# The End of Classical Physics, Part II

**Concepts:** Discovery of the Electron
Quantization of Charge
Structure of the Atom
Atomic spectra

**Chapter 37.1-37.9 (mostly reading for background and review)**

# More Failures of Classical Physics

- We have seen that classical (Newtonian) physics could not account for the spectrum of a blackbody
  - Planck had to suppose that matter could only store energy in units of $h\upsilon$ and that only certain $\upsilon$ values were allowed, i.e. that energy was ***quantized***

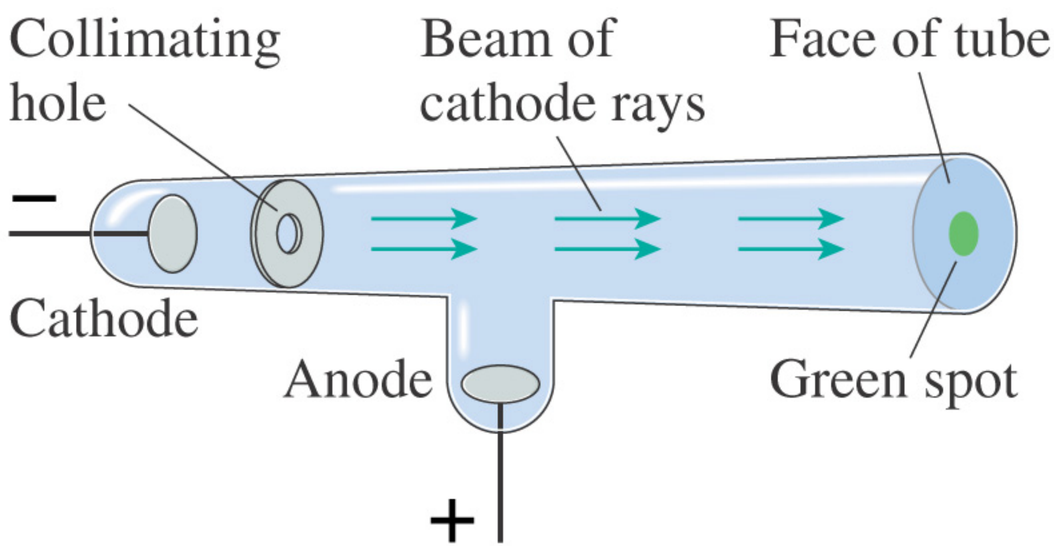
- The structure of the atom presented another major problem for classical physics which would also be solved by ***quantization***

# The Atom

- The idea that matter is subdivided into indivisible units has been around since the ancient Greeks and perhaps longer
- The atomic hypothesis is just another way of saying that matter is ***quantized***
- How could we prove this?
  - one way: demonstrate that <u>electric charge</u> comes in discrete, indivisible units

# Crookes Tube

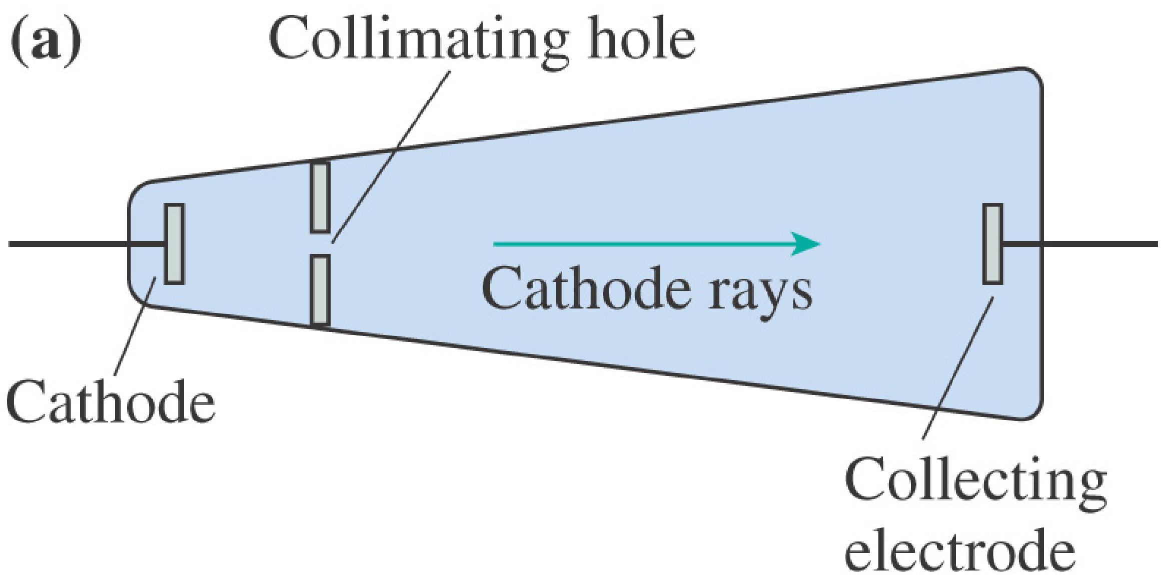
- Recall the Crookes tube demo:
  - put positive and negative electrodes in an evacuated tube
  - when you turn on the current, the negative electrode seems to produce rays which make a dot on a screen



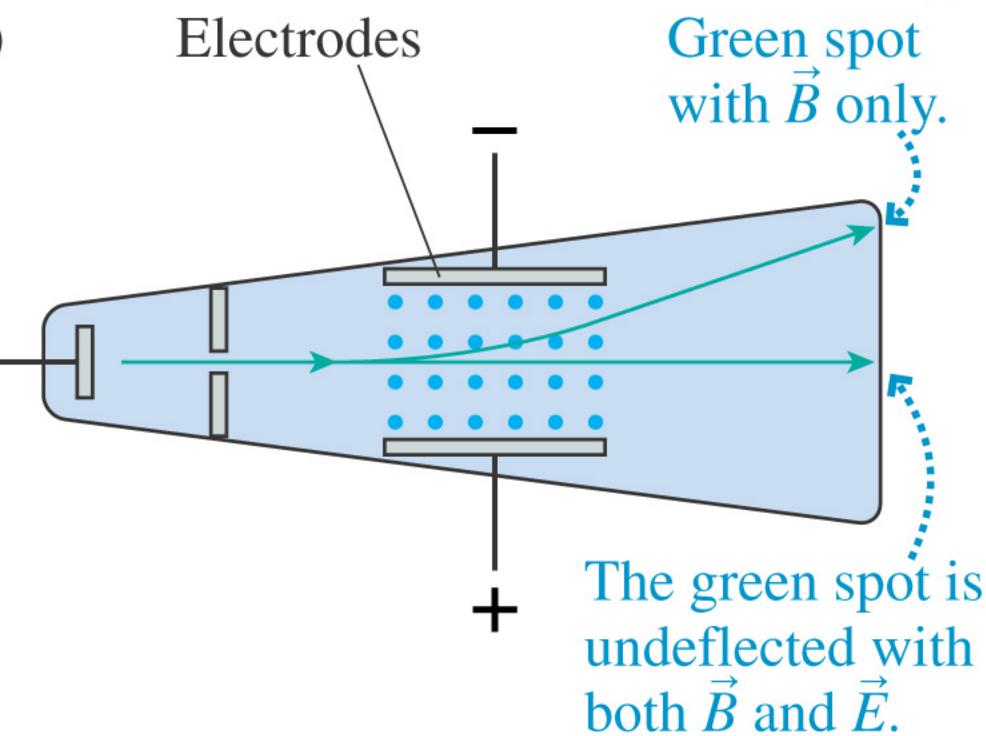
- Crookes found that :
  - there’s a current flowing through the tube while cathode rays are being emitted
  - the rays are deflected by a magnetic field as if they have negative charge
  - it doesn’t matter what the cathode is made of, as long as it’s a metal
  - the cathode rays can transfer energy
- For a long time, no one could figure out what the cathode rays ***<u>were</u>***
  - electromagnetic waves?
  - particles?

# Discovery of the Electron

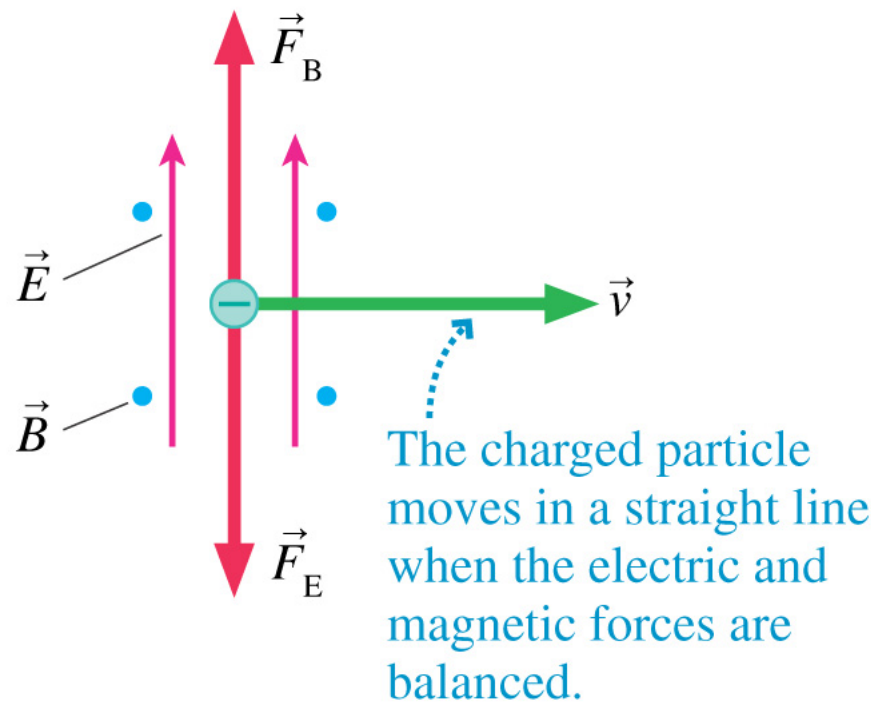
- J. J. Thomson demonstrated the existence of the electron in 1897 using a type of Crookes tube
- Consider a tube with no applied external fields:



- Now apply crossed E and B fields, as in our velocity selector (see mass spectrometer):





- As we have shown, if the electric and magnetic fields are balanced, then:

$$\Sigma\vec{F}_y = qE - qvB = 0$$

$$\boxed{v = E / B}$$

- So Thomson could determine the speed of cathode rays by figuring out which values of B and E caused them to pass through the tube undeflected
- Knowing v, he could then observe cathode rays moving through a pure magnetic field, measure their cyclotron radius, and determine q/m

$$r_{cyc} = \frac{m\,v}{q\,B}$$

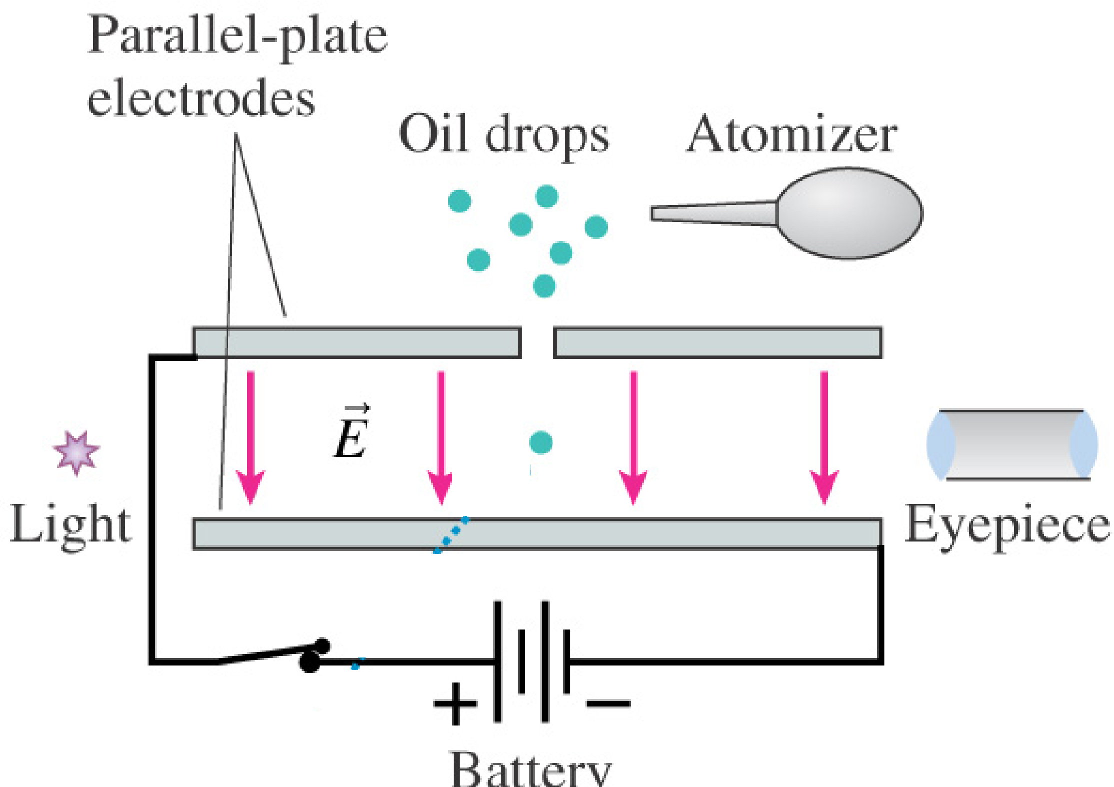
$$\boxed{\frac{q}{m} = \frac{v}{r_{cyc} B}}$$

- By showing that q/m was the same for **all cathode rays** coming from **all materials**, Thomson proved that all cathode rays were composed of the same types of particles
- These particles were later named ***electrons***

# Charge Quantization

- Thomson showed that cathode rays had a fixed q/m and that they were present in all materials
- Shining cathode rays on thin foils showed that they would pass through, whereas beams of ions would not
- This suggested that electrons must be much smaller than ions, and therefore hinted that atoms might not be the smallest constituents of matter

- To be sure that electrons were tiny, had to measure either m or q separately
- The first to do this precisely was Millikan, in 1906, using his ***oil drop experiment***

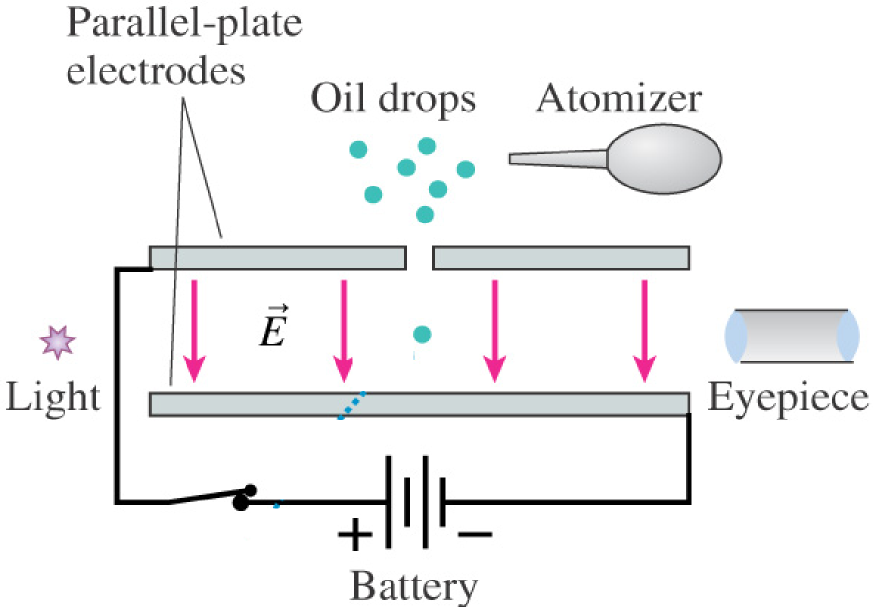


- Oil drops acquire charge through friction with the atomizer as they are sprayed.
- Tune the electric field until some of the drops hover in mid-air between the plates of the capacitor.
- Balance forces on the drops:

$$\Sigma F = m_{drop} g - q_{drop} E = 0$$

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

$$q_{drop} = \frac{m_{drop} g}{E}$$



- Millikan was able to measure the masses of the drops and he could set the electric field, so he could measure $q_{drop}$
- By running the experiment many times with many drops, he found that the charge on the drops was always an integer multiple of what we now call the charge on the electron:

$$e = 1.602 \times 10^{-19}\,C$$

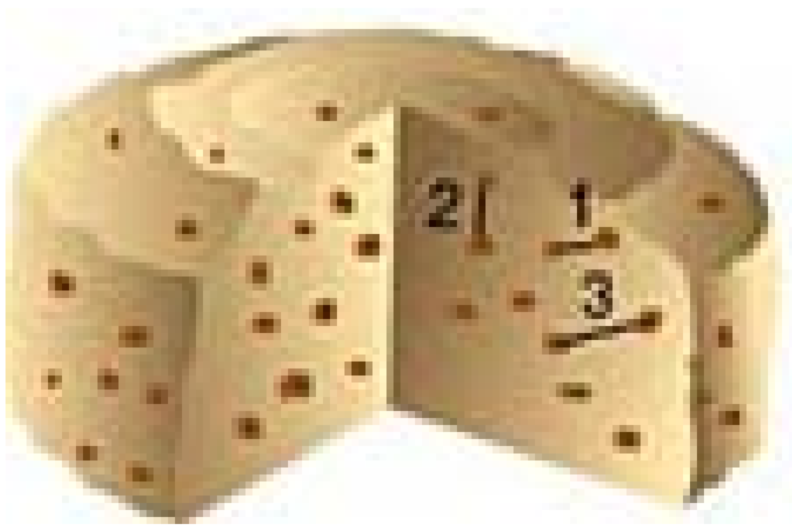
- Knowing the charge of the electron, Millikan could use Thomson's q/m ratio to determine the mass of the electron:

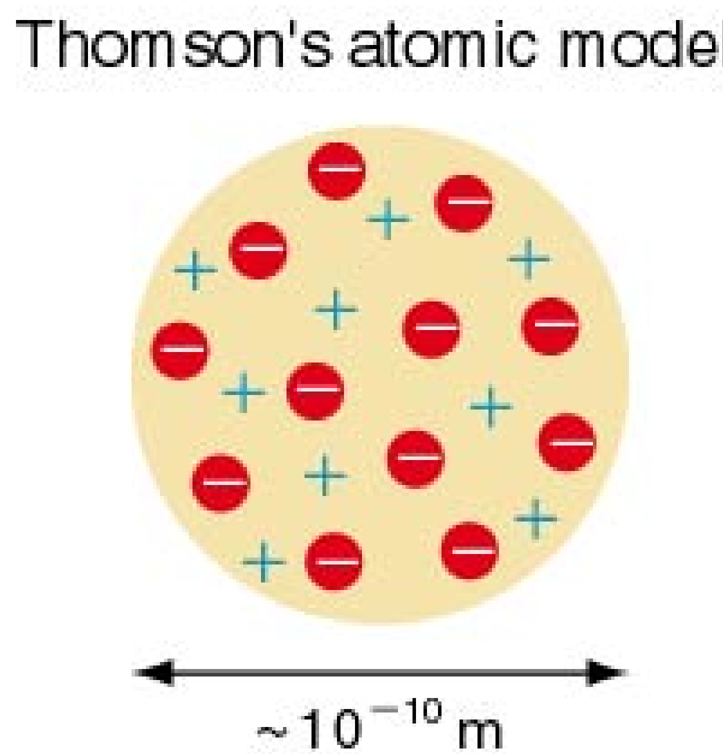
$$m_e = 9.11 \times 10^{-31} kg$$

- This measurement proved that:
  - ***charge was quantized***
  - ***negative charge was carried by electrons***
  - ***electrons had masses and sizes much smaller than those of atoms***

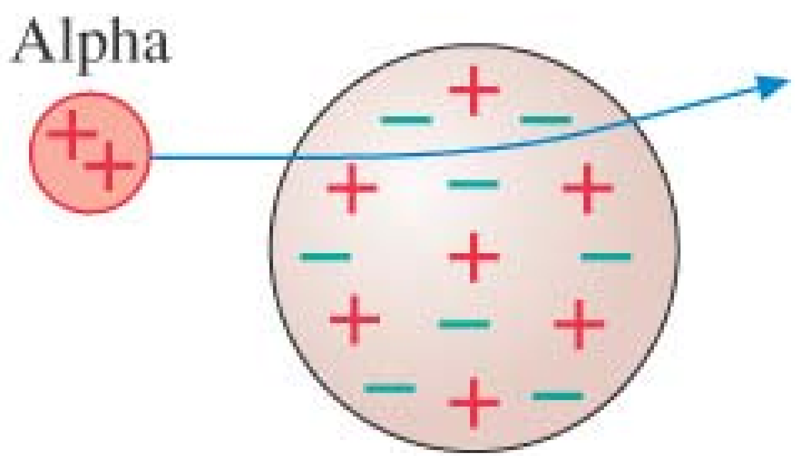
# Raisin-Cake Model

- Thomson's attempt at an atomic model pictured electrons distributed throughout some positively-charged medium, like raisins in a cake

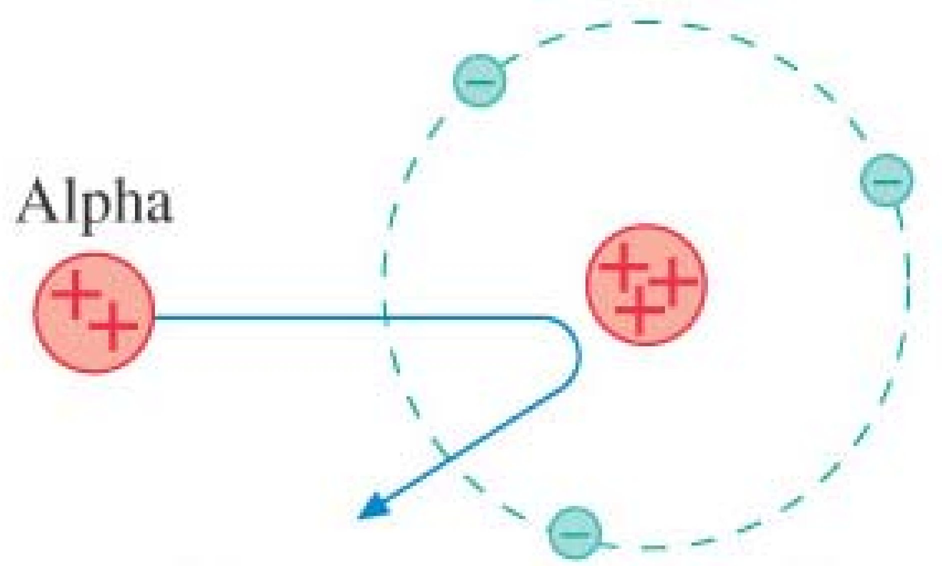


- Rutherford demonstrated that the positive charge ***also*** had to be concentrated in a very small volume
  - if matter consists of Thomson atoms, a positive particle moving through it would never encounter a concentration of positive charge, so it should not be deflected much



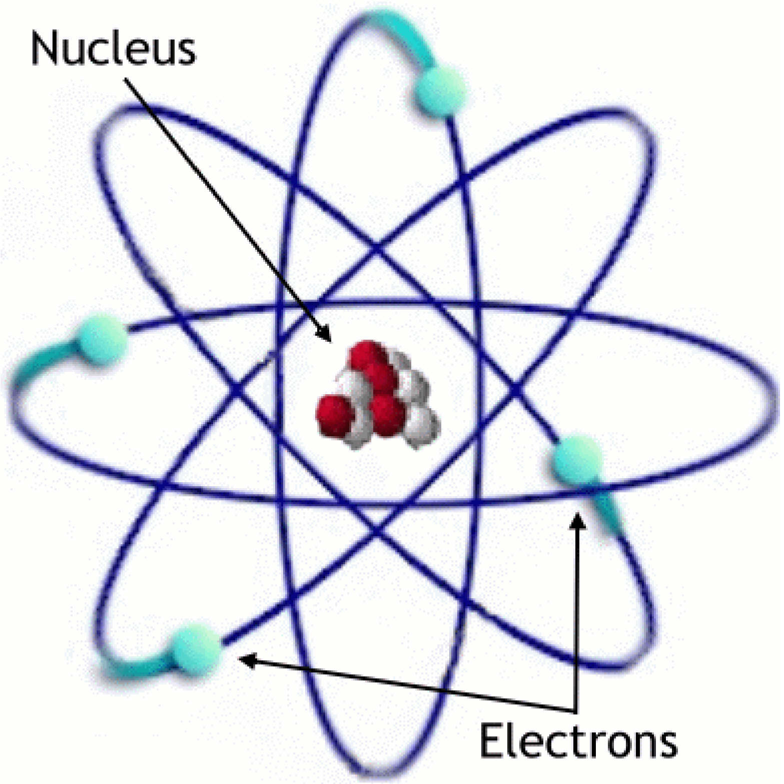
– If the atom’s positive charge were concentrated in a small volume, other positive charges passing by it would be strongly deflected



- In 1909: By projecting positively-charged He nuclei (then called alpha particles) on a thin metal foil, Rutherford found that indeed some alpha particles were deflected by large angles and a very small fraction rebounded as if they had collided with something
- Thus, Rutherford came up with the ***nuclear*** model of the atom, in which the positive charge is confined to a small nucleus

# Rutherford Atom

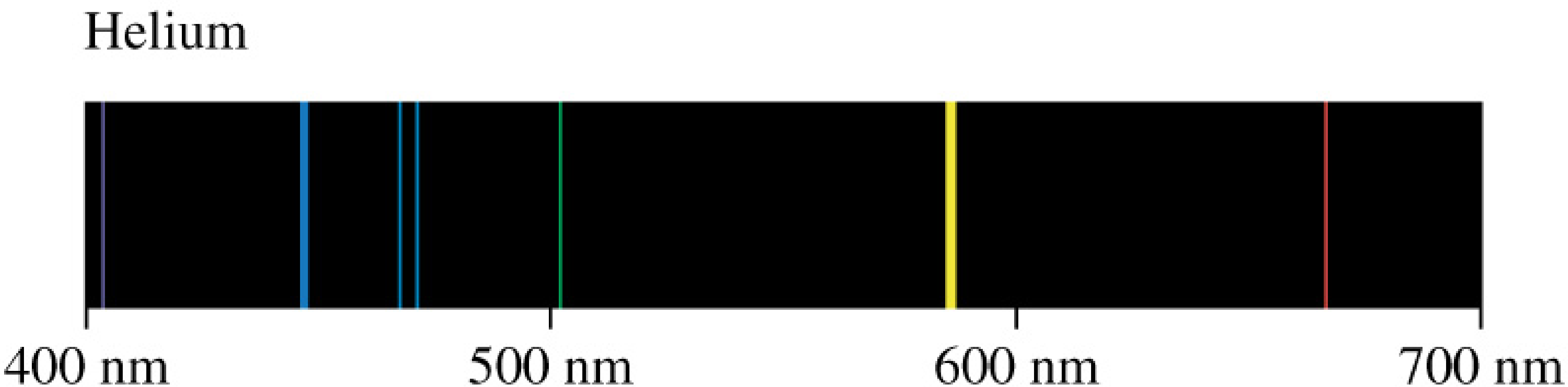
- Rutherford imagined electrons orbiting a positively charged nucleus like planets orbiting the Sun:



There are two serious problems with this model:

- Accelerating charges emit radiation (i.e. light)
- Classical physics predicts electrons in the Rutherford atom will lose orbital energy as they emit radiation
- Causes electrons to ultimately collide with the atomic nuclei they orbited within about $10^{-6}$ s
- The colour of the radiation emitted changes as the electron spirals into the atom

- Individual atoms don't emit a continuous rainbow spectrum—they emit only at discrete frequencies

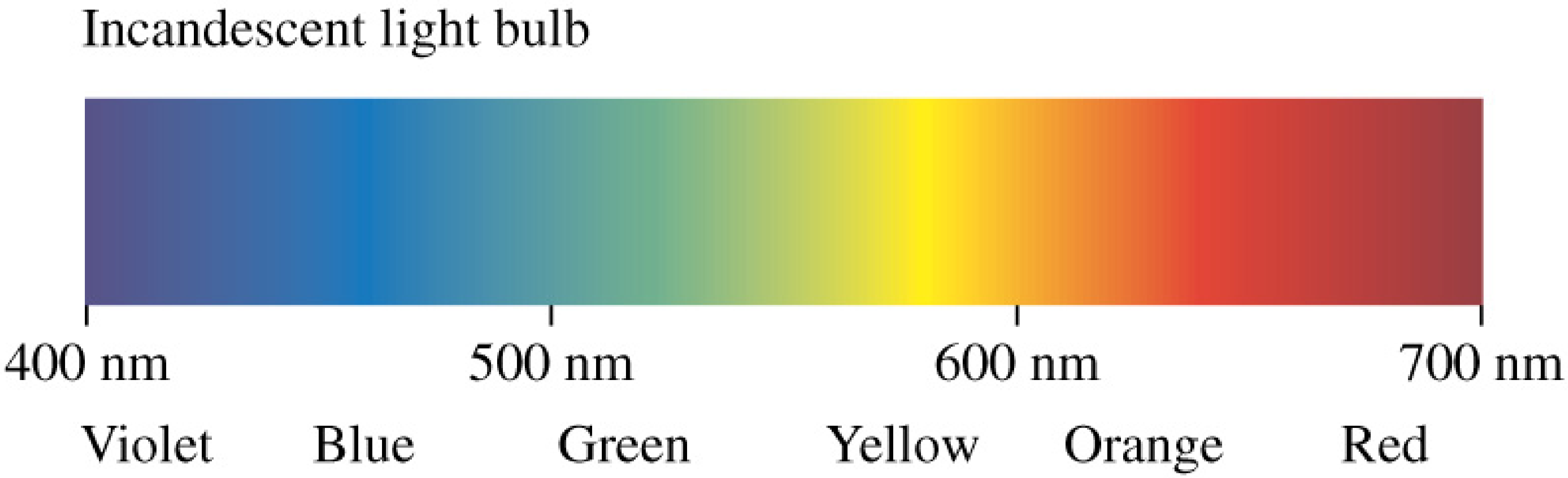



- Also, atoms last a lot longer than $10^{-6}$ s

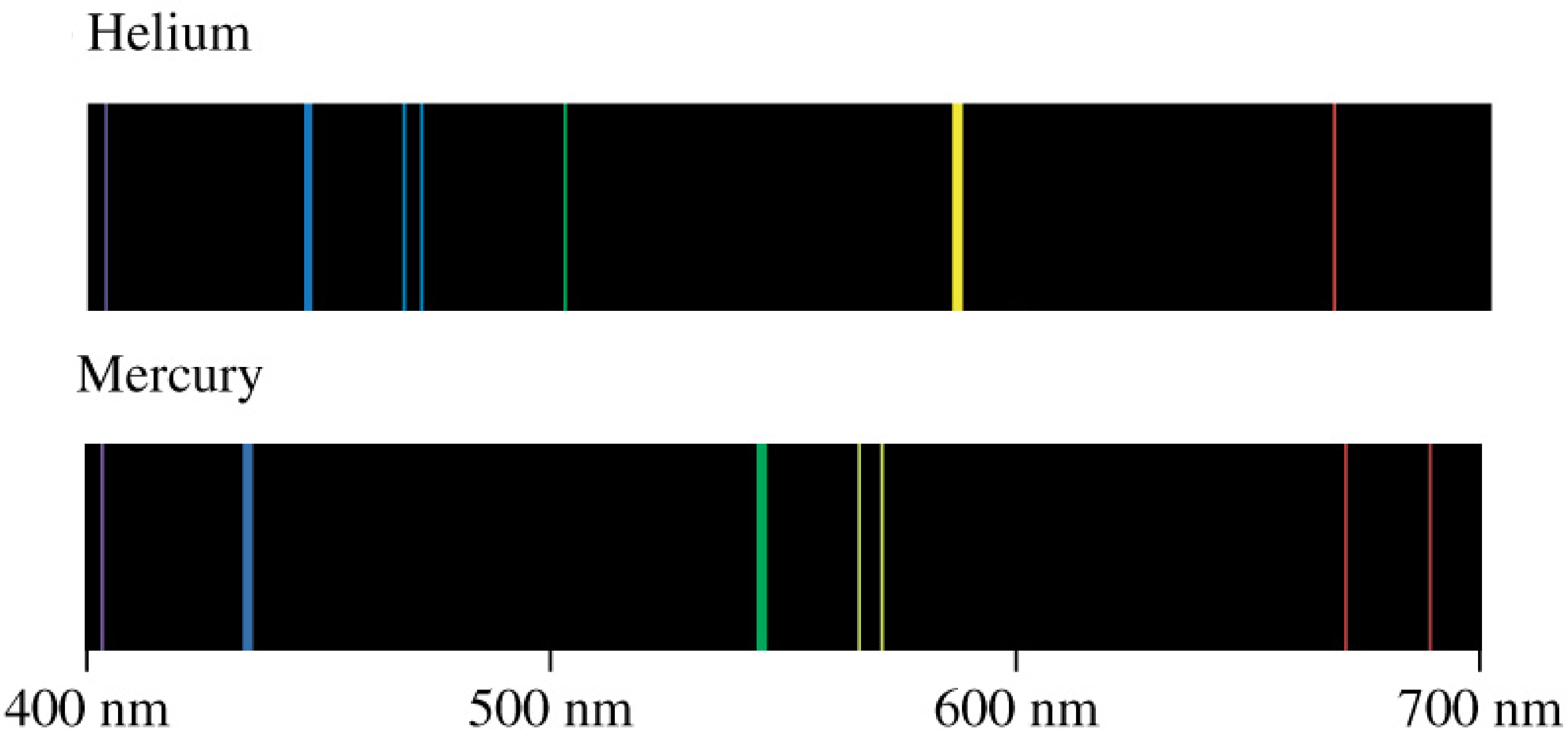
# Emission and Absorption of Light

- This should be largely review from earlier chemistry and physics classes
- Atoms cannot emit and absorb light of arbitrary wavelength (or frequency)
- Individual atoms can only absorb or emit light at ***discrete*** wavelengths:

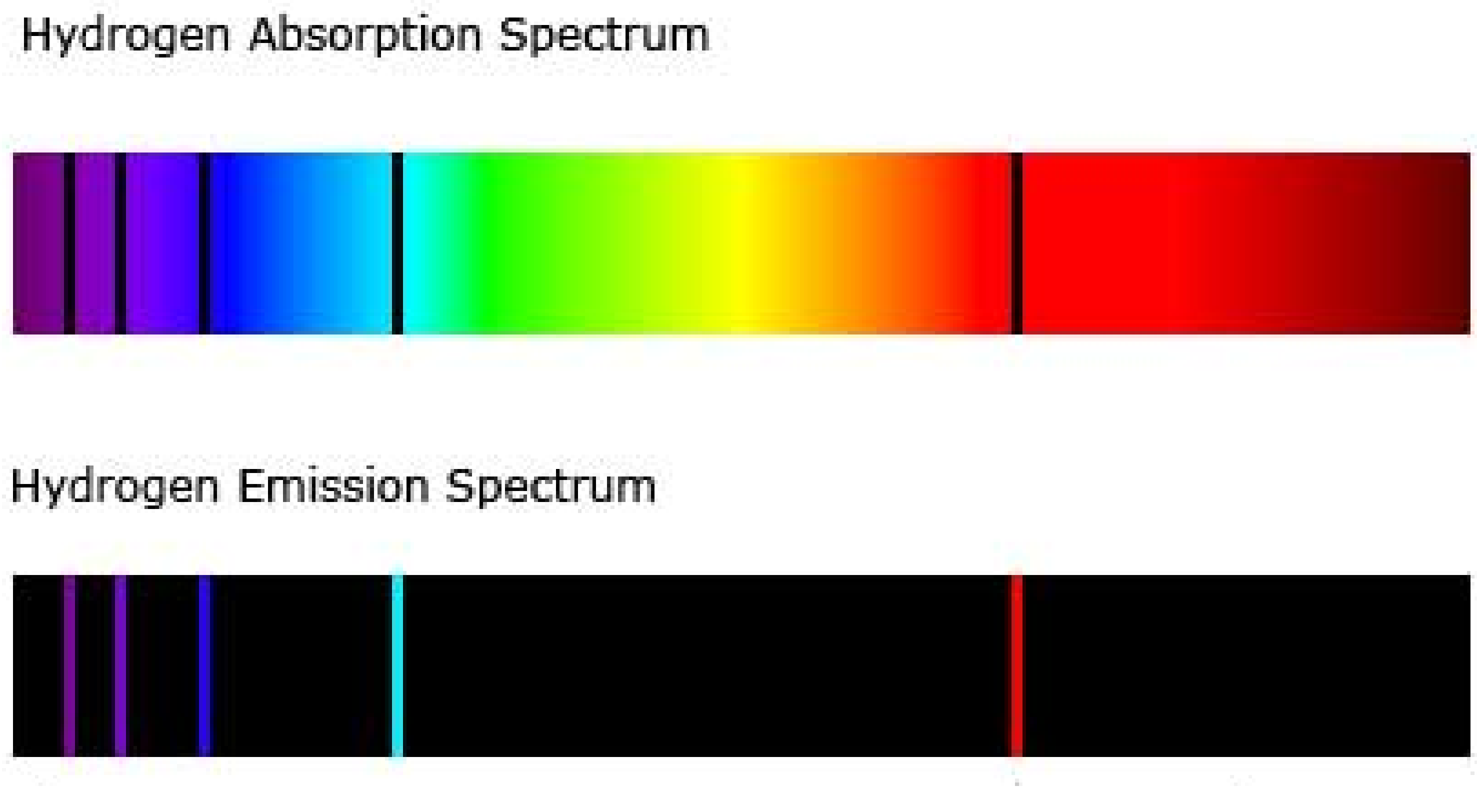
- A blackbody, such as the Sun or an incandescent light bulb, emits a ***continuous spectrum*** (some light at every wavelength)



- But a diffuse gas of a particular element emits a ***discrete spectrum*** (light at only a few wavelengths)

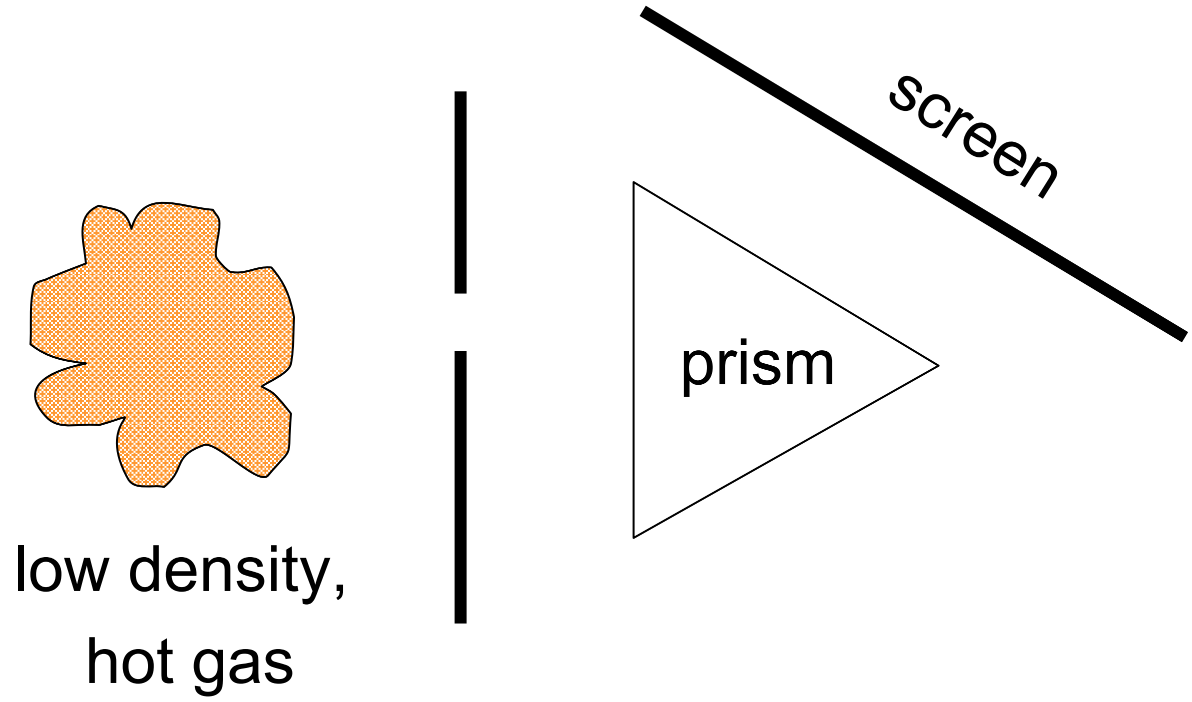


- A discrete spectrum can be either an ***absorption spectrum*** or an ***emission spectrum***



# Quick Quiz 76

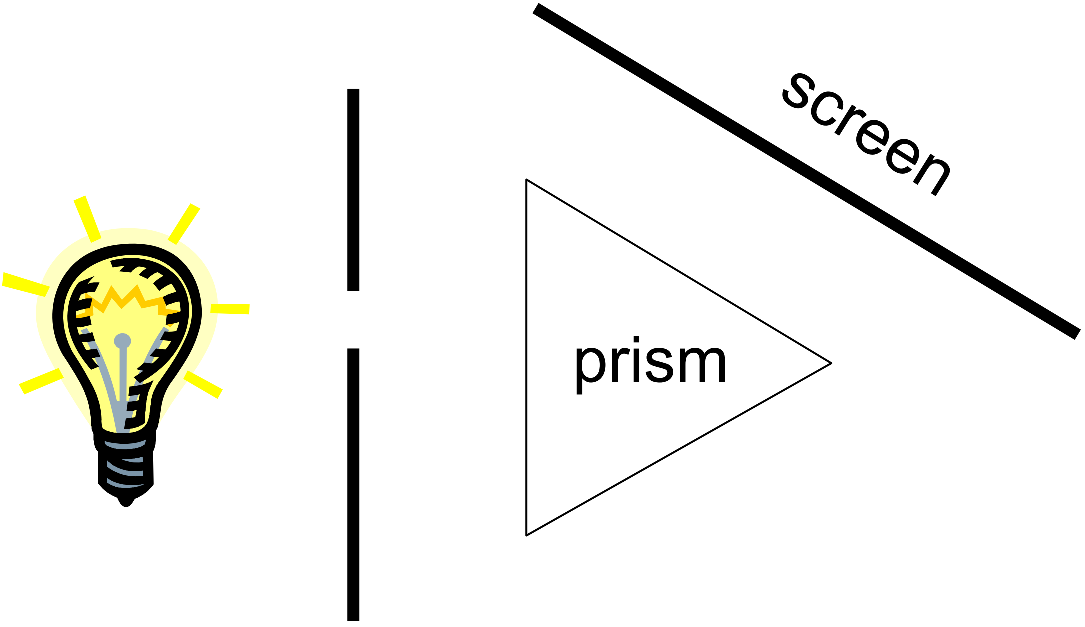
- What type of spectrum will be observed at the screen in the following experimental setup?




**A. emission** **B. absorption** **C. continuous**

# Quick Quiz 77

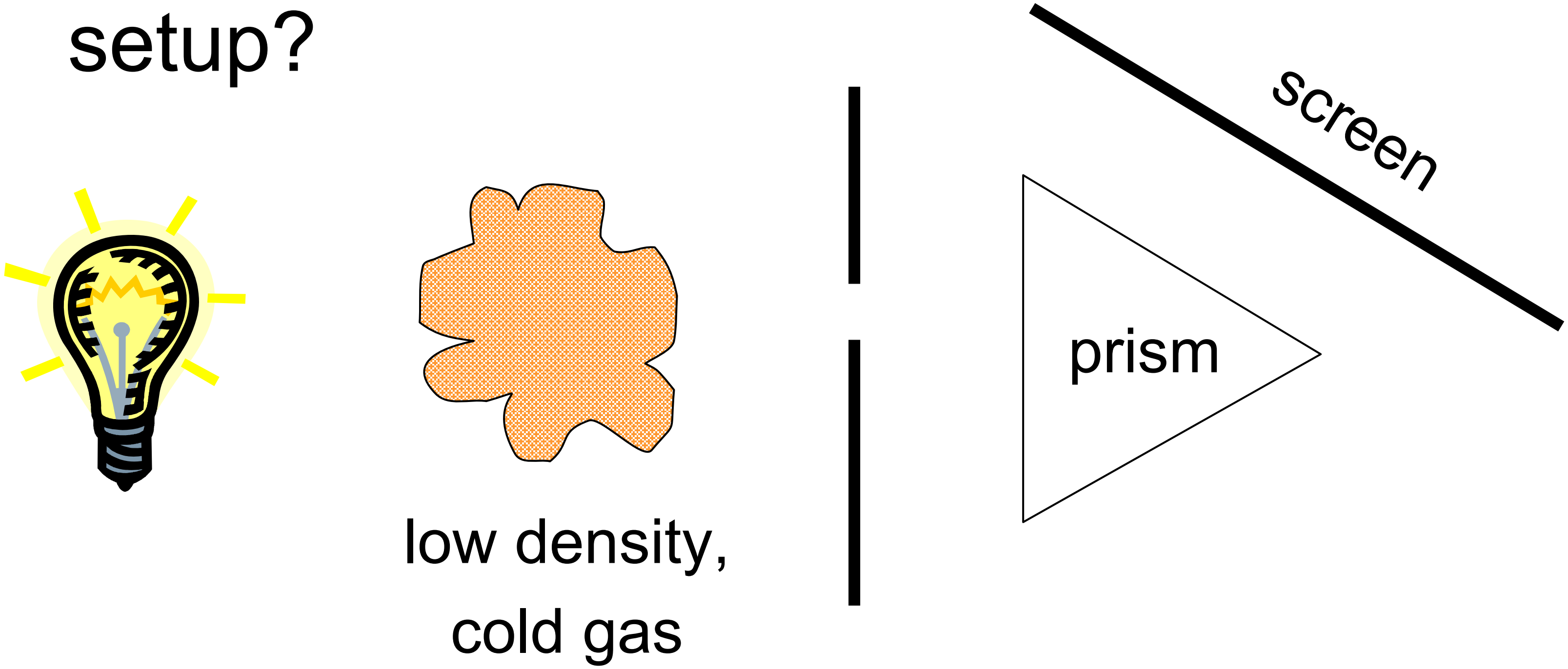
- What type of spectrum will be observed at the screen in the following experimental setup?




**A. emission** **B. absorption** **C. continuous**

# Quick Quiz 78

- What type of spectrum will be observed at the screen in the following experimental setup?




**A. emission** **B. absorption** **C. continuous**

- Emission and absorption lines appear at wavelengths which are characteristic of the particular element doing the emission
- For example, the ***Balmer series*** of hydrogen:

$$\lambda = \frac{91.18\,nm}{\left(\frac{1}{2^2} - \frac{1}{n^2}\right)} \qquad n = 3, 4, 5, \ldots$$

# Quick Quiz 79

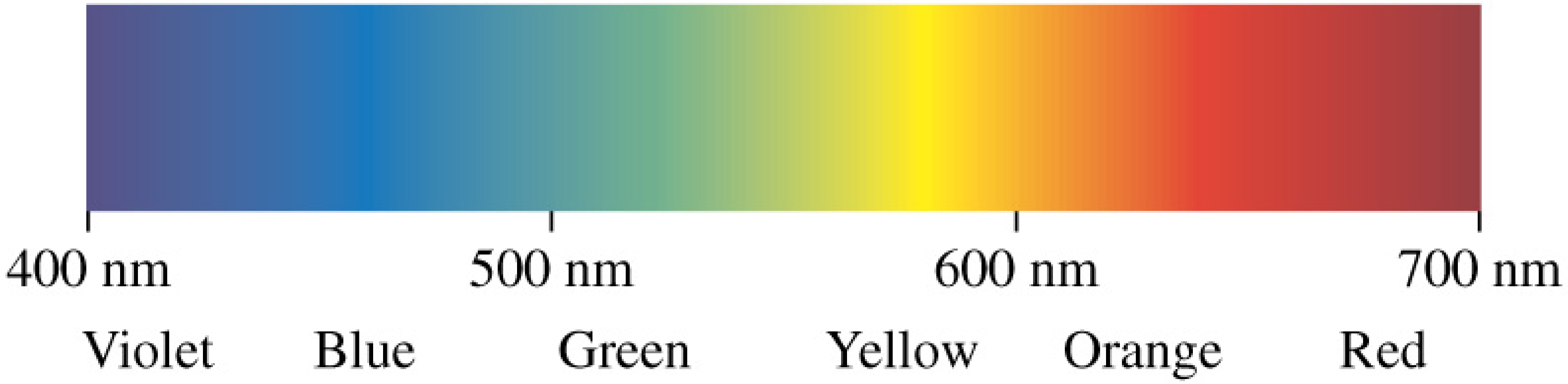
What colour is the n=3 Balmer line?

**A. infrared**

**B. red**

**C. blue**

**D. ultraviolet**



- Classical physics has ***NO WAY*** to account for the spectra of atoms
- What classical physics can understand about atoms:
  - ***mass comes in tiny pieces no smaller than the mass of an electron***
  - ***each electron carries exactly the same charge and mass***
- What classical physics cannot understand about atoms
  - ***why electrons don’t spiral into the nucleus***
  - ***why atoms can only absorb and emit light at certain wavelengths***

# A Subtler View of Light

- Things we know about light:
  - it diffracts when sent through a single narrow slit
  - it interferes when sent through two narrow slits
- These properties of light are clearly properties of waves

- Imagine we repeat Young’s double-slit experiment with light, but this time we reduce the light intensity as low as possible and use a sensitive video camera to record the resulting interference pattern

# Quick Quiz 80

- If light is a wave, what should happen to the pattern as we reduce the intensity of light?
  A. the interference pattern will become a diffraction pattern
  B. the spacing of the bright bands should change
  C. the whole pattern should get progressively fainter
  D. the light bands should switch with the dark bands

# Light Particles?

- Contrary to our expectations, the same interference pattern emerges, but one spot at a time!
- Waves are not localized at specific points in space, so how can they do this?
- This suggests particle-like behaviour…
- Note that the dots group into ***exactly*** the same pattern we see at higher light intensity

# Quantization

- This is our first hint of the ***quantum*** world
- A quantity is said to be ***quantized*** if it can only exist in discrete quantities
  - quantized things: people, computers, marbles
  - continuous (non-quantized) things: water, air, wood
- We can have a fixed number of computers but not an arbitrary amount of "computer"
- We can have an arbitrary amount of water, but not a fixed number of "waters"

# Photons

- We call the ***quantum*** of light a ***photon***
- As we shall see, the photon model of light ascribes various properties to photons:
  - they travel at the speed of light, $c=3x10^8$ m/s in a vacuum
  - they have no mass
  - their energies depend on their frequencies

- Photons are clearly ***not*** like classical particles
  - if they were, they would travel straight through the two slits and give two bright bands, not an interference pattern
- Even if we reduce the intensity of the light to a point so low that only a single photon is passing through the apparatus at a time, we still get the interference pattern!
- Therefore, a photon must be able to interfere ***with itself***

- But light can only interfere if there is light passing through both slits
- **Therefore the photon must pass through both slits at the same time!**

# Matter Waves

- What would happen if we did the same double slit experiment using electrons?
  - fire electrons through two tiny slits toward a detector and record the pattern that results

- This means that electrons, which we are used to thinking of as particles, have wave properties:
  - electrons diffract
  - electrons interfere with one another and with themselves
- The idea of ***matter waves*** was first proposed by Louis-Victor de Broglie
- de Broglie decided to assign a wavelength to particles even though, at the time, there was no evidence to suggest matter behaved like a wave

- de Brogile postulated that a particle's wavelength would be:

$$\lambda = \frac{h}{p}$$

***de Broglie wavelength***

where h = Planck's constant

p=mv is the particle's momentum

# Quick Quiz 81a

What is the wavelength of an electron travelling at one tenth the speed of light? (take $c = 3 \times 10^{8}$ m/s, $h = 7 \times 10^{-34}$ Js and $m_e = 10^{-30}$ kg).

A. $10^{-11}$ m
B. $10^{-9}$ m
C. $10^{-7}$ m
D. $10^{-5}$ m
E. $10^{-3}$ m

# Quick Quiz 81

A proton, electron, and an oxygen atom each pass separately but at the same speed through a 1 μm wide slit. Which one will produce the widest diffraction maximum? (i.e. the central band of the diffraction pattern)

A. electron
B. proton
C. oxygen
D. all 3 will produce the same pattern
E. none of them will produce a diffraction pattern

# Proton microscopy?

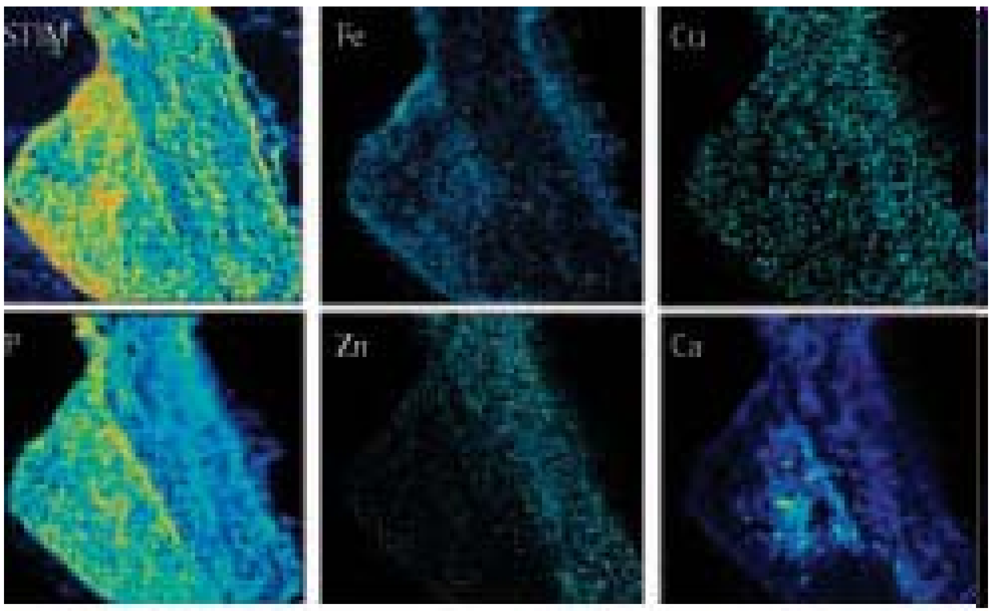



*Figure 3: Structural and elemental maps of a proton scan across a cross-section of artery-wall tissue from a New Zealand White Rabbit fed a high-cholesterol diet for eight weeks. The induced atherosclerotic lesion shows clearly in the STIM image as a bulge on the left-hand side of the artery wall.*

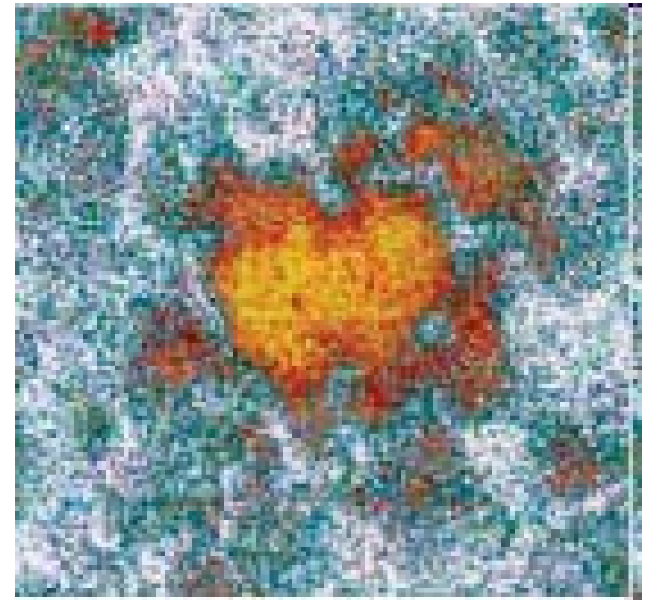
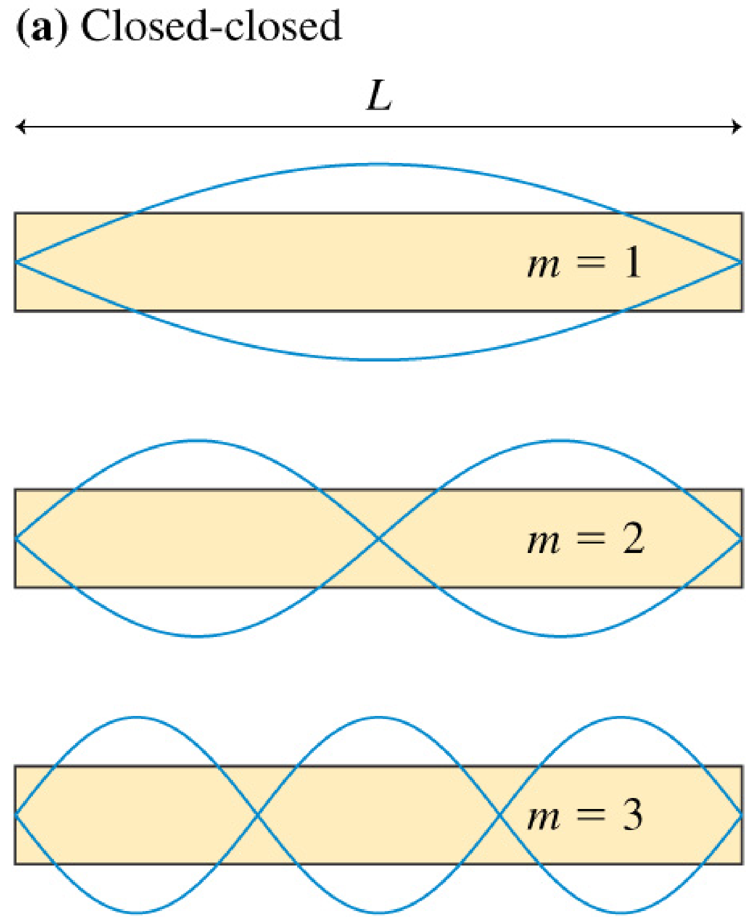


*Figure 1: Scanning-transmission ion micrograph (STIM) of an Alzheimer's disease (AD) plaque in an unstained 10µm section of AD tissue. The use of 2MeV protons captures the image of the amyloid, denser than the surrounding tissue. Simultaneous analysis using PIXE and RBS showed an absence of aluminium, challenging the then-prevailing theory that aluminium toxicity might cause the disease.*

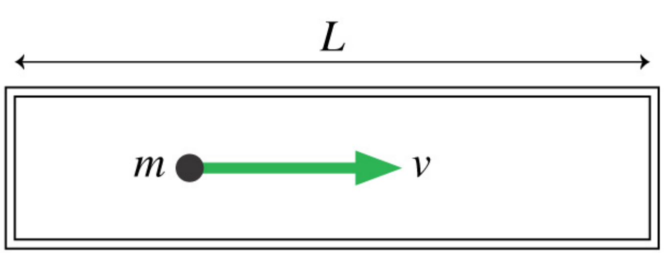
# Quantization of Energy

- Something very interesting emerges when we consider the energy of a particle in a box
- Recall that waves in boxes can only exist as ***standing waves*** with nodes at the ends of the box:



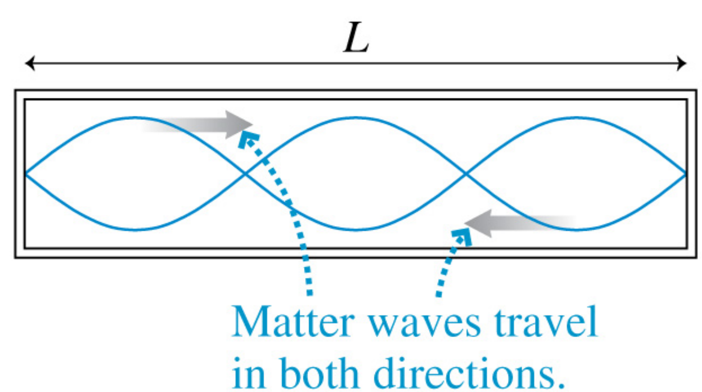
- This is a property of all waves, so if matter particles are also waves, they must only be able to exist as standing waves when confined
- This is very different from our expectation from classical physics

**(a)** A classical particle of mass $m$ bounces back and forth between the ends.

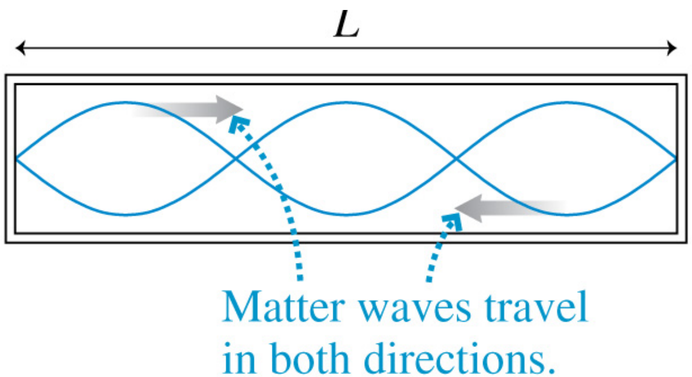





**(b)** Matter waves moving in opposite directions create standing waves.



- Recall: number of half-wavelengths in the box must be equal to the length of the box:




$$\lambda_n = \frac{2L}{n}, n = 1,2,3,4...$$

- Apply de Broglie wavelength definition:

$$\lambda_n = \frac{h}{p_n} = \frac{2L}{n}$$

$$p_n = n\frac{h}{2L} \quad , n = 1,2,3,4...$$

- Kinetic energy of a matter particle:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(p/m\right)^2 = \frac{p^2}{2m}$$

- Substitute in the momentum of the wave:

$$E_n = \frac{{p_n}^2}{2m} = \frac{1}{2m}\left(\frac{hn}{2L}\right)^2 = \frac{h^2}{8mL^2}n^2 \quad , \mathrm{n} = 1,2,3,4....$$

- This tells us that a particle confined to a box ***can only have certain energies!***

- In this sense, the energy of a particle is ***quantized***
- A confined particle can't simply have arbitrary energy
- It ***must*** have one of these energies:

$$\frac{h^2}{8mL^2}, \frac{4h^2}{8mL^2}, \frac{9h^2}{8mL^2}, \ldots\ldots$$

- This very neatly explains why each element can only emit and absorb light at discrete (i.e. quantized) wavelengths