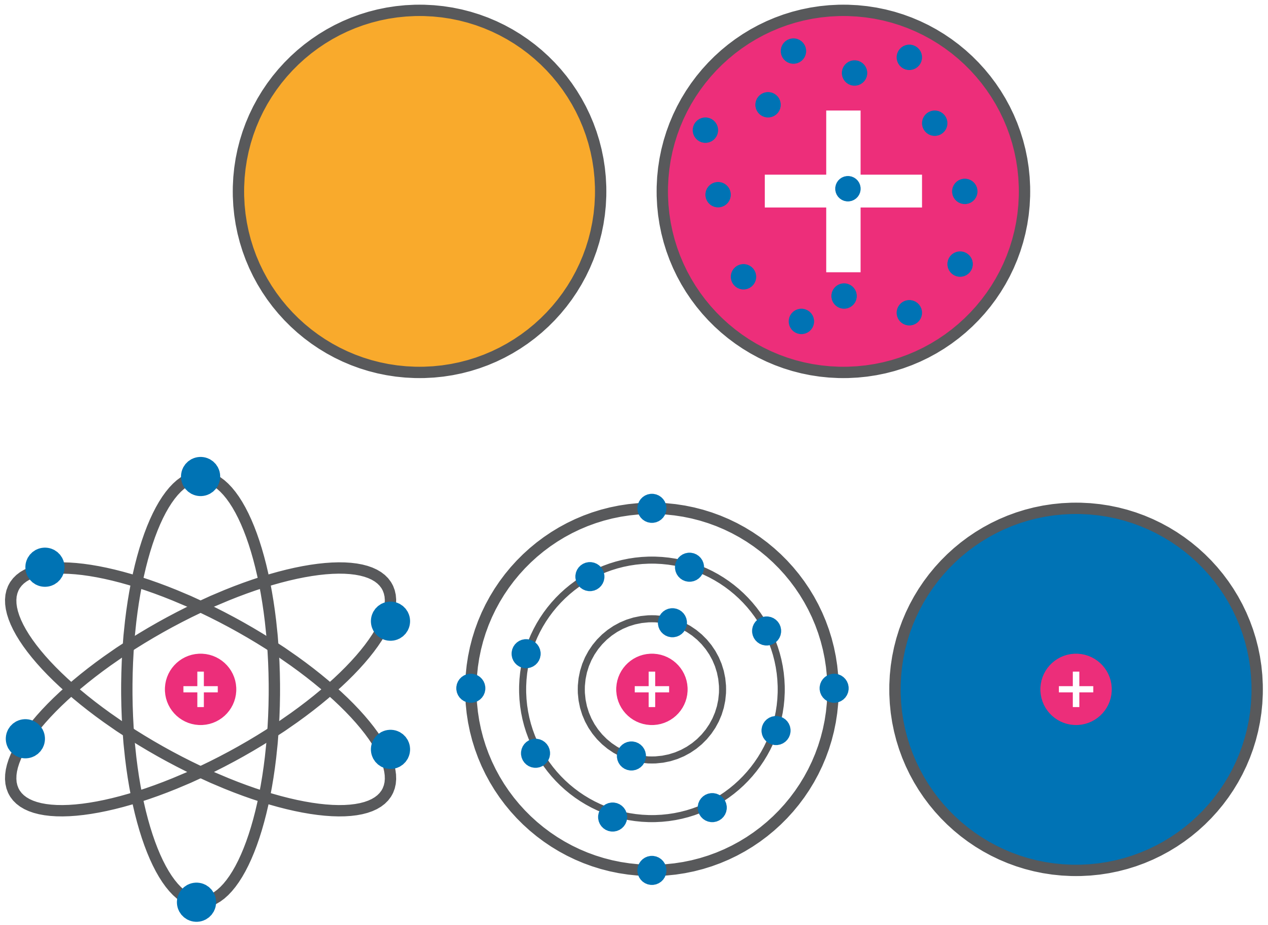
The Atomic Model



Lesson Objectives

You will be able to

- describe different models of the atom in order to explain how the atomic model has changed over time,
- recall the details of Dalton's hard sphere model, J. J. Thompson's plum pudding model, Rutherford's planetary model, and Bohr's electron shell model in order to highlight pivotal changes in our understanding,
- explain the details of the gold leaf experiment, Millikan's charge experiments, and the work of James Chadwick to show how our understanding of the structure of the atom developed to include subatomic particles,
- outline key aspects of the modern quantum mechanical model of the atom to begin to appreciate our latest understanding of atomic structure.

Historical Models of the Atoms

Democritus proposed that the universe is composed of indivisible particles more than 2400 years ago.

Aristotle was one of the most highly revered and respected opponents of the atomic model.

He alternatively proposed that matter is made up of what are now known as the classical elements (water, air, earth, and fire).

Materials were supposed to be distinguished from each other by the content of their four elements.

The four elements could be varied to transform one material into another.

It was relatively simple to propose an atomic model, but it was significantly more challenging to provide irrefutable evidence that the universe is composed of fundamental units of matter.

This all changed during the industrial revolution when bespoke and mass-manufactured scientific equipment could be obtained by different scientists all over the developed world.

Historical Models of the Atoms (Continued)

Boyle stated that there is such a thing as a pure element.

He presumed that matter is made up of elements much in the same way that the atomists proposed that all seemingly complex matter is made up of nothing more than simple atoms.

He stated that an element is a simple substance that cannot be changed to a simpler form through chemical reactions or methods.

Definition: Atoms

Atoms are the basic units of matter, and they can be used to understand the physical and chemical properties of the periodic table elements.

Dalton's Theory

John Dalton used some relatively simple scientific equipment to study matter.

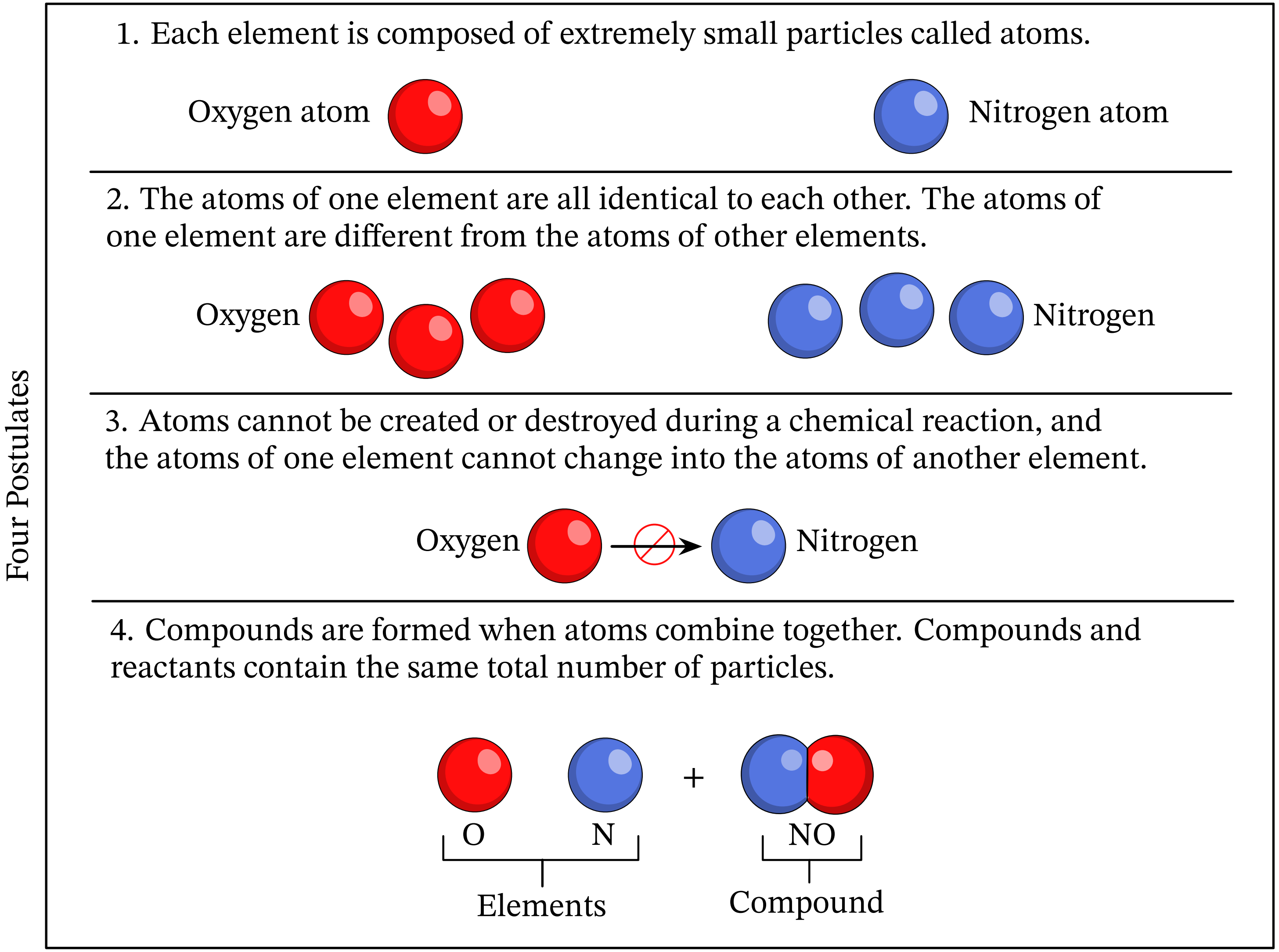
Dalton proposed the following:

- The chemical elements were all made up of indivisible atoms.
- The atoms of one chemical element were unique and different from the atoms of another chemical element.
- The atoms of one element could not be transformed into the atoms of another element.
- No one atom could be created or destroyed during any one chemical reaction process.
- All product compounds were supposed to have the same number and types of atoms as the reactants.

Dalton's Theory (Continued)

The following figure restates some of Dalton's postulates.

Dalton's Atomic Theory



Importance of Dalton's Theory

It explained many laws and scientific phenomena that had stymied other scientists all over the developed world.

He was able to satisfactorily explain why reactants always seemed to combine together in well-defined proportions.

He managed to explain why the mass of products always seemed to be determined by the mass of reactants.

Dalton was one of the first scientists to make some serious headway in determining the structure of the atom, and his theory and postulates are collectively known as the solid-sphere model or hard-sphere model.

The solid-sphere model was accepted and even revered for a while, but it had to be revised when J. J. Thomson showed that cathode rays are made up of almost unimaginably small negatively charged particles.

Example 1: Identifying What Dalton’s Solid-Sphere Model Proposed and What It Did Not Propose

Which of the following ideas was **not** supported by Dalton’s solid-sphere model of the atom?

1. Atoms of the same element are identical.
2. Atoms can be divided into smaller parts.
3. Atoms can chemically combine to form compounds.
4. Atoms of one element are never transformed into atoms of another element.
5. All elements are made of atoms.

Answer

Dalton proposed a relatively simple model for the structure of atoms that did not include a description of subatomic particles such as protons or electrons.

Example 1 (Continued)

Dalton’s model of the atom was pioneering, but it was nonetheless quite simplistic, and it would not be refined or corrected until much later when quantum physicists of the 20th century used more advanced machinery to understand what the atom was made of.

B must be the answer to this question because Dalton’s solid-sphere model does not support the idea that atoms can be divided into smaller parts.

History of the Cathode Ray

Eugen Goldstein originally coined the term *cathode ray* in 1876.

He coined this term to describe an unknown type of radiation emitted from the cathode of a vacuum tube.

No one 19th-century scientist was able to conclusively determine what cathode rays were and what they contained.

This all changed when J. J. Thomson started to conduct groundbreaking experiments with cathode ray tubes just after the start of the 20th century.

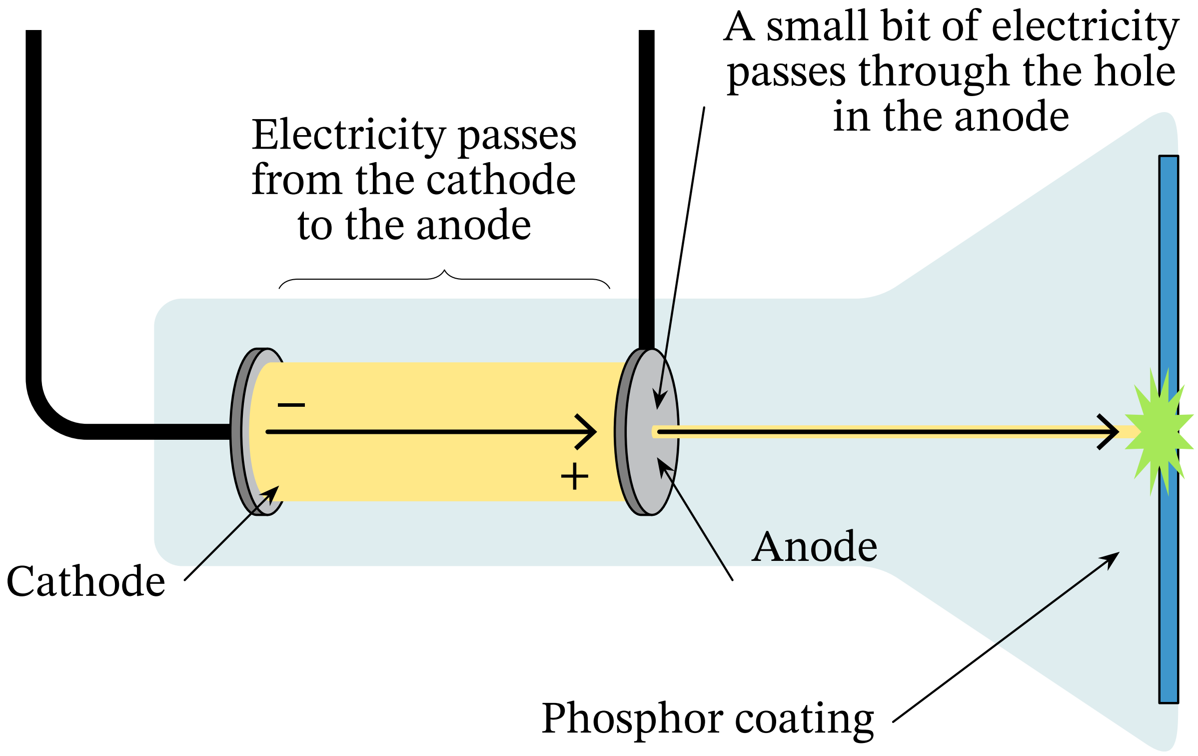
How Does a Cathode Ray Tube Operate?

The following figure shows a highly simplified schematic illustration of a cathode ray tube.

It contains a cathode and an anode at one end and a phosphorescent screen at the other end.

Cathode rays are generated when a large potential difference is applied between the cathode and anode.

These cathode rays travel through the cathode ray tube in a straight line, and they end up colliding with the phosphorescent screen.



How Does a Cathode Ray Tube Operate? (Continued)

The gas pressure is usually kept very low inside a cathode ray tube.

This helps to ensure that gas particles do not end up obstructing cathode rays as they move from the cathode toward the phosphorescent screen.

Properties of Cathode Rays

The cathode rays travel through the cathode ray tube in a straight line.

They can be described as having a thermal effect because they generate heat when they strike the phosphorescent screen or almost any other type of surface.

They are made up of negatively charged particles.

They are affected by electric fields and magnetic fields.

Cathode ray particles are subatomic particles that are a component of all atoms.

How Did J. J. Thompson Prove That Cathode Rays Are Made Up of Negatively Charged Particles?

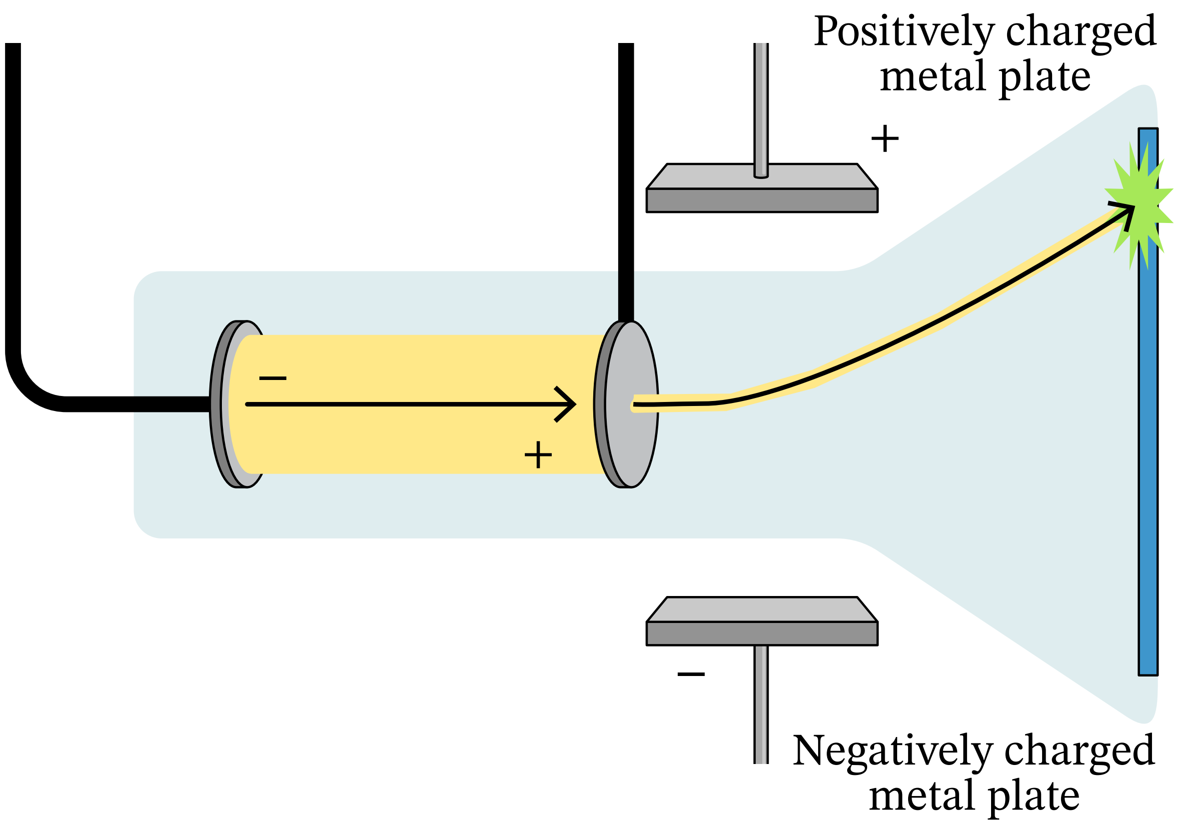
The opposite figure shows one of J. J. Thompson's most important experiments.

It shows that Thomson put two oppositely charged metal plates across a cathode ray tube.

He found that he could deflect the cathode ray with the electric field from the electrically charged plates.

Cathode rays always veered toward the positively charged plate and away from the negatively charged plate.

This experiment provided strong evidence that cathode rays are made up of negatively charged particles.



How Did J. J. Thompson Determine the Charge-to-Mass Ratio of the Cathode Ray Particles?

The following figure shows how Thomson used a combination of electric and magnetic fields to determine the charge-to-mass ratio of the cathode ray particles.

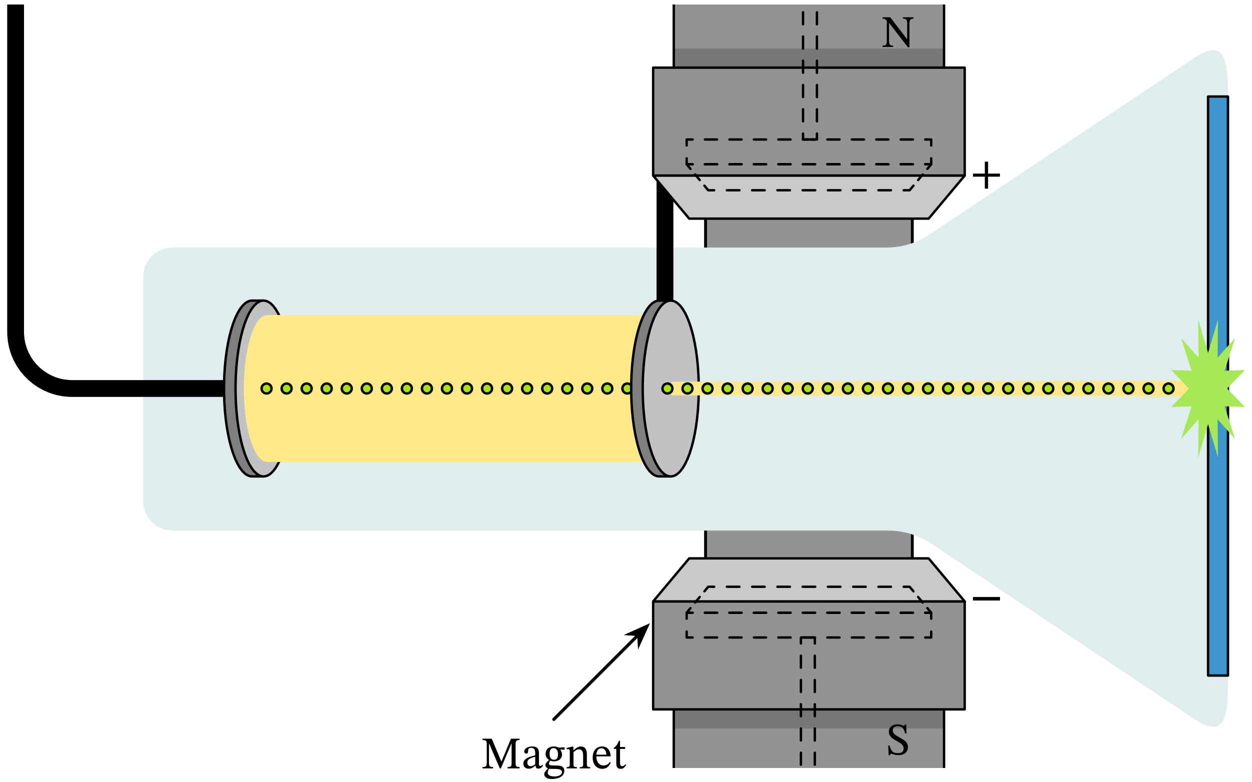
He initially generated an electric field with the oppositely charged plates that were put on either side of the cathode ray tube.

This caused the cathode ray to veer off to one side.

He then used an electromagnet to make a magnetic field.

He varied the strength of the magnetic field to make the deflected cathode ray straight again.

He was effectively balancing known electric and magnetic field strengths to determine a single charge-to-mass ratio.



How Did J. J. Thompson Determine the Charge-to-Mass Ratio of the Cathode Ray Particles? (Continued)

Thomson used this experiment and some simple calculations to show that cathode rays contain particles that have an incredibly low mass.

He showed that cathode rays contain negatively charged particles that are over 1 000 times lighter than a hydrogen atom.

Thomson would subsequently propose that cathode ray particles are fundamental units of matter.

He made the bold proposition that cathode ray particles are subatomic particles that are a component of all atoms.

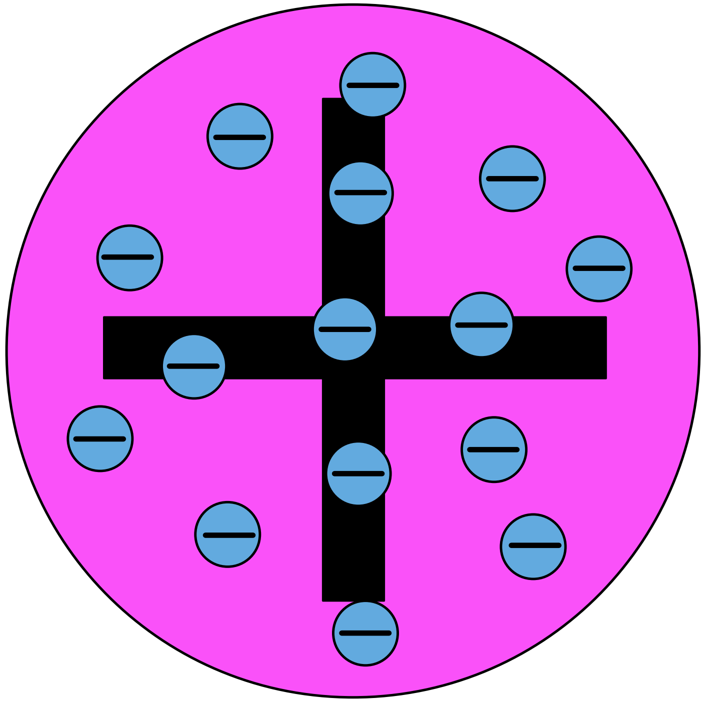
Plum Pudding Model

The opposite figure describes the plum pudding model.

The plum pudding model proposes that electrons are distributed in any one atom much like small raisins in a large plum pudding.

The electrons are supposed to be incredibly small negatively charged particles that are embedded in a sea of positive electric charge.

Each atom is supposed to be neutrally charged because it has enough negatively charged particles to balance its positive electrostatic charge.



Definition: Plum Pudding Model

The plum pudding model depicts atoms as a sea of positive electric charge with enough randomly distributed electrons to have no overall electrostatic charge.

Example 2: Identifying the Difference between the Plum Pudding and Hard-Sphere Models of the Atom

How was the plum pudding model different from the hard-sphere model of the atom?

A. The plum pudding model showed electrons making up the corners of a cube.
B. The plum pudding model included negatively charged particles known as electrons.
C. The plum pudding model included positively charged particles known as protons.
D. The plum pudding model described electrons orbiting a central nucleus.
E. The plum pudding model showed electrons occupying different energy levels.

Answer

J. J. Thomson is the Nobel Prize–winning physicist who first proved the existence of electrons and famously publicized the idea of the plum pudding model for atoms.

J. J. Thomson described atoms as being positively charged spheres that contain lots of negatively charged electrons.

Example 2 (Continued)

Thomson thought the electrons were arranged in atoms somewhat like raisins are arranged in plum pudding.

The hard-sphere model of the atom proposed that atoms have a relatively basic structure and that they do not contain any subatomic particles.

We can use these statements to determine that B is the correct answer to this question.

Determining the Electric Charge of an Electron (Oil Drop Experiment)

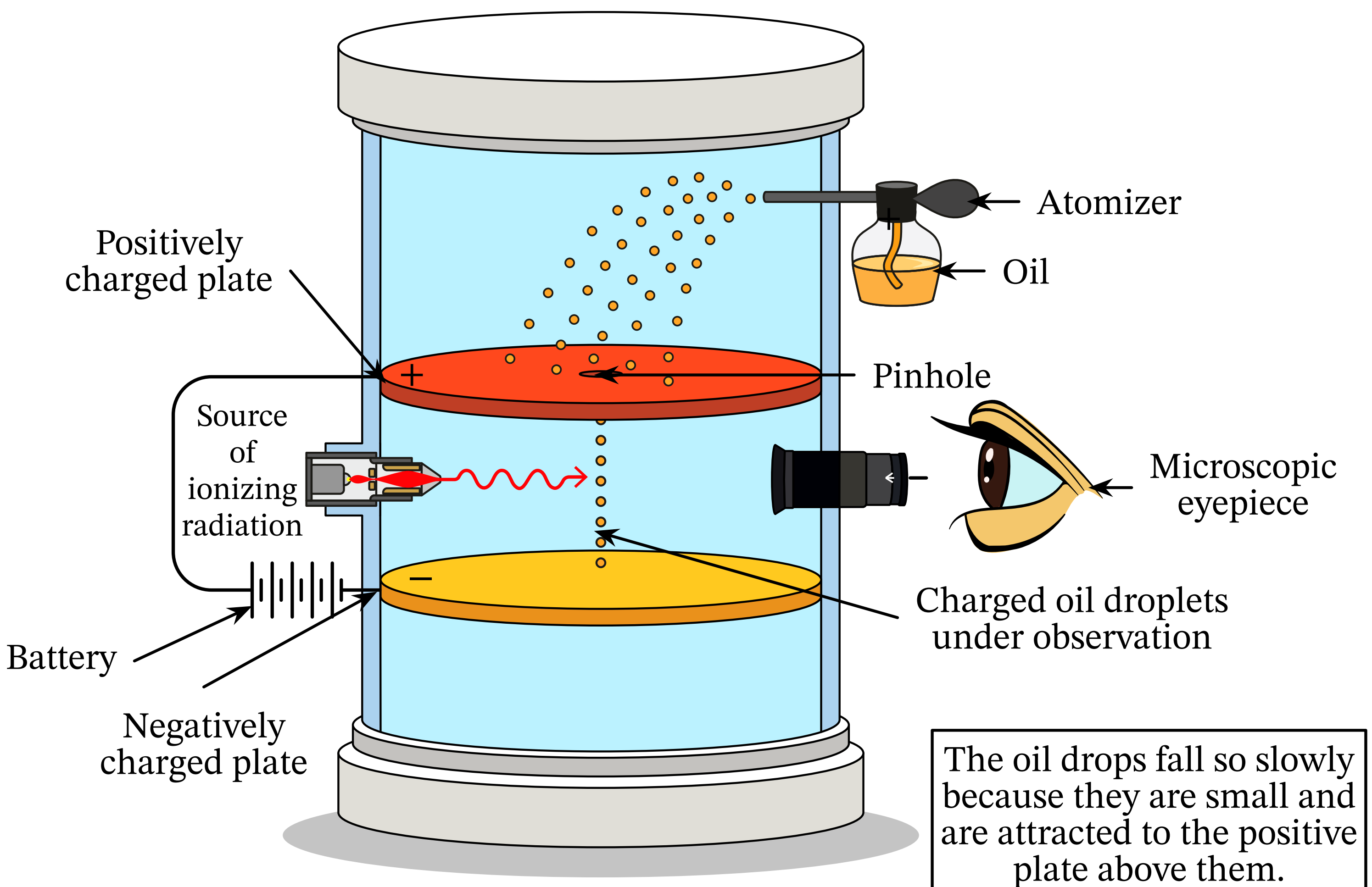
Robert A. Millikan and Harvey Fletcher used the now famous oil drop experiment to determine the electric charge of an electron in 1909.

They attempted to determine the charge of an electron by analyzing the properties of tiny electrically charged oil droplets when they were positioned between two oppositely charged metal plates.

Their experiment was a huge success, and it helped them determine the charge of an electron.

The opposite figure shows how Millikan and Fletcher used radiation and oil drops to determine the charge of an electron.

Millikan's Oil Drop Experiment



The oil drops fall so slowly because they are small and are attracted to the positive plate above them.

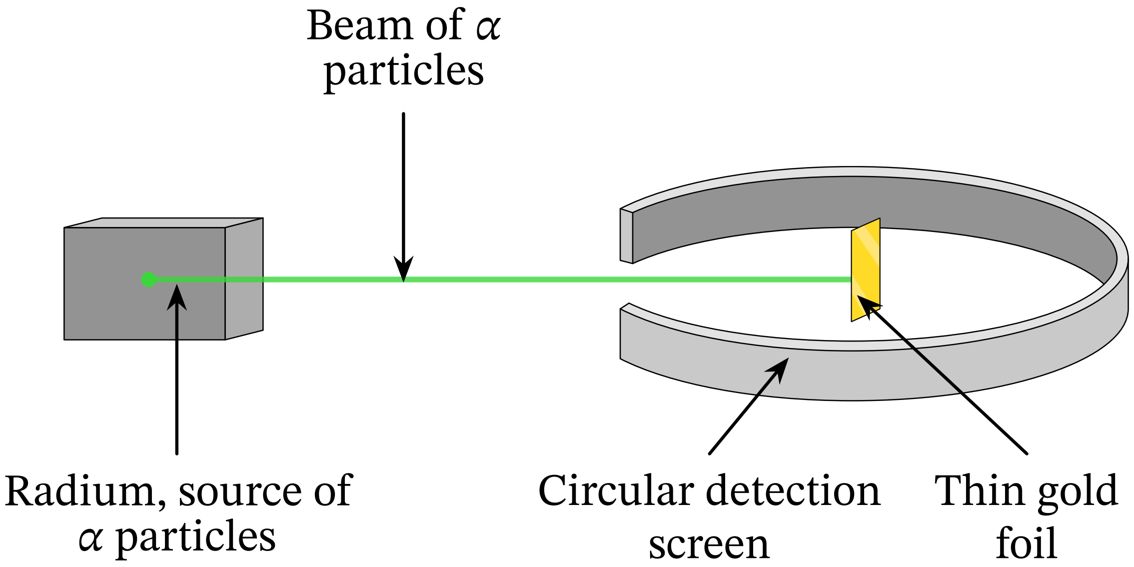
Gold Leaf or Gold Foil Experiment

The gold leaf experiment is arguably the most groundbreaking scientific experiment that has ever been conducted.

This experiment was designed and directed by Ernest Rutherford, but it was actually performed by his assistants Hans Geiger and Ernest Marsden.

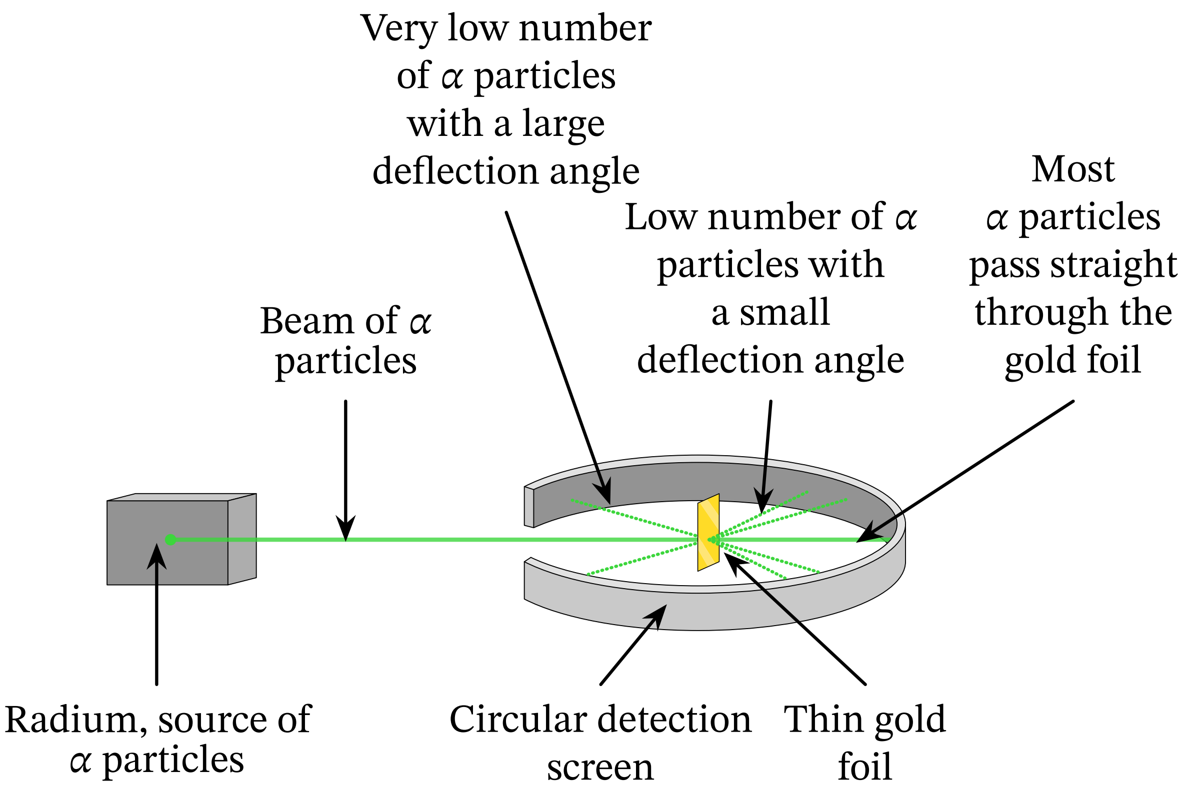
The scientists used a source of radium to produce a beam of alpha (α) particles.

They directed this beam at a piece of thin gold foil and monitored how the alpha particles bounced off the gold foil and interacted with a circular luminescent detection screen.



Observations and Results of the Gold Foil Experiment

Observations	Results
Most of the alpha particles were relatively unperturbed when they interacted with the thin piece of gold foil.	An atom contains lots of empty space.
Some of the alpha particles were deflected by a relatively small angle.	The atom contains an area of concentrated positive charge.
Some of the alpha particles essentially bounced back close to or directly toward the direction of the alpha particle source.	The atom contains an extremely dense and positively charged nucleus.



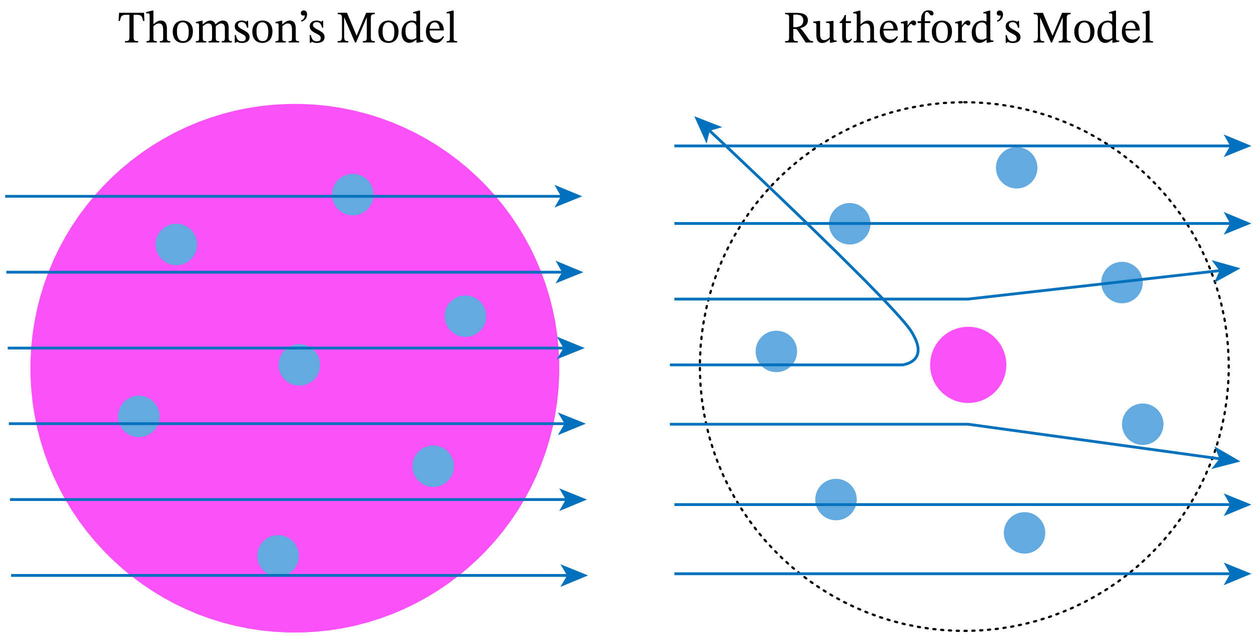
Why the Gold Foil Experiment Could Not Be Reconciled with the Plum Pudding Model

Thomson had stated that any one atom contains small electrons that are embedded in a sea of positive charge.

This means that the positively charged mass of the atom should not be concentrated at one incredibly small point in space, but it should be spread out relatively evenly across the whole width of the atom.

Alpha particles should not have strong interactions with atoms if the plum pudding model is an accurate description of atomic structure.

Rutherford figured this out for himself, and he ended up proposing the nuclear or Rutherford model of the atom.



Rutherford Atomic Model (Nuclear Atomic Model)

The nuclear model states that

- the atom contains a nucleus;
- the nucleus is positively charged, and it occupies an incredibly small percentage of the whole volume of the atom;
- the positively charged nucleus was supposed to be orbited by the low-mass electrons;
- there was supposed to be a significant amount of space in between the positively charged nucleus and its low-mass electrons;
- the atom was not supposed to be uniformly dense in the nuclear model;
- the atom had an overall neutral electrostatic charge because the sum of the negative electric charges was supposed to equal the positive charge of the atomic nucleus;
- the electrons would not fall into the nucleus because they would be orbiting it at a tremendous speed;
- the attraction force between electrons and the nucleus was supposed to be equal and opposite to the centrifugal force experienced by the electrons;
- the nuclear model of the atom can be compared with the structure of the solar system.

Flaws of the Rutherford Atomic Model

The nuclear model of the atom managed to successively explain the befuddling observations of the gold leaf experiment, but it could not be used to understand the emission spectrum of hydrogen atoms.

It also failed to satisfactorily describe why electrons do not lose all their energy as they orbit the positively charged nucleus.

It was obvious that the atomic model was still incomplete, and this led Niels Bohr to propose a new model for atomic structure.

Example 3: Recalling What Landmark Scientific Experiments Proved and What They Disproved

Which of the experiments listed below did not match its given conclusion?

A. The Rutherford experiment was useful in determining the nuclear charge on the atom.
B. The Rutherford experiment confirmed the presence of a positively charged nucleus in the center of the atom.
C. The Rutherford experiment proved the Thomson plum pudding model of the atom to be essentially correct.
D. Thomson's work on the electric discharge tube showed the existence of negatively charged particles called electrons.
E. Millikan's oil drop experiment determined the charge of the electron.

Example 3 (Continued)

Answer

Ernest Rutherford used the gold foil experiment to show that positive atomic charge was concentrated at an incredibly small point in atoms, and this disputed the plum pudding model that had been proposed by J. J. Thomson.

The alpha particles would have traveled through the gold foil essentially unaffected if J. J. Thomson was correct in stating that atoms have their positive charge spread fairly evenly across their width.

Ernest Rutherford showed that alpha particles could sometimes be deflected through very large angles when they collided with gold atoms, and this proved that atoms have a very dense and positively charged nucleus.

These statements can be used to determine that C is the correct answer to this question.

Definition: Line Emission Spectrum

Line emission spectra are the wavelengths of light emitted from an element when its electrons drop from a high energy state to a lower energy state.

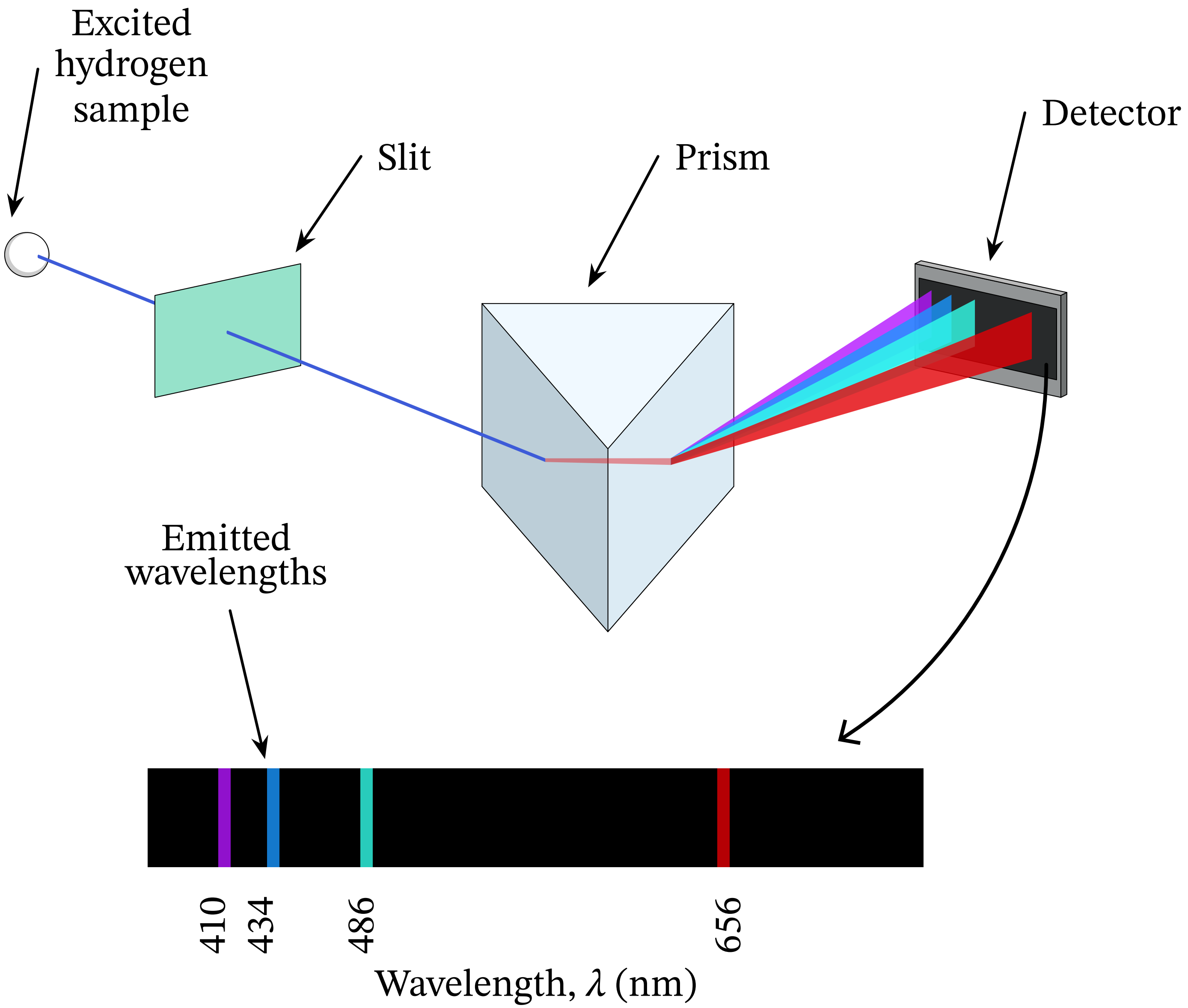
Generating an Emission Spectrum Using Hydrogen Gas

Scientists can use an electric current to excite or destabilize a sample of hydrogen gas.

This excited hydrogen gas ends up emitting radiation that has an intense blue color.

The blue-light radiation can then be separated into its component photons if it is refracted with a glass prism.

The wavelength of each photon can be determined if the photons are made to interact with some light-detection apparatus.

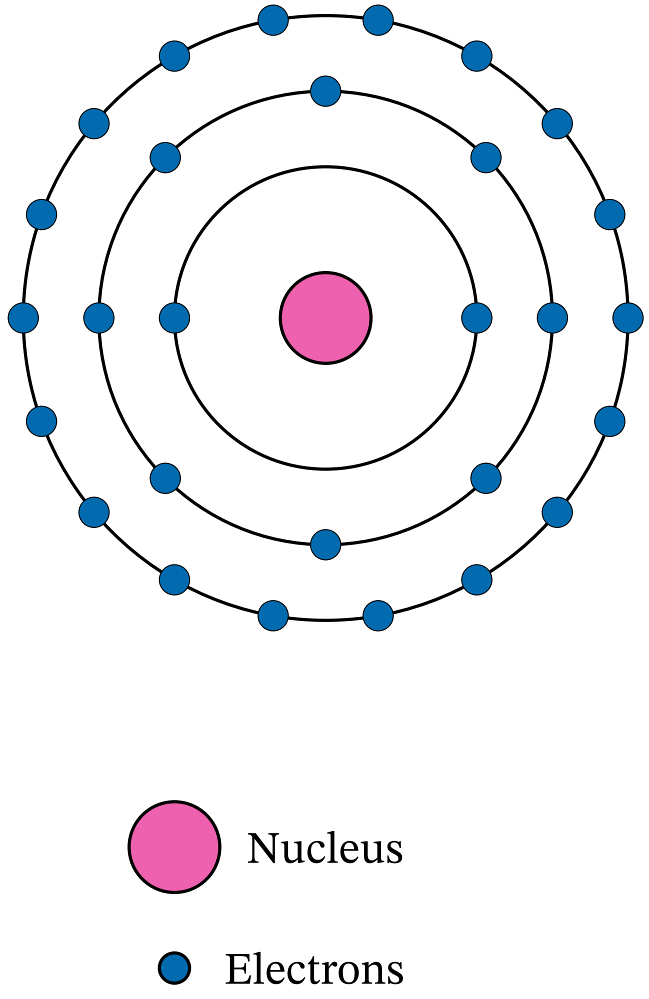


Bohr's Atomic Model

Bohr studied the emission spectrum of hydrogen, and he ended up proposing a new atomic model.

He proposed the following:

- Atomic nuclei are surrounded by electrons that are essentially confined to discrete energy levels as they orbit the nucleus.
- Some electrons would stay at one energy level, and other electrons would stay at an altogether different energy level.
- The electrons would rapidly orbit the central positively charged atomic nucleus much like planets orbiting the Sun.
- The energy state of each electron was supposed to be determined by the radius of its orbit.
- Electrons would have relatively low energy if they had a small radius of orbit, and they would have relatively high energy if they had a large radius of orbit.



Bohr's Atomic Model (Continued)

Bohr used the principal quantum number (n) to effectively describe the radius of orbit.

Low principal quantum numbers were used for electrons with the smallest radius of orbit, and higher principal quantum numbers were used for electrons with a larger radius of orbit.

Bohr proposed that the electrons of any one atom would ordinarily incessantly orbit the atomic nucleus at one well-defined energy level.

There would not be any movement of electrons toward or away from the atomic nucleus unless the electrons were affected by external energy.

External energy could force an electron to move from a ground state to a higher and less stable energy state. This would only happen if the absorbed energy matched the "energy gap" between the ground state and the higher and less stable energy state.

The unstable electron would then rapidly return to its original ground state. The deexcitation process was supposed to release a photon whose energy or wavelength could be determined as the difference in energy between the excited and deexcited energy states.

Definition: Excited Atom

An excited atom has at least one of its electrons promoted out of its ground state to a higher energy level.

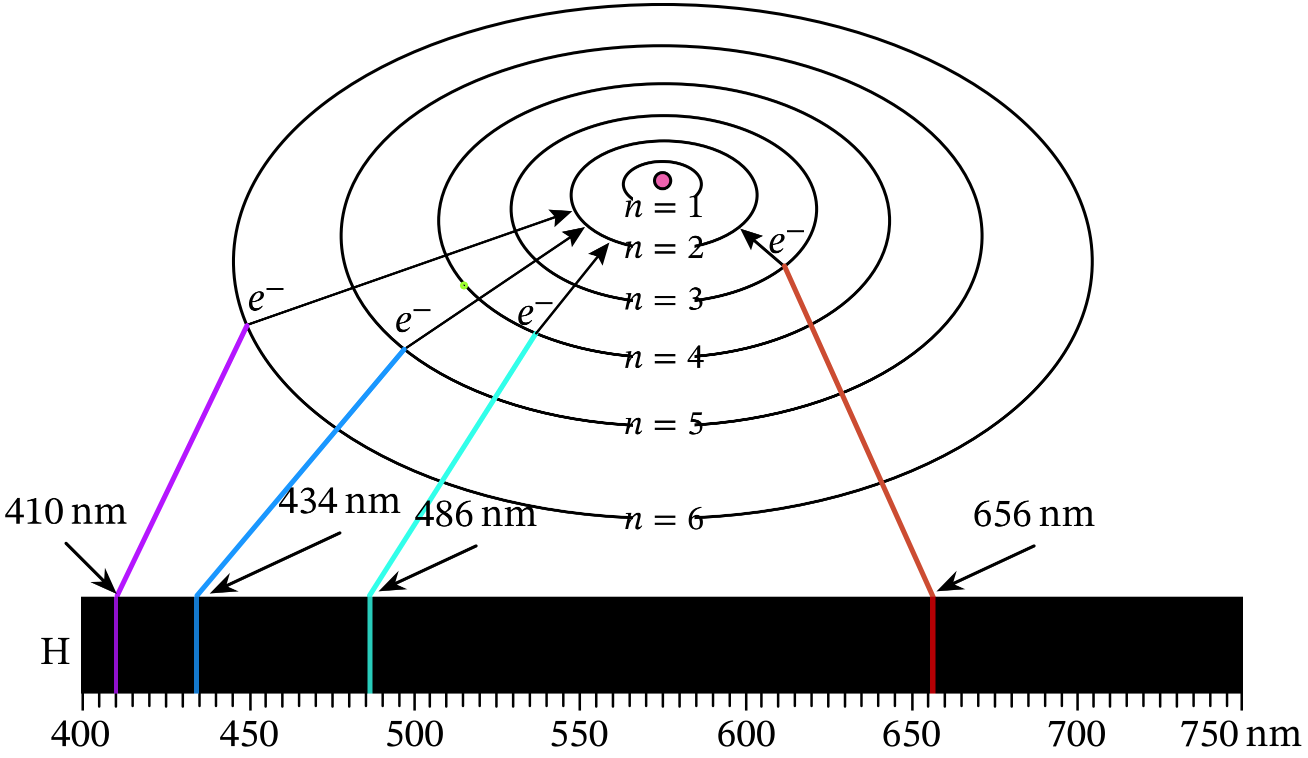
How the Bohr Model of the Atom Can Be Used to Explain the Emission Spectrum of Hydrogen

All of the emitted photons are supposed to be associated with a specific electron excitation and deexcitation process.

The emitted red photons are supposed to be associated with the movement of excited electrons from the third energy ($n = 3$) to the second energy level ($n = 2$).

The blue and green photons are supposed to be associated with electron transitions between the fifth ($n = 5$) and second ($n = 2$) energy levels for blue photons and between the fourth ($n = 4$) and second ($n = 2$) energy levels for green photons.

The violet photons are supposed to be associated with electron transitions between the sixth ($n = 6$) and second ($n = 2$) energy levels.



The Bohr Model of the Atom Is Called a Quantum Mechanical Model

The Bohr model of the atom is called a quantum mechanical model because it describes how electrons can absorb or emit discrete packets of energy (quanta).

Electrons will not move from one energy level to another unless they absorb the appropriate amount of energy.

They will not move from a ground state to an excited state unless they absorb photons that have exactly the right wavelength.

It is important to appreciate that the energy difference between successive electron shells is not always equal.

There is a relatively large energy difference between some adjacent electron shells and a much smaller energy difference between other adjacent electron shells.

The “energy gap” between successive electron shells is supposed to become smaller with increasing distance from the atomic nucleus.

Definition: Quanta

Quanta are discrete packets of energy.

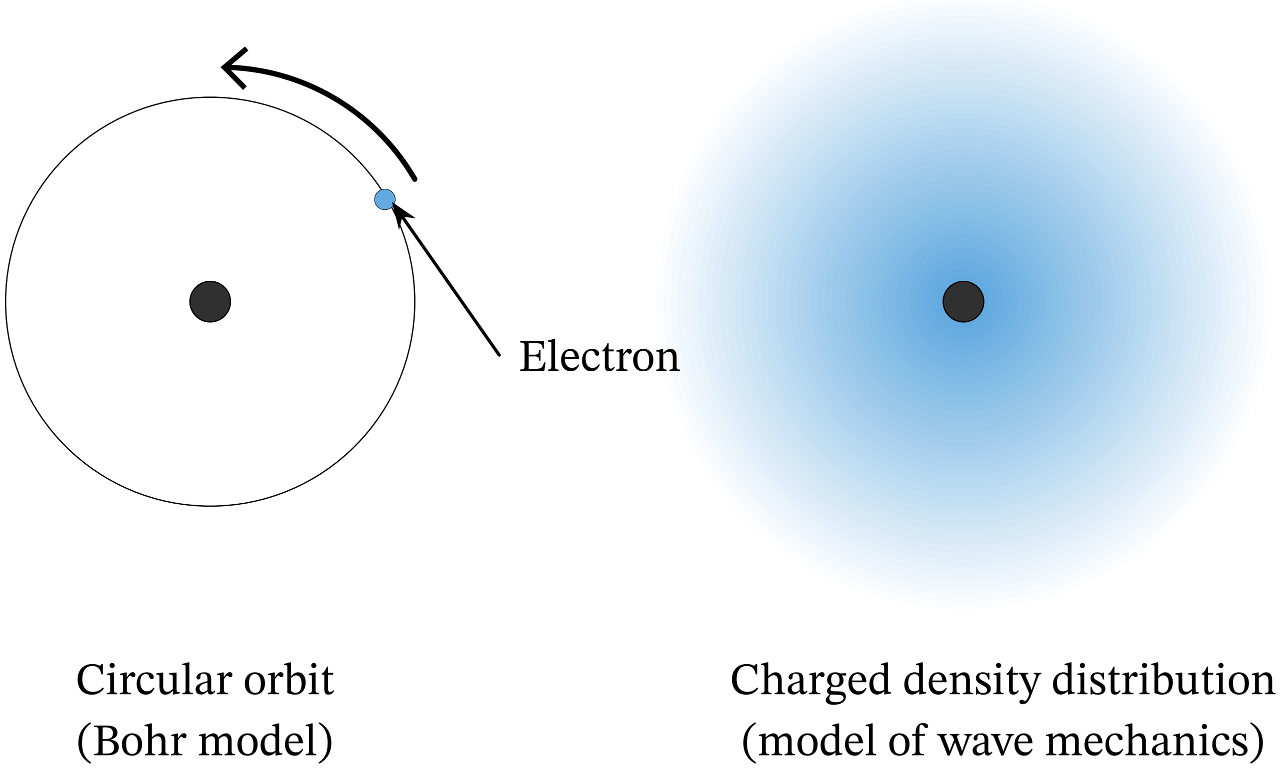
The Flaws of Bohr's Atomic Model

It was nonetheless still an obviously imperfect model because it could not be applied to understand the emission spectra of atoms, other than hydrogen, that had a higher atomic number.

Bohr was not aware of the uncertainty principle, and he incorrectly assumed that electrons move in set paths around positively charged nuclei.

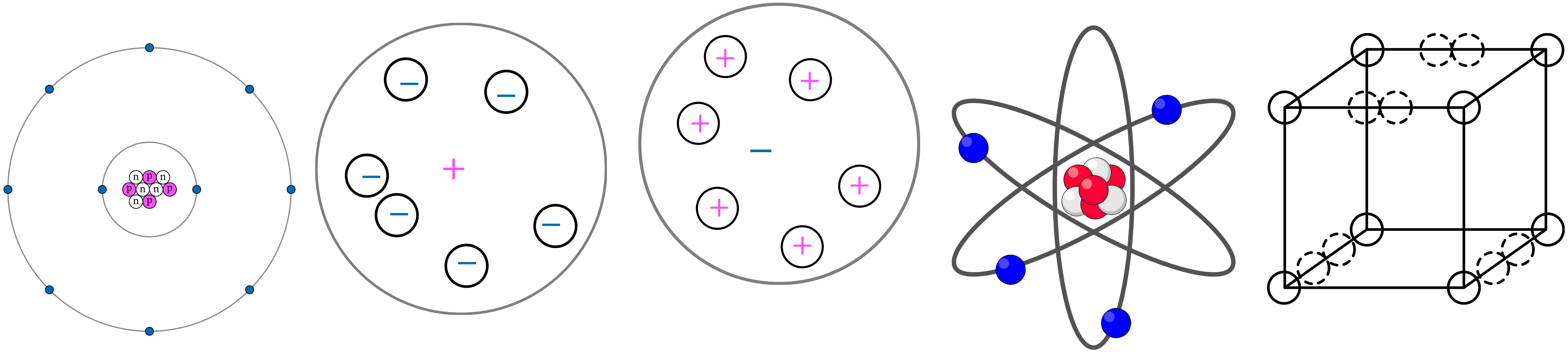
He assumed that atoms were essentially planar and contained electrons that orbit nuclei much like planets orbit the Sun.

The opposite figure contrasts the simplistic Bohr model of the atom with the much more accurate model that was established by Erwin Schrödinger.



Example 4: Identifying the Most Accurate Depiction of the Planetary Model of the Atom

Which diagram most closely represents Bohr’s electron-shell model of the atom?



(A) (B) (C) (D) (E)

Example 4 (Continued)

Answer

Niels Bohr proposed an atomic model that was able to explain the hydrogen emission spectrum of hydrogen atoms.

Bohr proposed that the atom contains a positively charged nucleus that is orbited by extremely low-mass electrons.

Each electron of any one atom would ordinarily incessantly orbit the atomic nucleus at one well-defined energy level.

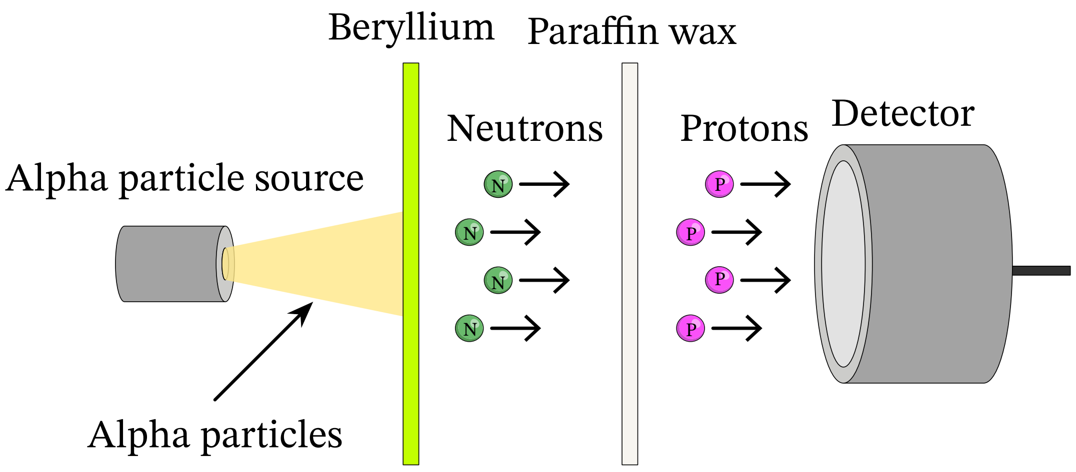
The energy state of each electron was supposed to be determined by the radius of its orbit.

Electrons would have a relatively low energy if they had a small orbit radius, and they would have a relatively high energy if they had a large orbit radius.

We can use these statements to determine that A is the correct answer to this question.

James Chadwick and Discovering the Neutrons

- James Chadwick conducted some scientific experiments that helped him refine the atomic model.
- He used a source of alpha particles, and he directed these alpha particles toward some beryllium.
- The beryllium released an unknown type of radiation as it was bombarded with the alpha particles.
- This unknown radiation was then directed at some paraffin wax.
- This interaction disturbed the paraffin wax, and it ended up emitting protons.
- The protons were counted with a detector.
- James Chadwick used this experiment to show that the unknown radiation was made up of neutrally charged particles that are now known as neutrons.
- Chadwick discovered the existence of the neutron, and his work was used to explain the existence of chemical isotopes.



Definition: Isotope

Atoms that have the same number of protons but a different number of neutrons are called an isotope.

Example 5: Identifying What James Chadwick Helped Prove or Validate

Fill in the blank: James Chadwick proved the existence of ______.

A. the quantum atomic model
B. the electron cloud model
C. the electron
D. the neutron
E. the proton

Answer

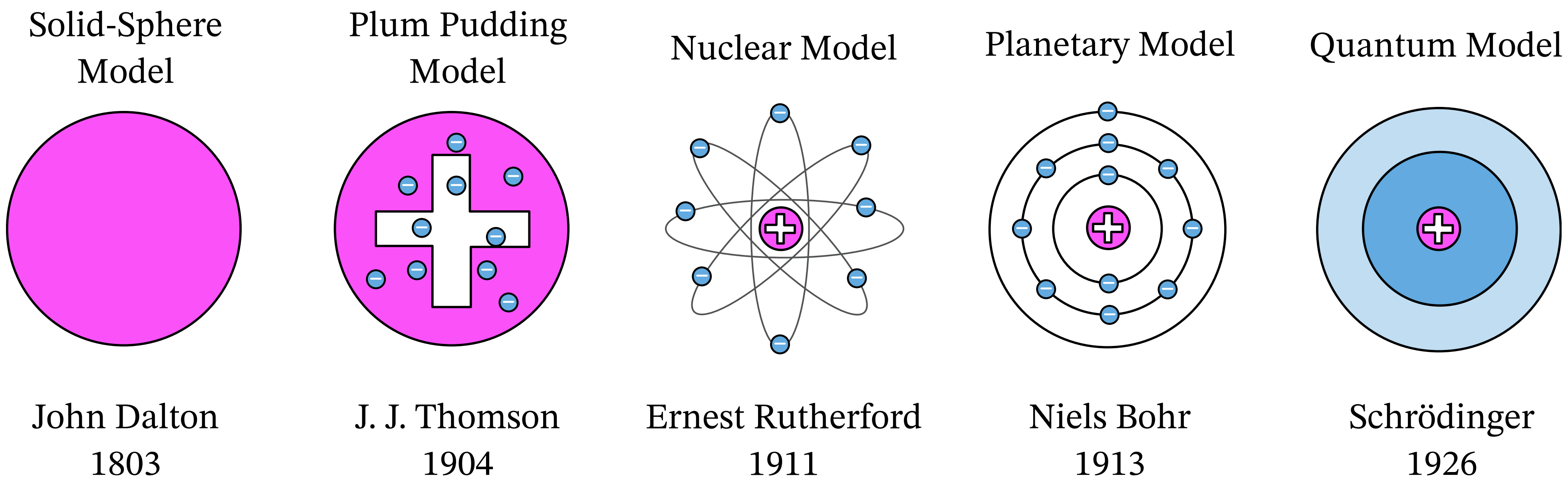
James Chadwick proved the existence of the neutron by bombarding paraffin wax with ionizing radiation.

It was quickly accepted that the neutron was a fundamental component of the atomic nucleus because this conclusion can be used to explain why most elements have different isotopes.

These statements can be used to determine that option D is the correct answer to this question.

Schematic Illustrations of Different Atomic Models

The following figure provides simple and easy-to-understand schematic illustrations to describe how society progressively went from seeing atoms as featureless solid spheres to seeing atoms as negatively charged electrons orbiting a positively charged core of protons and neutrons.



Key Points

- The atomic model has progressively been refined through scientific experimentation and the production of new scientific theories.
- Dalton proposed that the chemical elements are all made up of indivisible atoms and that the atoms of one chemical element are unique and different from the atoms of another chemical element.
- J. J. Thomson showed that cathode rays are made up of electrons, and he came up with the now very famous plum pudding model.
- Robert A. Millikan is credited with determining the charge of the electron when he conducted oil drop experiments with Harvey Fletcher.
- Ernest Rutherford proved the existence of the atomic nucleus through an ingenious set of experiments that involved relatively simple gold foil and ionizing alpha radiation.
- Niels Bohr proposed that electrons orbit positively charged nuclei much in the same way that planets orbit the Sun in our solar system.
- James Chadwick proved the existence of the neutron by bombarding paraffin wax with unknown radiation from an excited source of beryllium.