Atomic and Molecular Physics

Presented by

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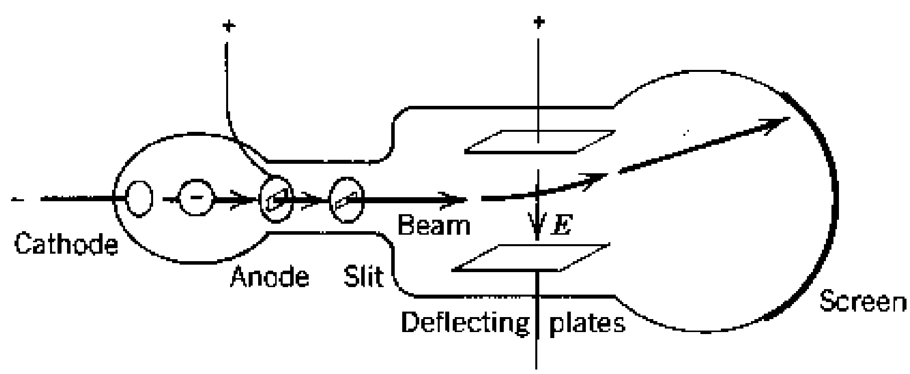
Second-year students

1. Historical perspective

In the years before Bohr formulated his theory of the atom, based upon the principles of quantum physics, some steps had been made on the understanding of the atomic structure. We list here some important contributions:

- **Mendeleev had developed a concept for arranging the known chemical elements based on their mass. Order was given in terms of increasing mass, while the elements were further arranged according to the ordering principle of chemical behaviour. The columns in the table of the elements relate to chemical valence. In 1869 the Periodic Table was not yet complete.**
- **Avogadro had conceived the idea that gasses consist of discrete particles and had established the law that equal volumes of gas at equal pressure and temperature contain the *same* number of such particles, although the actual number was not yet determined. Avogadro's hypothesis was not accepted by many physicists for a long time.**
- **It was realized for some time that electrostatic charges were important for the building blocks of matter. This followed from Faradays experiments on electrolysis , from which it was deduced that ions move in a liquid as charged particles, and from the experiments on radioactivity in which electrically charged particles were emitted.**
- **Thomson's experiments on cathode rays were important for the determination of some properties of the constituents of matter. The charged particles, emitted from a cathode, were deflected in a combination of crossed static electric and magnetic fields, and detected on the phosphorent screen (see Fig). Hence impinging charged particles could be made visible by the light emitted by the screen.**

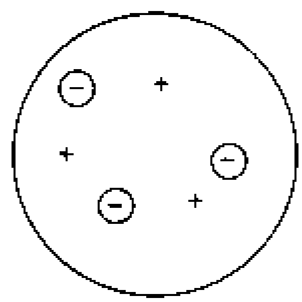


- After the ratio (e/m) was determined Millikan performed his famous oil-drop experiment from which the two values of e and m could be unravelled.

Chapter one: Atomic Models

1.1 Thomson's model

Based on these concepts Thomson developed a model for the atom consisting of the electrons as negatively charged particles of low mass and some substance that should carry positive charge and nearly all the mass within the atom. Since the elements were arranged according to their mass number A, the atoms were thought to consist of A positive particles and A electrons in a structure as shown below. Note that the atomic number Z does not play a role yet.

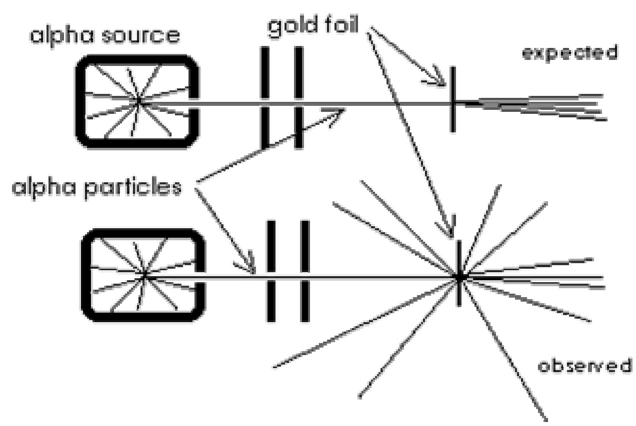


1.2 Rutherford scattering

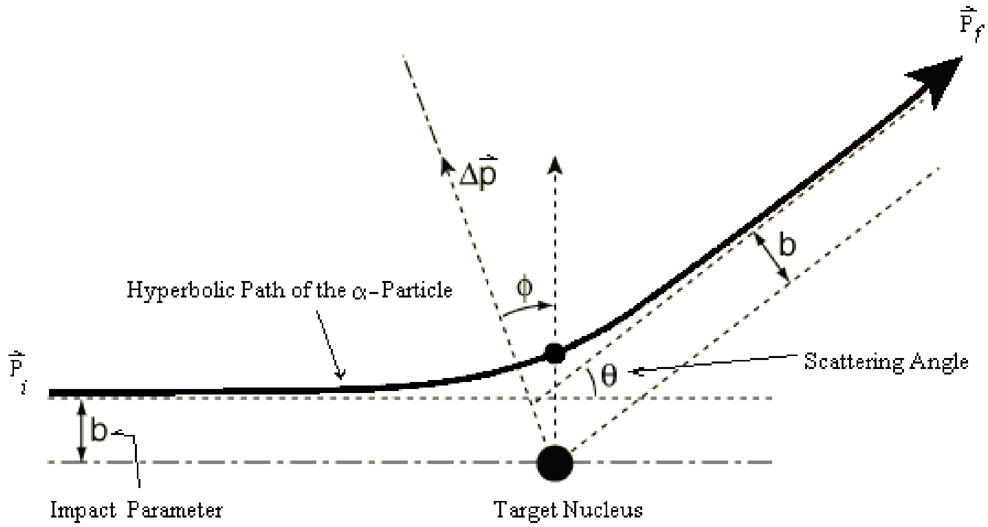
Rutherford scattering is a phenomenon that was explained by Ernest Rutherford in 1911, and led to the development of the orbital theory of the atom. It is now exploited by the materials analytical technique Rutherford backscattering. Rutherford scattering is also sometimes referred to as Coulomb scattering because it relies on static electric (Coulomb) forces.

Highlights of Rutherford's Experiment:

- A beam of α particles were aimed at a thin gold foil.
- Most of the particles passed through without deflection.
- Others were deflected by various angles.
- Some were backscattered.



From these results Rutherford concluded that the majority of the mass was concentrated in a minute, positively charged region (the nucleus) surrounded by electrons. When a (positive) alpha particle approached sufficiently close to the nucleus, it was repelled strongly enough to rebound at high angles. The small size of the nucleus explained the small number of alpha particles that were repelled in this way. Rutherford showed,using the method below, that the size of the nucleus was less than about 10^{-14} m .



The relationship between the scattering angle θ, the initial kinetic energy $K = \frac{1}{2}mv_0^2$ and the impact parameter b is given by,

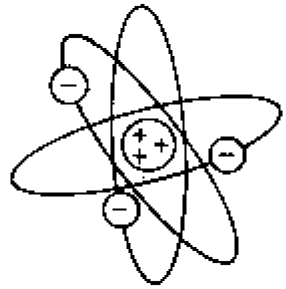
$$b = \frac{zZ}{2K}\frac{e^2}{4\pi\varepsilon_0}\cot\left(\frac{\theta}{2}\right),$$ **where z =2 for α-particle and Z = 79 for gold.**

1.3 Rutherford's model of the atom

Sir Ernest Rutherford proposed a model of the atom based on the results of alpha particle scattering that the atom consisted mainly of empty space with a tiny, positively charged nucleus, containing most of the mass of the atom, surrounded by negative electrons in orbit around the nucleus like planets orbiting the Sun.

According to Maxwell's electromagnetic theory, a charged particle in circular motion radiates energy and so an electron in a Rutherford's atom should continuously lose energy as it moves in a planetary orbit and eventually should spiral down to the nucleus at the centre of the atom, which does not happen. Rutherford's model though a much improved picture of the atom, but could not explain stability of the atom.

Furthermore, according to classical physics, the energy emitted by an electron as it spirals down to the nucleus should have all frequencies, in other words the emitted spectrum should be continuous which is not the case. The emitted spectrum consist of lines in a dark background. Thus, Rutherford's model could not explain the observed line spectra of elements.



There are however a number of shortcomings to this planetary model of an atom bound by classical electromagnetic forces:

- **the problem of stability with accelerated electrons in orbit loosing energy.**
- **the model gives no indication of the size of the atom.**
- **the model gives no explanation for the characteristic spectroscopy of atoms.**

1.4 The Bohr model of the atom

Niels Bohr proposed an atomic model that would explain the discrepancies between the observed line spectra emitted by elements and the spectra predicted by the Rutherford's atomic model.

Bohr proposed the following postulates:

1. **An electron in an atom moves in a circular orbit about the nucleus under the influence of the Coulomb force between the electron and the nucleus.**
2. **An electron moves in an orbit for which its orbital angular momentum L is an integral multiple of $\hbar$ ($L = n\hbar$).**
3. **An electron moving in an allowed orbit does not radiate electromagnetic energy. Thus, its total energy E remains constant.**
4. **Electromagnetic radiation is emitted if an electron, initially moving in an orbit of total energy E_i, discontinuously changes its motion so that it moves in an orbit of total energy E_f. The frequency ν of the emitted radiation is equal to the quantity $\left(\nu = \frac{E_f - E_i}{\hbar}\right)$.**

1.5 Bohr-Sommerfield model

Bohr, in his semiclassical analysis, had only allowed for circular orbits in his model. Later the model was extended by Sommerfeld also allowing for elliptical orbits. This version, based on the same ad hoc quantization condition for the angular momentum is referred to as the Bohr-Sommerfeld model. Sommerfeld already postulated the azimuthal quantum number, in addition to the principle quantum number n defined by Bohr.

Q1. Which scientist proposed arranging chemical elements by increasing mass and chemical behavior?
A) Avogadro
B) Mendeleev
C) Rutherford
D) Thomson

Q2. Avogadro's law states that:
A) Equal volumes of gas at same T and P contain the same number of particles
B) All gases have identical densities at room temperature
C) Gas pressure is inversely proportional to temperature
D) Atoms are indivisible

Q3. What did Faraday's experiments on electrolysis demonstrate?
A) Atoms are indivisible
B) Ions move as charged particles in solution
C) Energy is quantized
D) Light behaves as particles

Q4. The cathode ray experiments by J.J. Thomson proved the existence of:
A) Nucleus
B) Electrons
C) Neutrons
D) Protons

Q5. Who performed the oil-drop experiment to measure electron charge?
A) Rutherford
B) Millikan
C) Bohr
D) Sommerfeld

Q6. Thomson's atomic model suggested that:
A) Atoms are indivisible
B) Atoms consist of electrons embedded in a positively charged "pudding"
C) Atoms are mainly empty space
D) Atoms emit continuous spectra

Q7. In Rutherford's gold foil experiment, most α-particles:
A) Rebounded straight back
B) Deflected at large angles
C) Passed through without deflection
D) Converted to beta particles

Q8. Rutherford concluded that the atom:
A) Has electrons orbiting in fixed shells
B) Is a uniform sphere of positive charge

C) Has a dense nucleus with electrons orbiting around
D) Is indivisible

Q9. Which force explains Rutherford scattering?
A) Gravitational force
B) Strong nuclear force
C) Coulomb electrostatic force
D) Weak interaction

Q10. According to Rutherford's model, electrons should spiral into the nucleus because:
A) Electrons have no charge
B) Accelerated charges radiate energy
C) Nucleus attracts electrons infinitely
D) Magnetic forces dominate

Q11. What major limitation of Rutherford's model was observed in emission spectra?
A) Continuous spectrum predicted vs. line spectra observed
B) Absence of nucleus
C) Electron mass miscalculated
D) Inability to explain isotopes

Q12. Bohr introduced the idea that:
A) Atoms are indivisible
B) Electrons orbit in quantized energy levels
C) Electrons are stationary in the nucleus
D) Atoms radiate energy continuously

Q13. Which of the following is a Bohr postulate?
A) Electrons emit energy in circular orbit
B) Angular momentum is quantized as $n\hbar$
C) Atoms have no nucleus
D) Electrons exist only in elliptical paths

Q14. In Bohr's model, when an electron jumps from higher to lower orbit:
A) Energy is absorbed as radiation
B) Energy is emitted as radiation
C) Electron mass decreases
D) Electron charge changes

Q15. The frequency of emitted radiation in Bohr's model is proportional to:
A) Energy difference between two levels
B) Velocity of electron
C) Mass of nucleus
D) Radius of orbit

Q16. The Bohr-Sommerfeld model extended Bohr's by allowing:
A) Helical orbits
B) Elliptical orbits
C) Parabolic orbits
D) Hyperbolic orbits

Q17. Which new quantum number was introduced by Sommerfeld?
A) Spin quantum number
B) Magnetic quantum number
C) Azimuthal (orbital) quantum number
D) Principal quantum number

Q18. One major success of Bohr's model was explaining:
A) The mass of the proton
B) Line spectra of hydrogen
C) Discovery of neutrons
D) Beta decay

Q19. The limitation of the Bohr-Sommerfeld model was:
A) Failure to explain Zeeman effect
B) Inability to explain elliptical orbits
C) Overestimation of nuclear size
D) Incorrect value of electron charge

Q20. Which model first described atoms as "mainly empty space" with a dense nucleus?
A) Bohr's Model
B) Thomson's Model
C) Rutherford's Model
D) Bohr-Sommerfeld Model