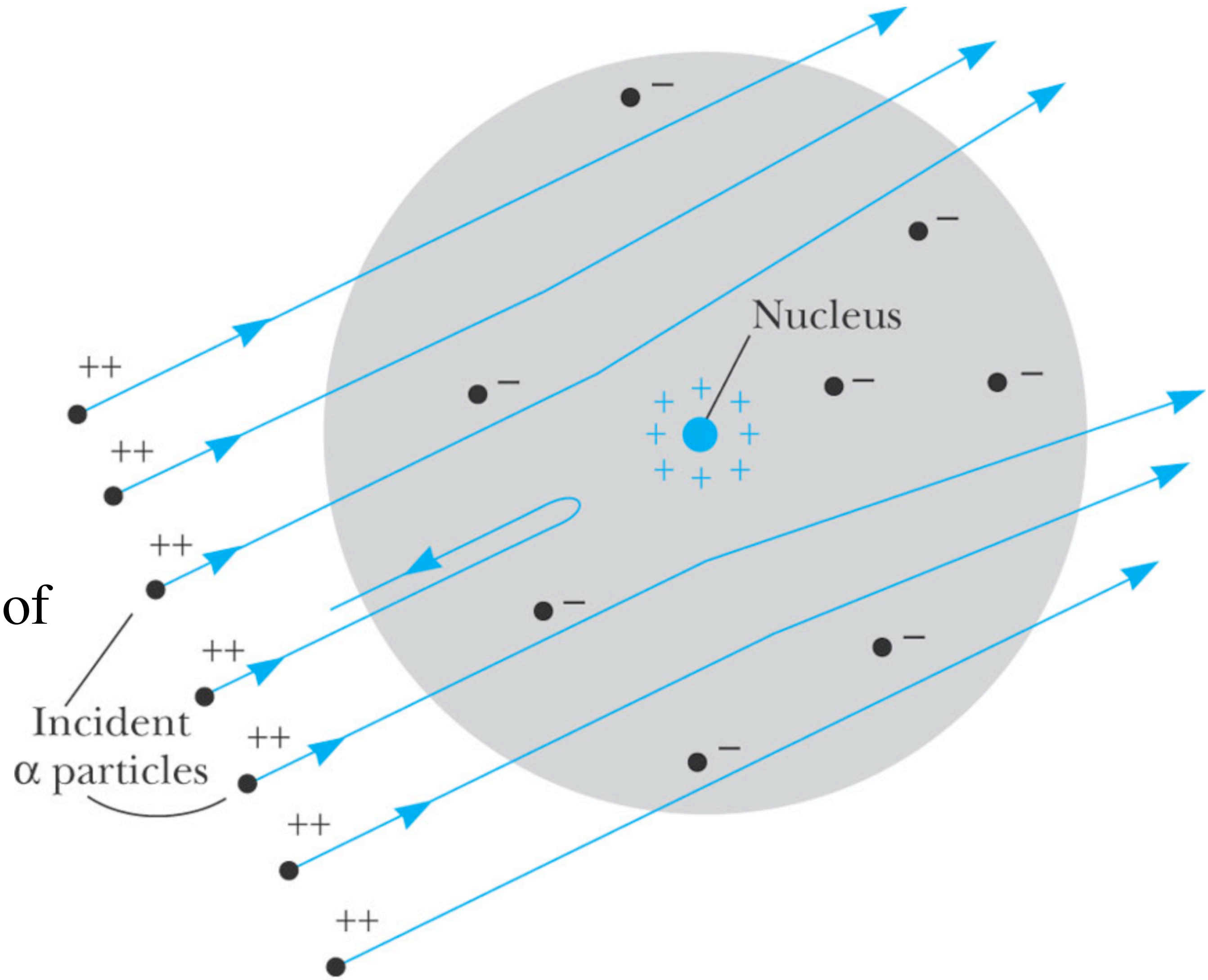
(b)

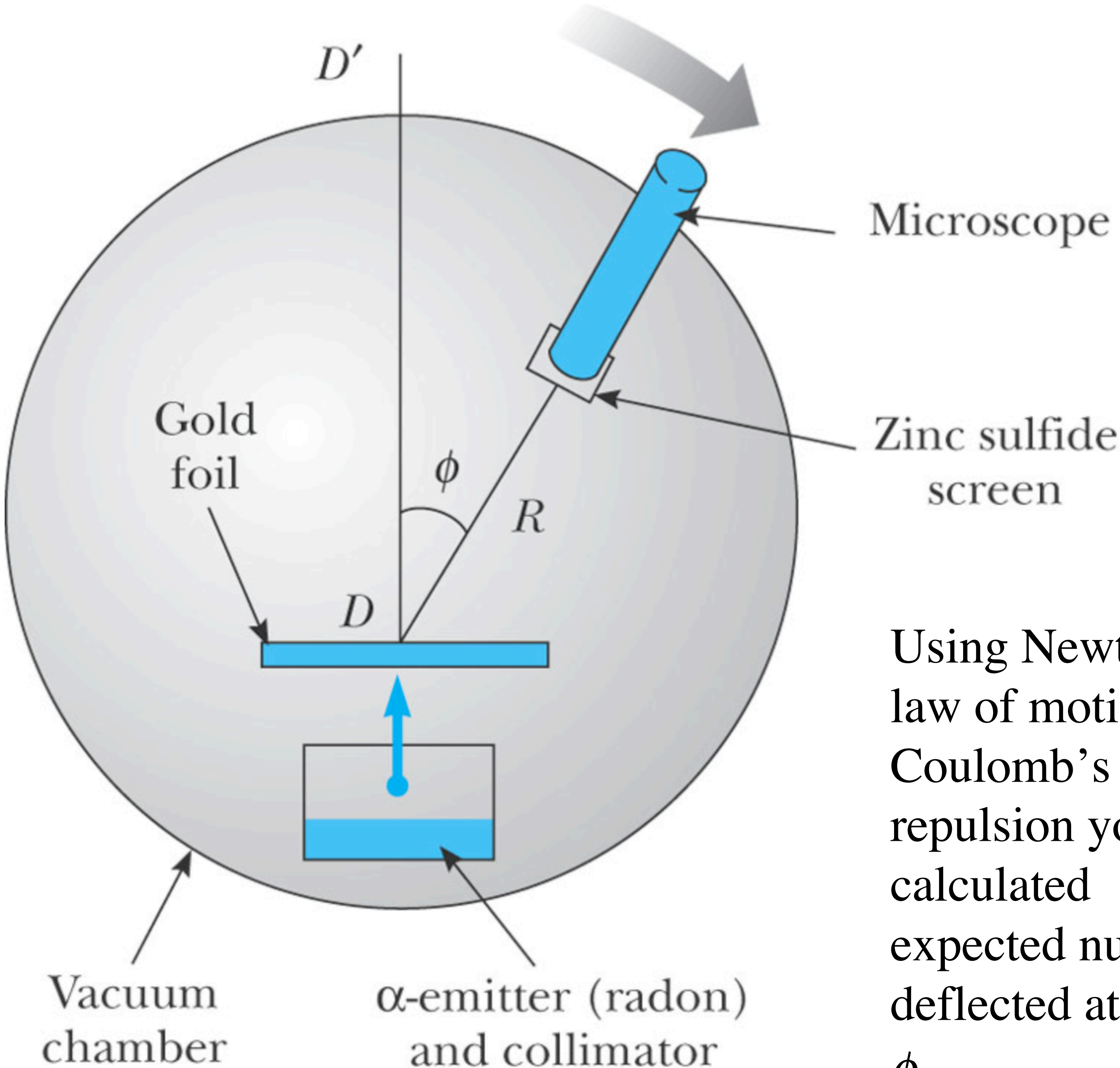


If the atom has a concentrated positive nucleus, some alpha particles will be able to come very close to the nucleus and thus feel a very strong repulsive force.

What are the distribution of angles into which the alphas scatter?

This problem can be solved by application of Newton’s laws of motion.

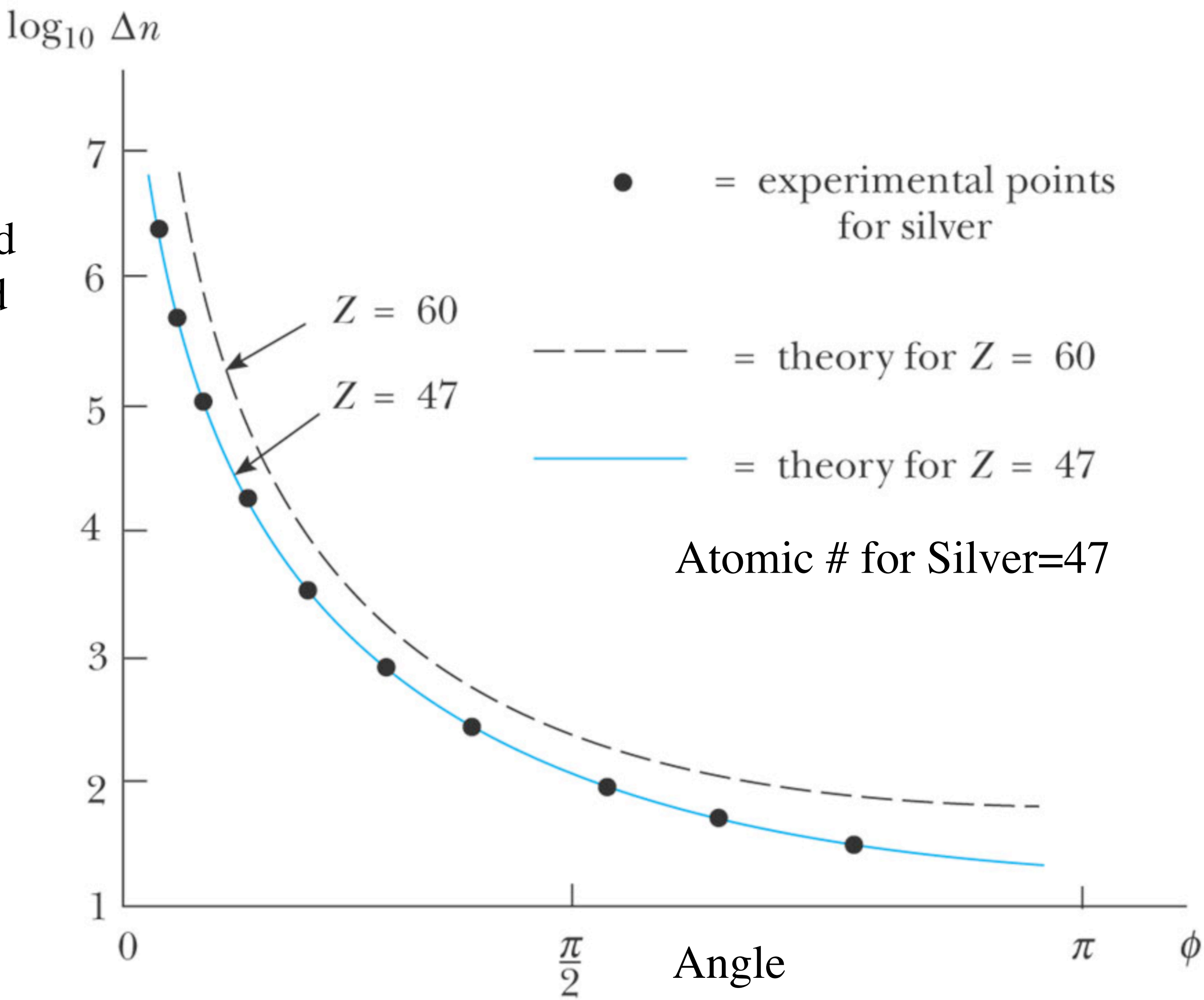




Using Newton's law of motion + Coulomb's law of repulsion you can calculated expected number deflected at angle ϕ.

Fig. 4-10, p. 120

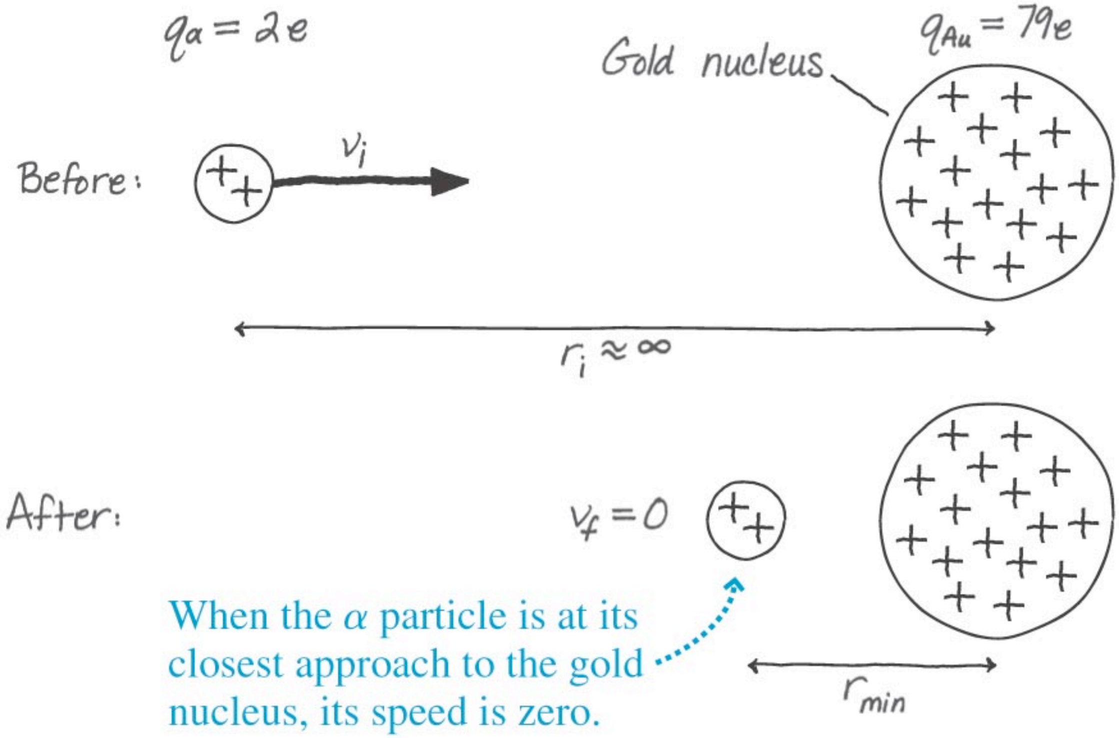
Number deflected per solid angle



Atomic # for Silver=47

Angle

Fig. 4-12, p. 123



What is the point of closest approach for a head-on collision?

Use conservation of energy.

Total energy is conserved:
$K_i+U_i=K_f+U_f$

$$K_i = \frac{1}{2}m_\alpha v_i^2$$

$$U_i = 0$$

$$K_f = \frac{1}{2}m_\alpha v_f^2 = 0$$

$$U_f = \frac{q_\alpha q_{Au}}{4\pi\varepsilon_0 r_{\min}}$$

$$U_f = \frac{q_\alpha q_{Au}}{4\pi\varepsilon_0 r_{\min}} = K_i = \frac{1}{2}m_\alpha v_i^2$$

Numbers:

$$v_i = 2\times10^7\, m/s$$
$$q_\alpha = 2e$$
$$q_{Au} = 79e$$
$$m_\alpha = 6.64\times10^{-27}\, Kg$$

$$r_{\min} = 2.7\times10^{-14}\, m$$

Energy of an electron bound in a Hydrogen atom ($r=5.3\times10^{-11}$ m, $v=2.2\times10^{6}$ m/sec)-> -13.6 eV. Need energy more than 13.6 eV to ionize it

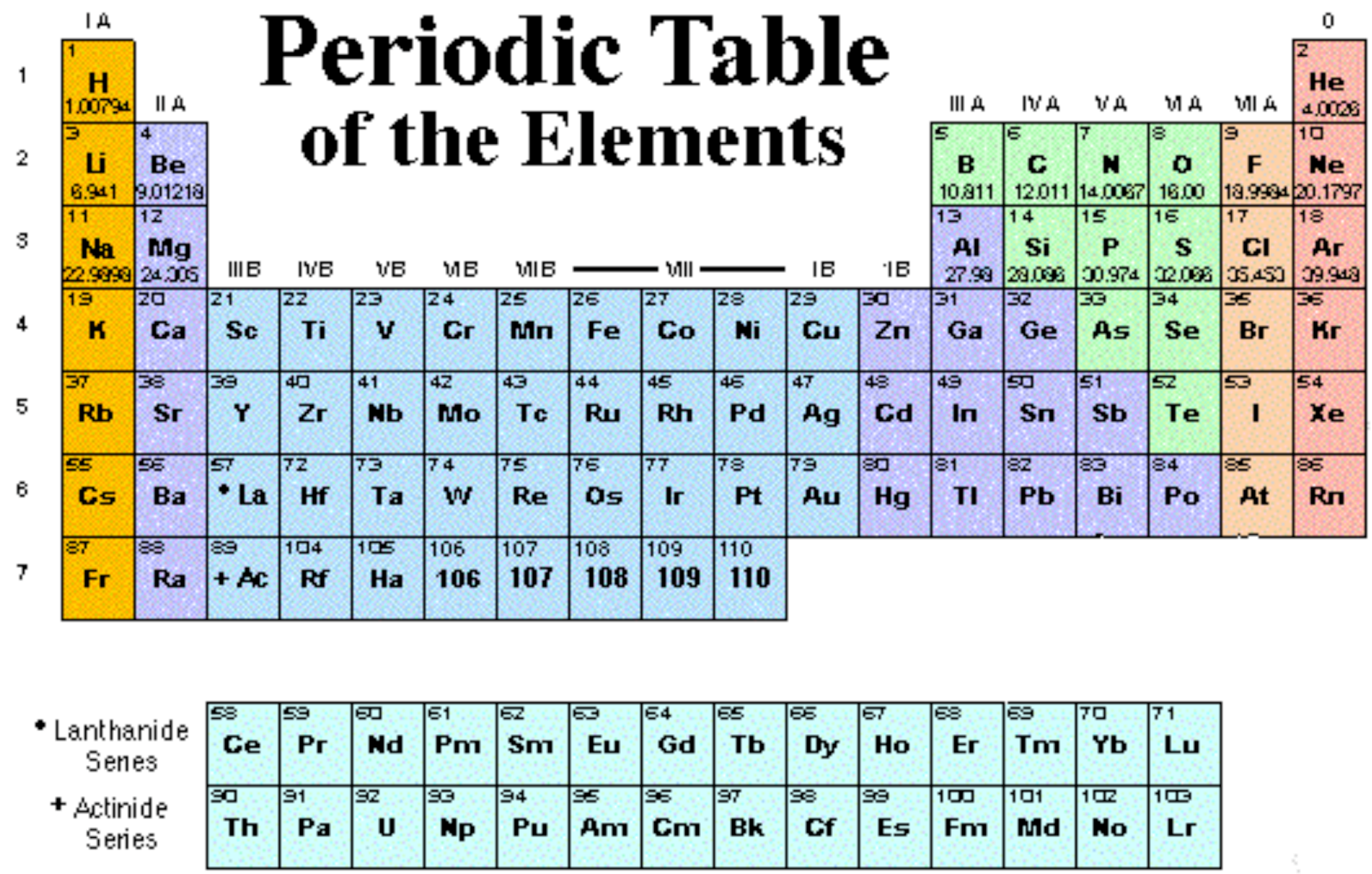
Ionization confirmed Rutherford's model

When rubbing electron easily transferred – but protons hidden deep in the nucleus do not

Into the Nucleus

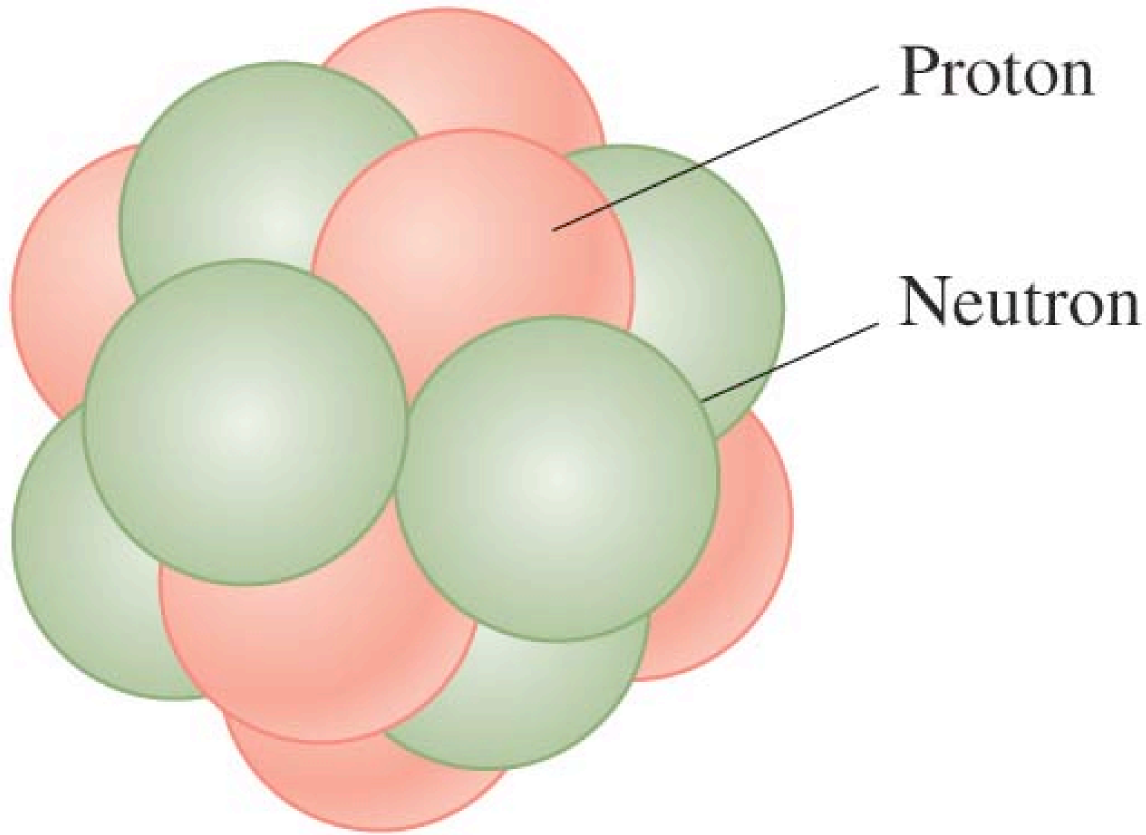
- The **atomic number** Z of an element describes the number of protons in the nucleus. Elements are listed in the periodic table by their atomic number.
- There are a *range* of neutron numbers N that happily form a nucleus with Z protons, creating a series of nuclei having the same Z-value but different masses. Such a series of nuclei are called **isotopes.**
- An atom's **mass number** A is defined to be $A = Z + N$. It is the total number of protons and neutrons in a nucleus.
- The notation used to label isotopes is ${}^{A}Z$, where the mass number A is given as a *leading* superscript. The proton number Z is not specified by an actual number but, equivalently, by the chemical symbol for that element.

Atomic number Z number of electrons and number of positive charges nucleus

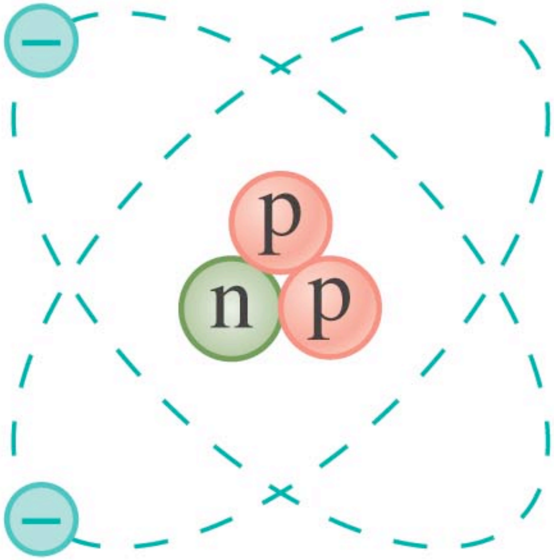


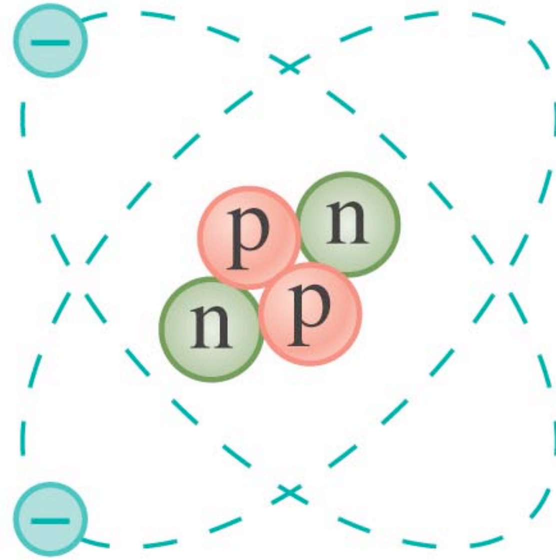
Puzzle atom mass more than Zm_p -> neutron

FIGURE 38.17 The nucleus of an atom contains protons and neutrons.



Two isotopes of Helium





^{3}He

$Z = 2 \qquad N = 1$

$A = 3$

0.0001% abundance

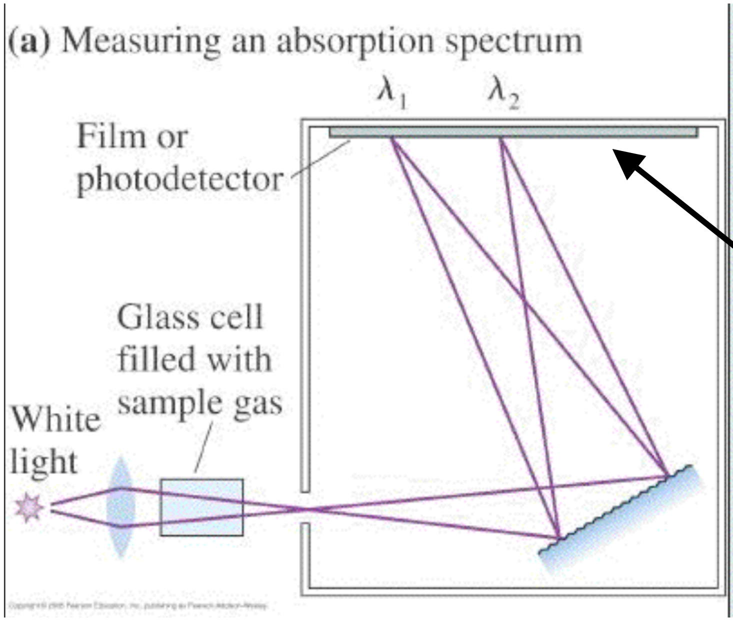
^{4}He

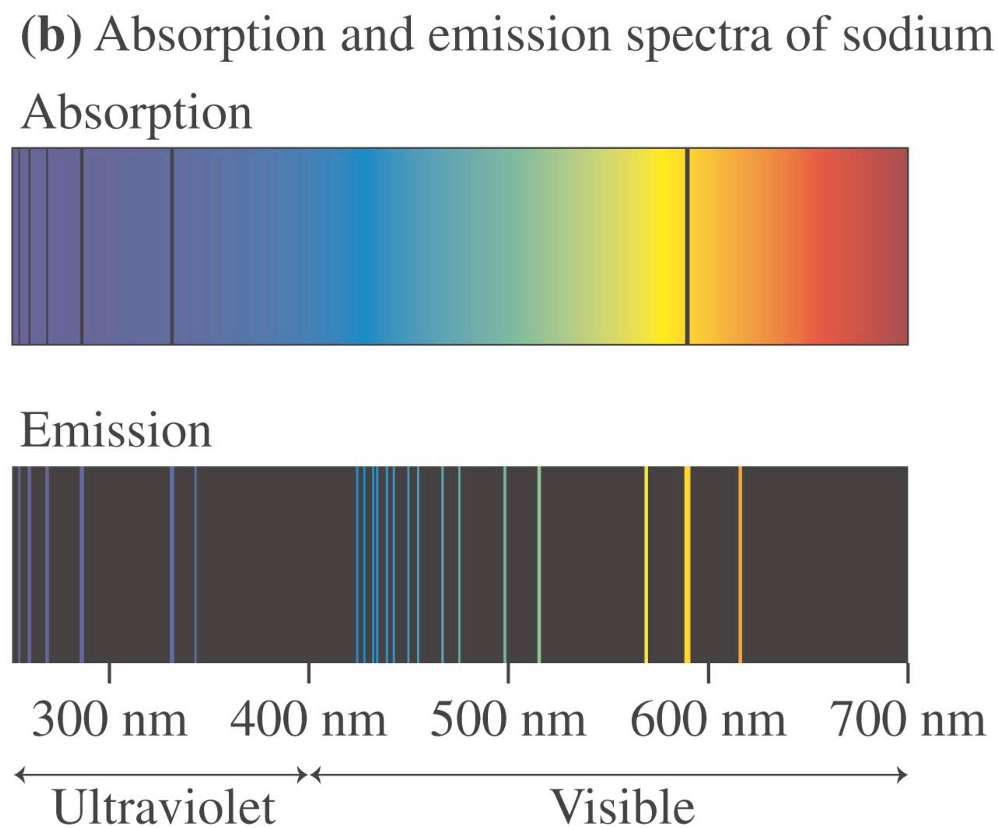
$Z = 2 \qquad N = 2$

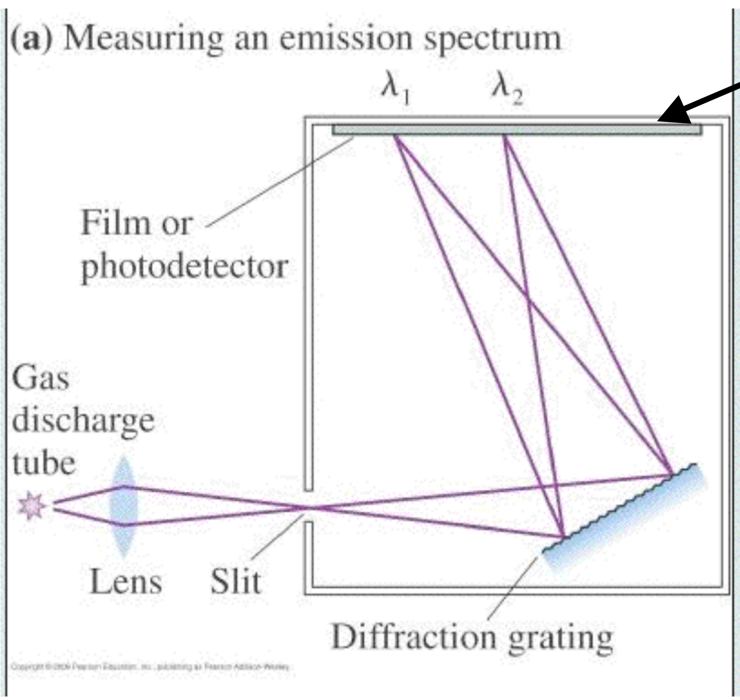
$A = 4$

99.9999% abundance

The Emission and Absorption of Light


(a) Measuring an absorption spectrum
λ1
λ2
Film or photodetector
Glass cell filled with sample gas
White light

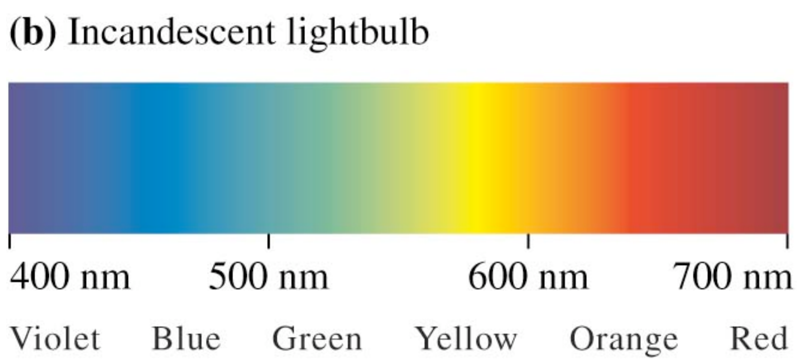

(b) Absorption and emission spectra of sodium
Absorption
Emission
300 nm
400 nm
500 nm
600 nm
700 nm
Ultraviolet
Visible


(a) Measuring an emission spectrum
λ1
λ2
Film or photodetector
Gas discharge tube
Lens
Slit
Diffraction grating

The Emission of Light

Hot, self-luminous objects, such as the sun or an incandescent lightbulb, form a rainbow-like **continuous spectrum** in which light is emitted at every possible wavelength. The figure shows a continuous spectrum.

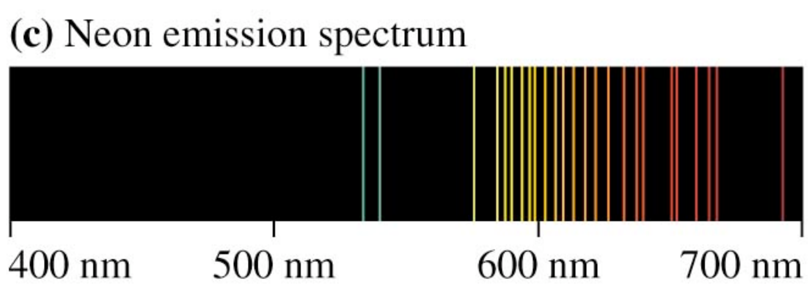
FIGURE 38.19 A grating spectrometer is used to study the emission of light.

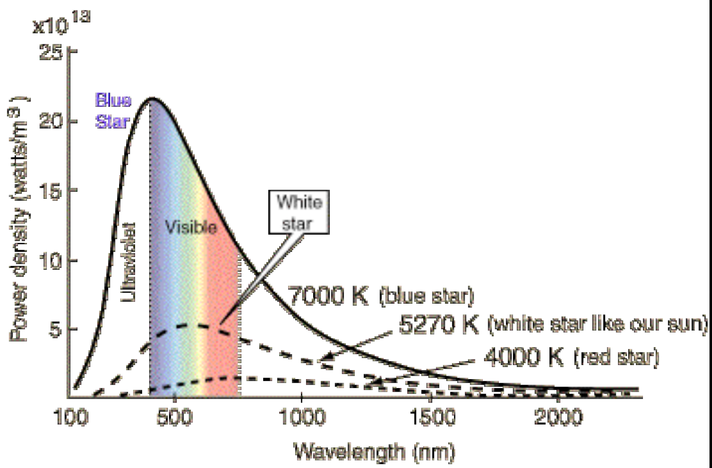


The Emission of Light

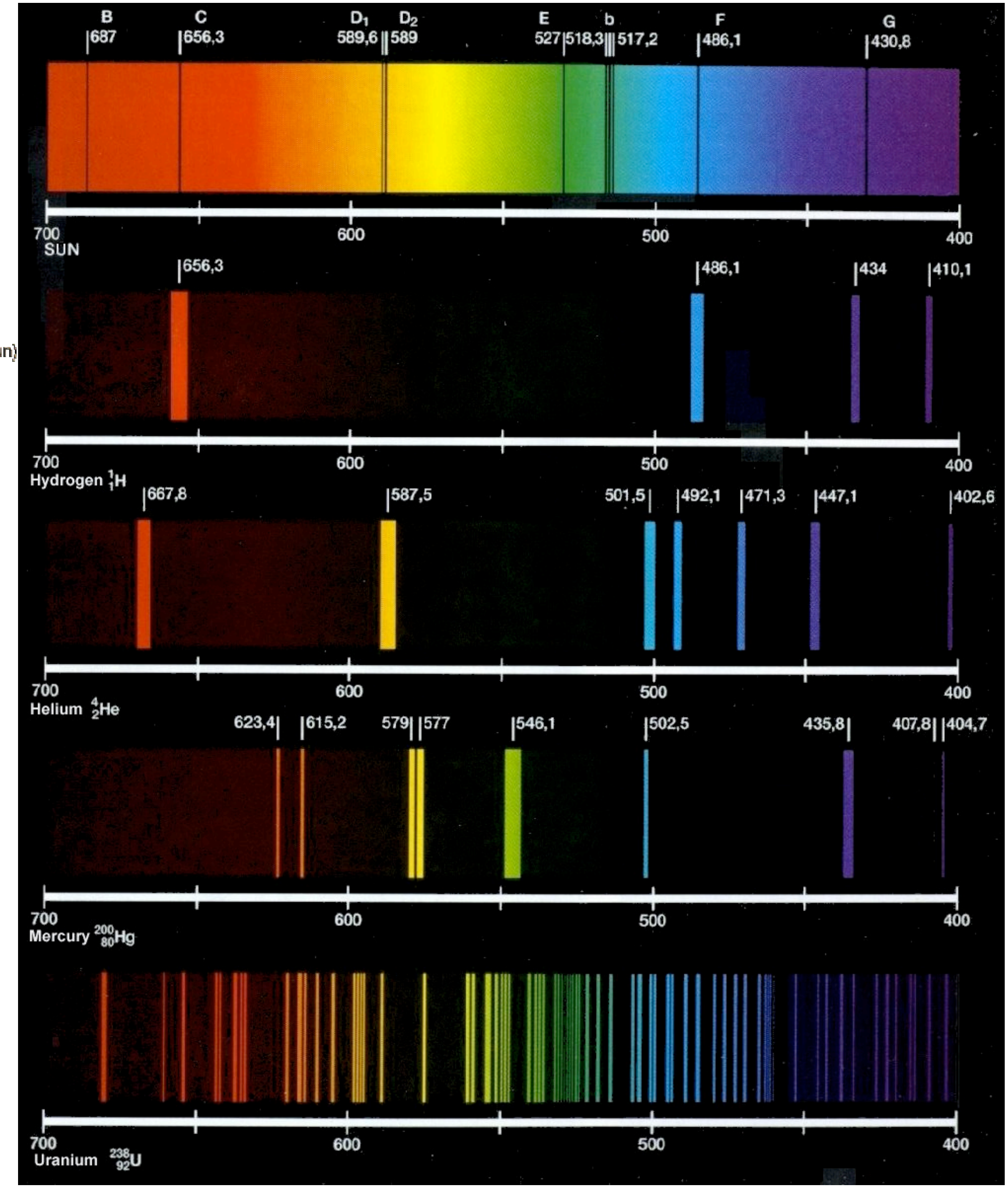
The light emitted by one of Faraday's gas discharge tubes contains only certain discrete, individual wavelengths. Such a spectrum is called a **discrete spectrum.** Each wavelength in a discrete spectrum is called a **spectral line** because of its appearance in photographs such as the one shown.

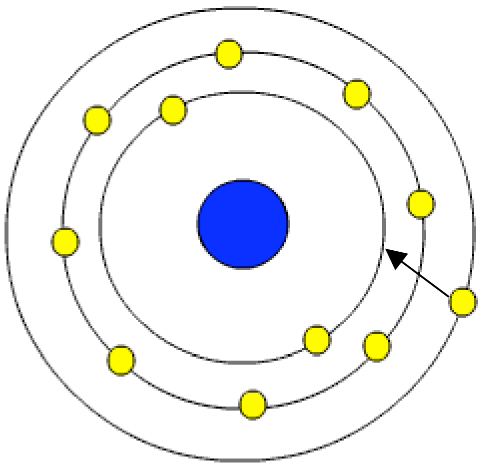
FIGURE 38.19 A grating spectrometer is used to study the emission of light.



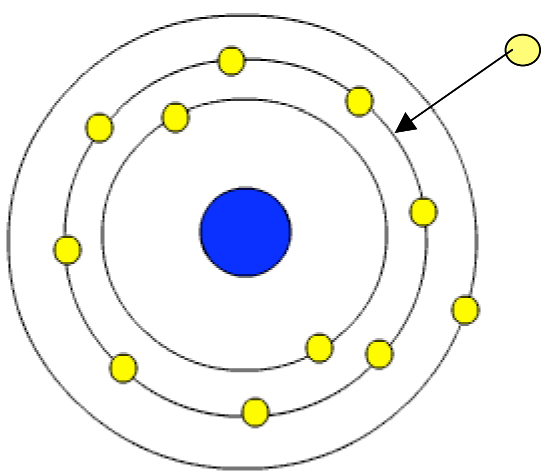


Why is the spectrum continuous in some cases but discrete in others?





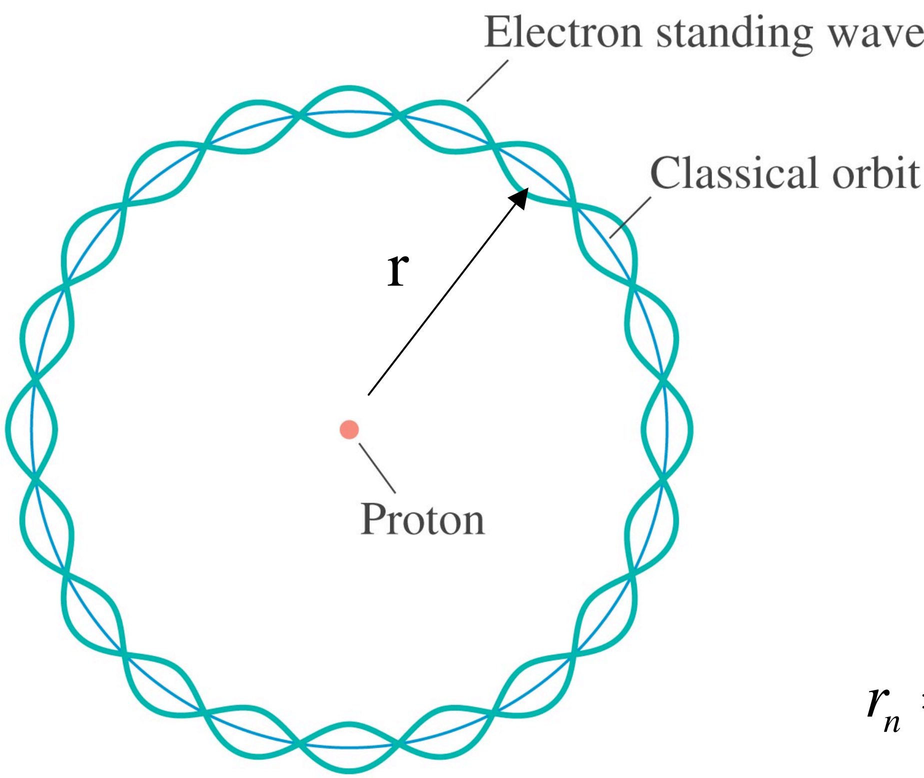
Energy levels of an isolated atom are quantized. When an electron makes a transition from one state to another it gives up a specific amount of energy that creates a photon with a specific wavelength.



A free electron can have any energy. When it is captured by an ion the amount of energy going to make a photon is not some specific value but falls in a range of values.

Quantum mechanics: Orbit must be an integer # of de Broglie wavelengths

$$2\pi r = n\lambda$$



$$mv = h/\lambda = \frac{hn}{2\pi r}$$

Plug in and solve for r.

$$m\frac{v^2}{r} = \frac{e^2}{4\pi\varepsilon_0 r^2}$$

Only certain r's are allowed.

$$r_n = n^2 a_0 \qquad a_0 = \frac{\varepsilon_0 h^2}{\pi m e^2}$$

Bohr radius $a_0 = 5.3\times10^{-11}\,\text{m}$

What are the total energies (Kinetic + Potential) of these states?

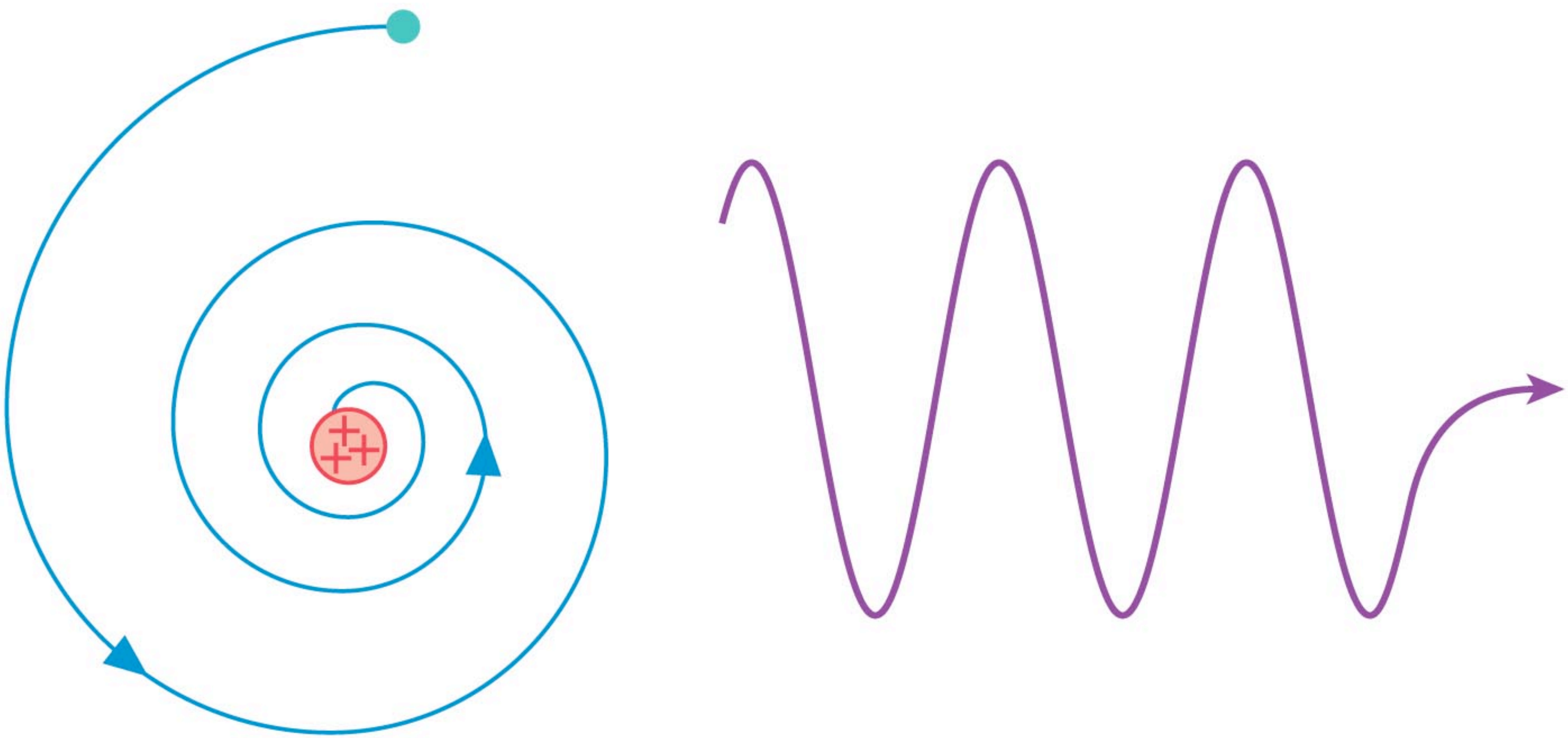
Kinetic Energy: $$K = m\frac{v_n{}^2}{2}$$ ← use $$mv_n = h/\lambda_n = \frac{hn}{2\pi r_n}$$

Potential Energy: $$U = -\frac{e^2}{4\pi\varepsilon_0 r_n}$$

Combining, E=K+U $$E_n = -\frac{1}{n^2}\frac{e^2}{8\pi\varepsilon_0 a_0} = -\frac{2.18\times10^{-18}}{n^2}\,\mathrm{J}$$

Gives Balmer spectrum

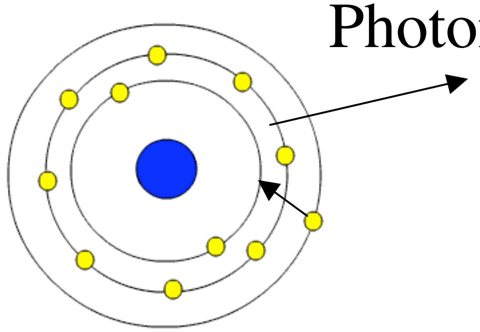
Classically electrons would just radiate energy and spiral in to the nucleus.



Emission vs Absorption in Isolated atoms

Emission

Photon $f = \Delta E/h$



Electron makes a transition from a higher energy state to a lower energy state and gives up a photon of prescribed energy and frequency.

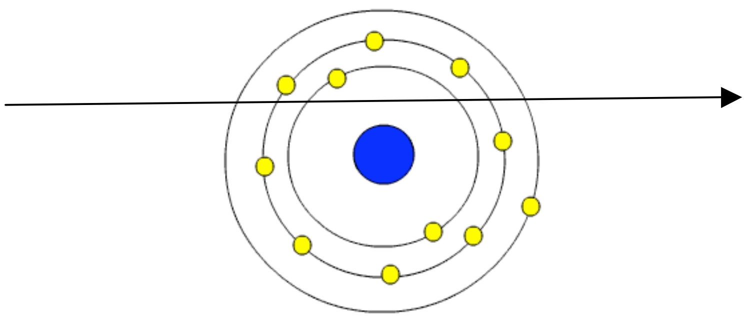
The more electrons in higher energy states the more different frequency transitions are possible.

If the atom is “cold” and all electrons are in the lowest possible states then no photons are observed.

Emission vs Absorption in Isolated atoms

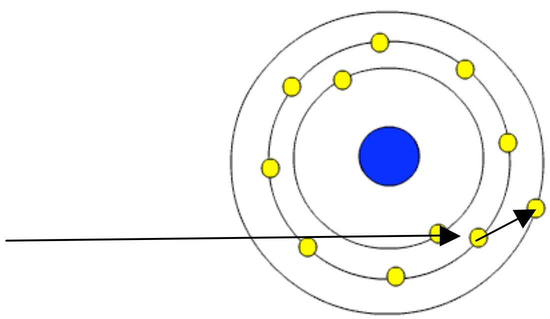
Absorption

Photon $f \neq \Delta E / h$



If photon frequency does not match any possible transition, photon passes through atom without being absorbed.

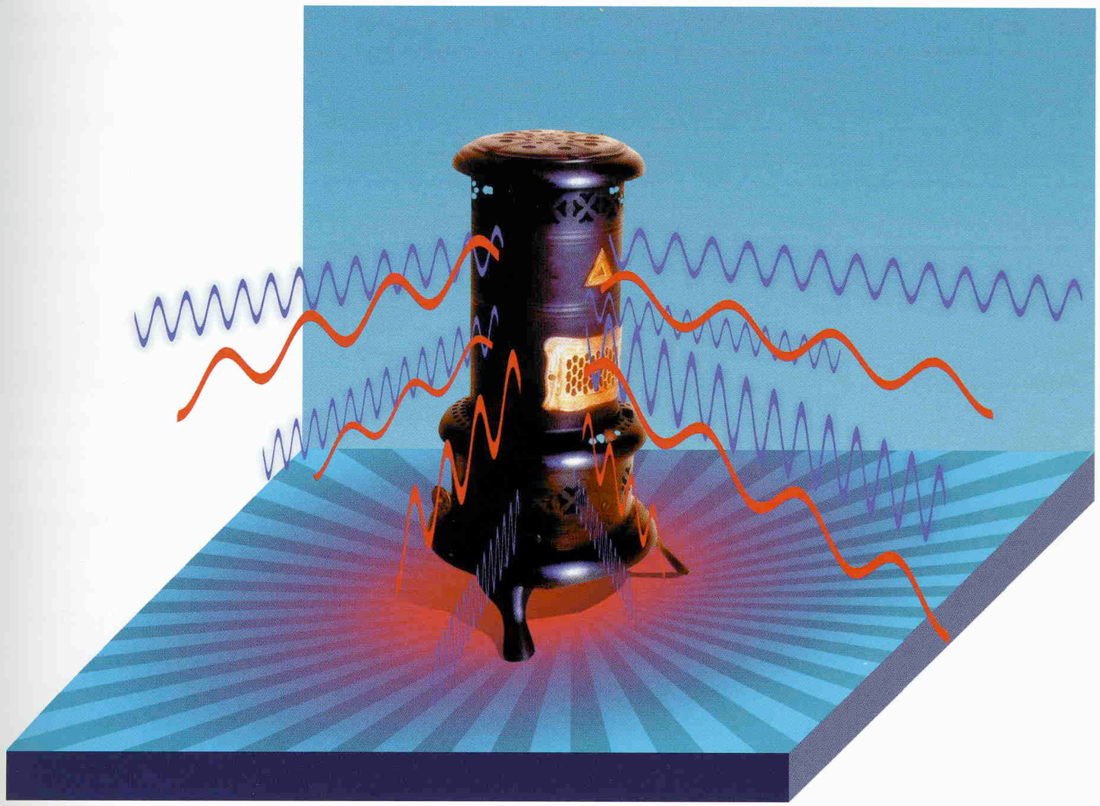
Photon $f = \Delta E / h$



If photon frequency does matches a possible transition, photon can be absorbed

If the atom is "cold" and all electrons are in the lowest possible states then only transitions from those states to higher states will lead to absorption. Generally fewer lines observed than for emission from a hot atoms.

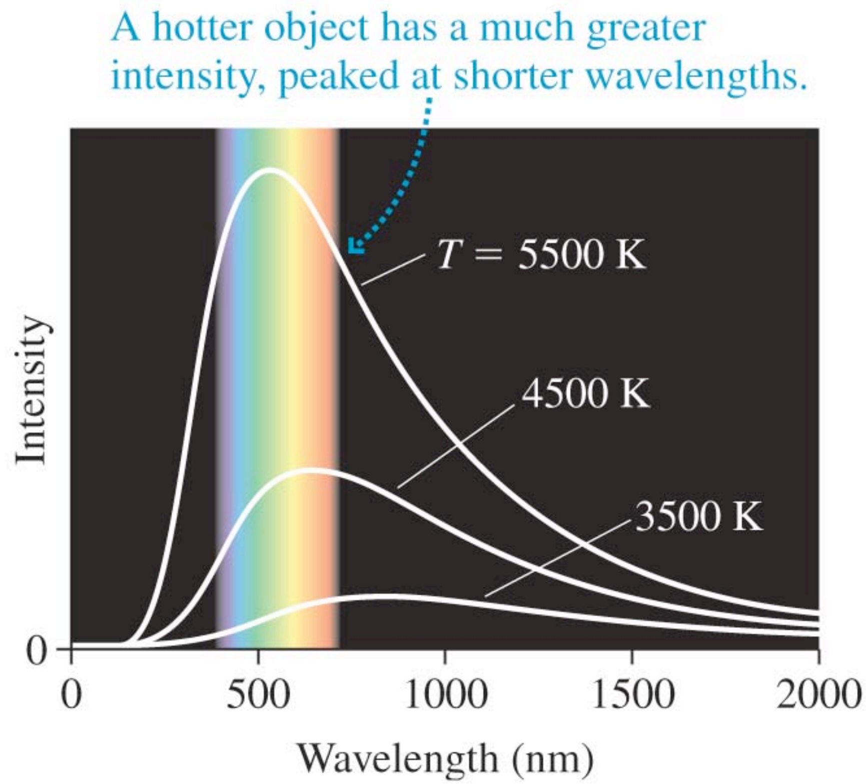
Black Body Radiation



A black body, approximated by this old-fashioned iron stove, radiates heat over all wavelengths. The dominant wavelength depends on its temperature.

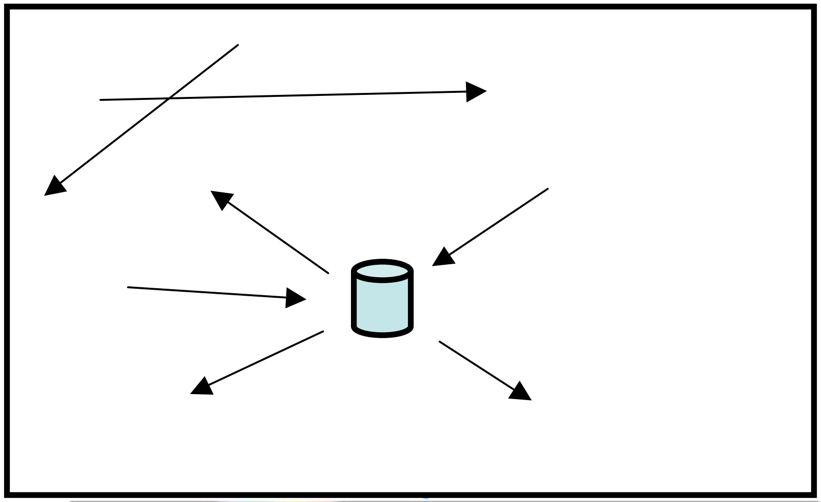
Lava glows when hot

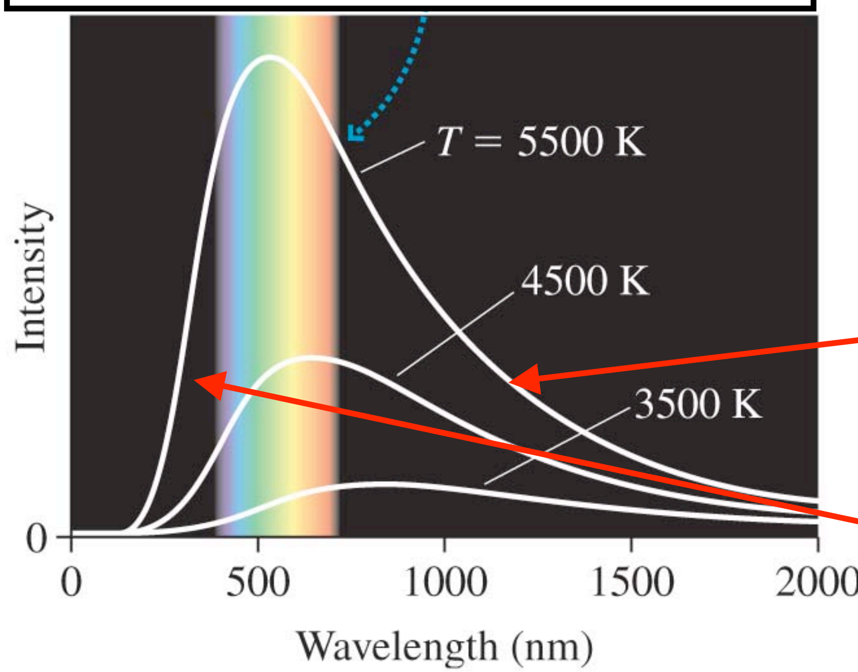
Blackbody Radiation



Objects that radiate continuous spectra have similar spectra. In fact in many cases the shape of the spectrum depends only on the temperature of the body.

Box with object at temperature T and photons





Assume the walls of the box are perfectly reflecting and the object is perfectly absorbing.

In thermodynamic equilibrium the distribution of photons can only depend on the temperature of the object.

Whatever rate photons strike the object and are absorbed, an equal number must be emitted at the same rate.

Planck introduced his constant to explain the small wavelength cut-off

Can treat photons as classical fields

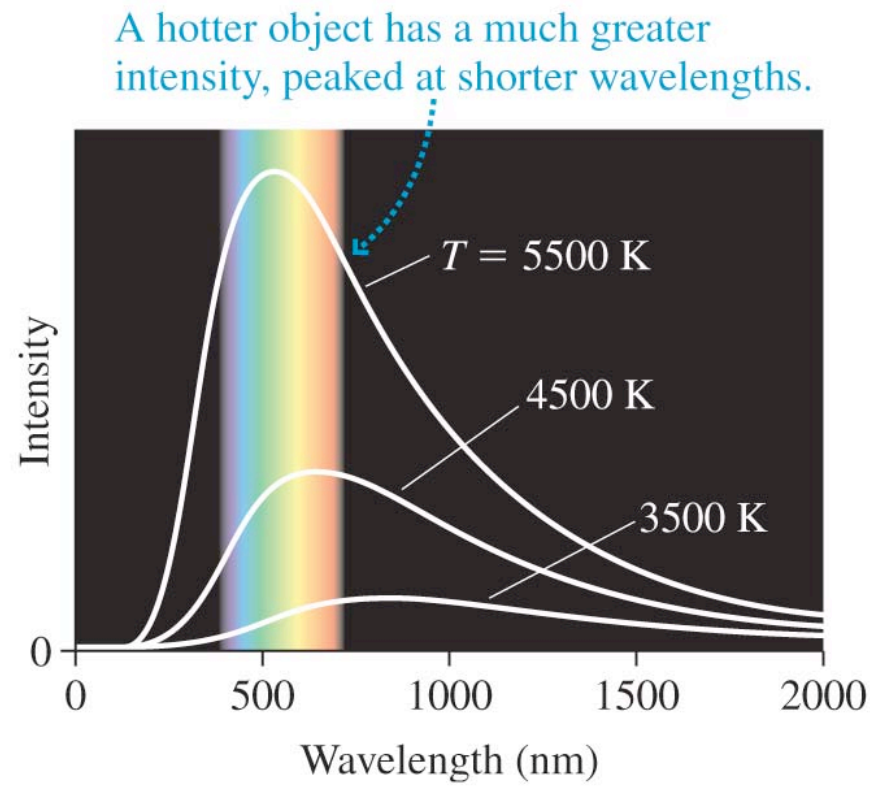
Must treat photons as photons, need h

Blackbody Radiation

The heat energy *Q* radiated in a time interval Δ*t* by an object with surface area *A* and absolute temperature *T* is given by

$$\frac{Q}{\Delta t} = e\sigma A T^4$$

where σ = 5.67 x10^{8} W/m^{2}K^4 is the Stefan-Boltzmann constant. The parameter *e* is the *emissivity* of the surface, a measure of how effectively it radiates. The value of *e* ranges from 0 to 1. A perfectly absorbing—and thus perfectly emitting—object with *e* = 1 is called a *blackbody*, and the thermal radiation emitted by a blackbody is called **blackbody radiation.**



The wavelength of the peak in the intensity graph is given by Wien's law (T must be in kelvin):

$$\lambda_{\text{peak}}(\text{in nm}) = \frac{2.90 \times 10^6\ \text{nm K}}{T}$$

Wien's Displacement Law

EXAMPLE 38.7 Finding peak wavelengths

QUESTIONS:

EXAMPLE 38.7 Finding peak wavelengths

What are the peak wavelengths and the corresponding spectral regions for thermal radiation from the sun, a glowing ball of gas with a surface temperature of 5800 K, and from the earth, whose average surface temperature is 15°C?

EXAMPLE 38.7 Finding peak wavelengths

MODEL The sun and the earth are well approximated as blackbodies.

EXAMPLE 38.7 Finding peak wavelengths

SOLVE The sun's wavelength of peak intensity is given by Wien's law:

$$\lambda_{peak} = \frac{2.90 \times 10^6 \text{ nm K}}{5800 \text{ K}} = 500 \text{ nm}$$

This is right in the middle of the visible spectrum. The earth's wavelength of peak intensity is

$$\lambda_{peak} = \frac{2.90 \times 10^6 \text{ nm K}}{288 \text{ K}} = 10{,}000 \text{ nm}$$

where we converted the surface temperature to kelvin before computing. This is rather far into the infrared portion of the spectrum, which is not surprising because we don't "see" the earth glowing.

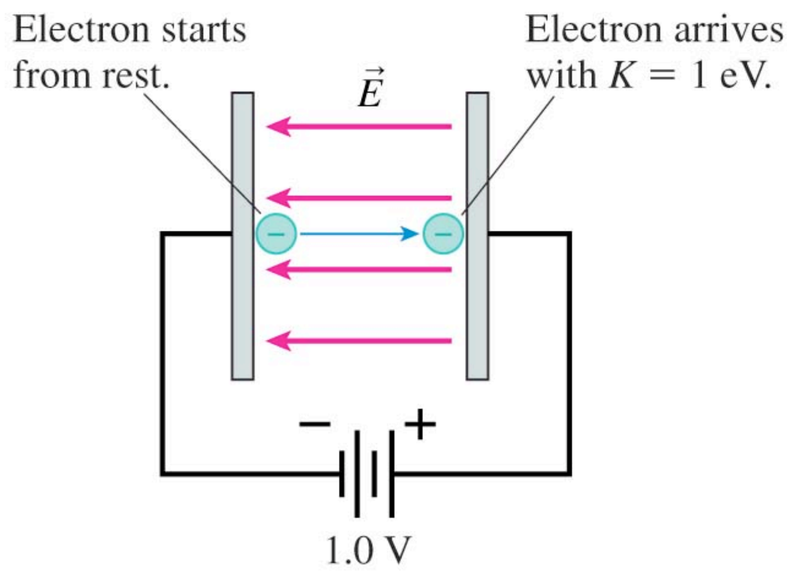
EXAMPLE 38.7 Finding peak wavelengths

ASSESS The difference between these two wavelengths is quite important for understanding the earth's greenhouse effect. Most of the energy from the sun—it's spectrum is much like the highest curve in Figure 38.20—arrives as visible light. The earth's atmosphere is transparent to visible wavelengths, so this energy reaches the ground and is absorbed. The earth must radiate an equal amount of energy back to space, but it does so with long-wavelength infrared radiation. These wavelengths are strongly absorbed by some gases in the atmosphere, so the atmosphere acts as a blanket to keep the earth's surface warmer than it would be otherwise.

The Electron Volt

- Consider an electron accelerating (in a vacuum) from rest across a parallel plate capacitor with a 1.0 V potential difference.
- The electron's kinetic energy when it reaches the positive plate is 1.60×10^{-19} J.
- Let us define a new unit of energy, called the **electron volt,** as 1 eV = 1.60×10^{-19} J.

FIGURE 38.14 An electron accelerating across a 1 V potential difference gains 1 eV of kinetic energy.



EXAMPLE 38.5 Energy of an electron

QUESTION:

EXAMPLE 38.5 Energy of an electron

In a simple model of the hydrogen atom, the electron orbits the proton at 2.19×10^6 m/s in a circle with radius 5.29×10^{-11} m. What is the atom's energy in eV?

EXAMPLE 38.5 Energy of an electron

MODEL The electron has a kinetic energy of motion, and the electron + proton system has an electric potential energy.

EXAMPLE 38.5 Energy of an electron

SOLVE The potential energy is that of two point charges, with $q_{\text{proton}} = +e$ and $q_{\text{elec}} = -e$. Thus

$$E = K + U = \frac{1}{2}m_{\text{elec}}v^2 + \frac{1}{4\pi\epsilon_0}\frac{(e)(-e)}{r} = -2.17 \times 10^{-18}\ \text{J}$$

Conversion to eV gives

$$E = -2.17 \times 10^{-18}\ \text{J} \times \frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \text{J}} = -13.6\ \text{eV}$$

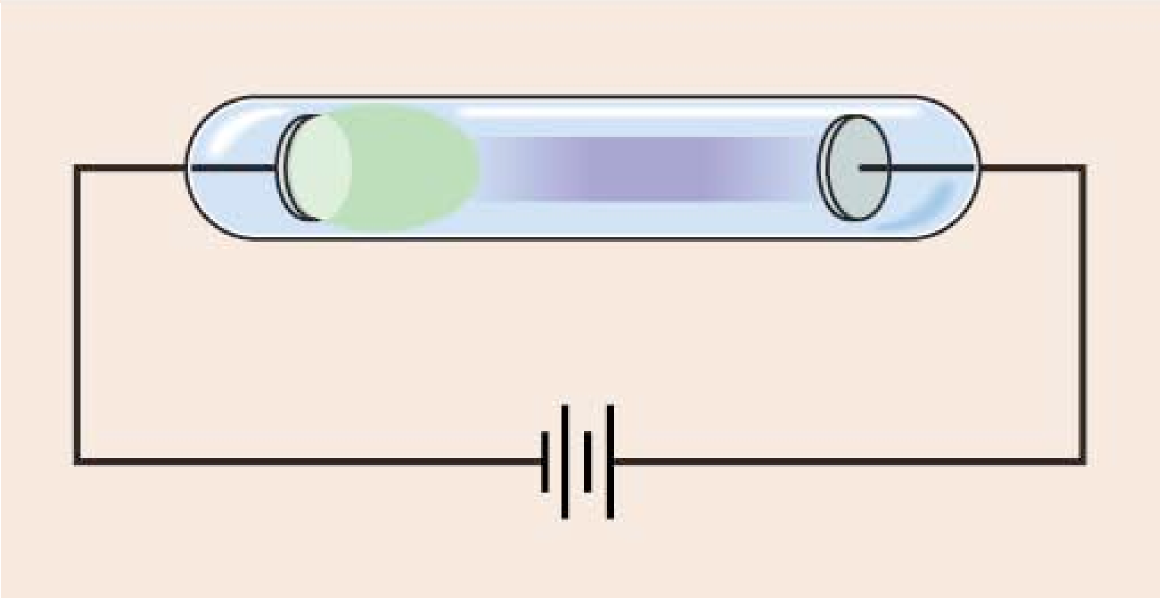
EXAMPLE 38.5 Energy of an electron

ASSESS The negative energy reflects the fact that the electron is *bound* to the proton. You would need to *add* energy to remove the electron.

Chapter 38. Summary Slides

Important Concepts/Experiments

Nineteenth-century scientists focused on understanding matter, electricity, and light. Faraday's invention of the gas discharge tube launched two important avenues of inquiry.



Important

Cathode Rays and Atomic Structure

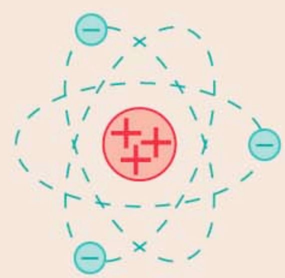
Thomson found that cathode rays are negative, subatomic particles. These were soon named electrons. Electrons are

- Constituents of atoms.
- The fundamental units of negative charge.

Rutherford discovered the atomic nucleus. His nuclear model of the atom proposes

- A very small, dense positive nucleus.
- Orbiting negative electrons.

Later, different isotopes were recognized to contain different numbers of **neutrons** in a nucleus with the same number of **protons.**



Important

Atomic Spectra and the Nature of Light

The spectra emitted by the gas in a discharge tube consist of discrete wavelengths.

- Every element has a unique spectrum.
- Every spectral line in an element's absorption spectrum is present in its emission spectrum, but not all emission lines are seen in the absorption spectrum.

Balmer found that the wavelengths of the hydrogen emission spectrum are

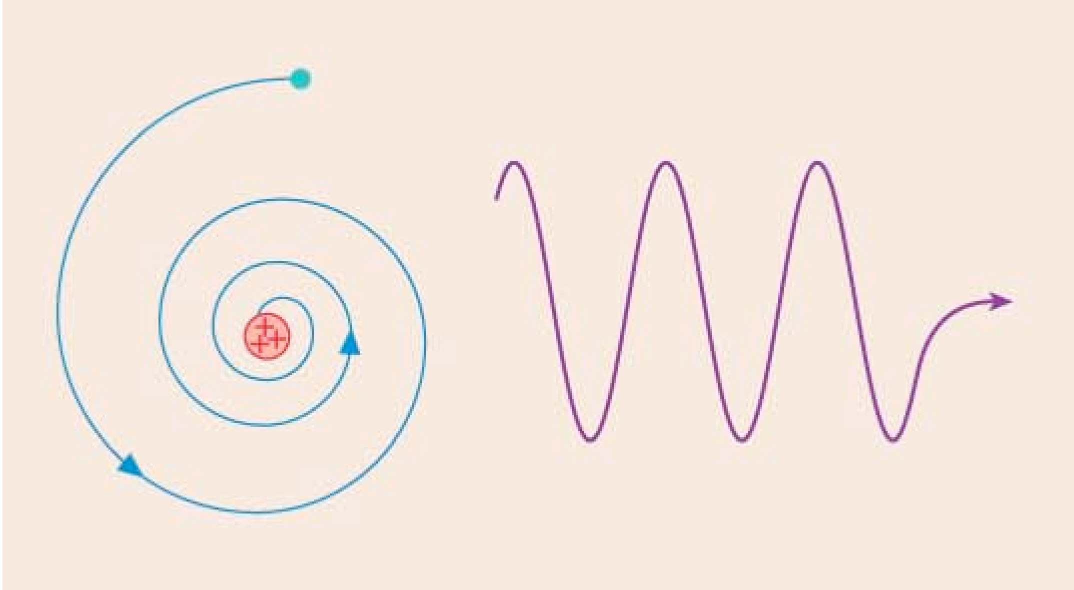
$$\lambda = \frac{91.18\text{ nm}}{\left(\frac{1}{m^2} - \frac{1}{n^2}\right)}, \qquad m = 1, 2, 3, \ldots \qquad n = m + 1, m + 2, \ldots$$

Important

The end of classical physics. . .

Atomic spectra had to be related to atomic structure, but no one could understand how. Classical physics could not explain

- The stability of matter.
- Discrete atomic spectra.
- Continuous blackbody spectra.



Applications

Millikan's oil-drop experiment measured the fundamental unit of charge:

$$e = 1.60 \times 10^{-19}\ \mathrm{C}$$

Applications

One electron volt (1 eV) is the energy an electron or proton (charge $\pm e$) gains by accelerating through a potential difference of 1 V:

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Millikan's Oil Drop experiment

Determining the electron charge e separately.

- *Spray small droplets of oil which quickly reach terminal velocity due to air resistance.*
- *Small number of droplets fall between two plates into to a region of constant electric field. Velocity of fall can be estimated by measuring the time to fall a distance d.*
- *Ionizing radiation then charges the droplet, introducing an electric force.*
- *Charge is quantized. By measuring the velocity of a number of particles with the field on and off and assuming that the electric charges must be multiples of each other, e can be determined.*