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Outlines of Rutherford's α-particles scattering Experiment

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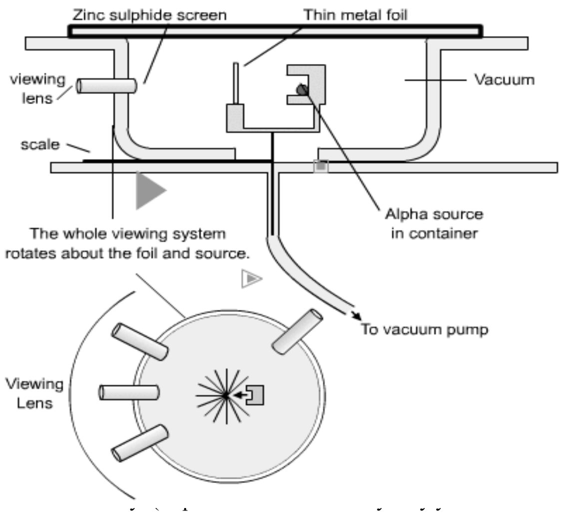
ABSTRACT

Rutherford's α-particles scattering experiment was one of the milestone for the physics community as it provided an insight to an atom thus discarding the previously prevailed Thomson's model. Through this article we shall examine the theoretical formulation of Rutherford's experiment and how it helped to shape the modern physics.

Keywords: Rutherford's α-particle scattering, Differential scattering, Rutherford's Experiment

Introduction

Rutherford in 1911 performed his famous α-particle scattering experiment by the incident of collinated beam of α-particles from the radioactive source radium on thin gold foil of about 1μm, placed on a movable ZnS screen.



[Fig: Experimental setup for Rutherford's Experiment Image Source [1]]

The emitted α-particles scattered at the gold foil at varying from 0^0 to 180^0 . α-particles are doubly charged helium atoms that have already lost both of their electrons thus have mass four

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time of the mass of Hydrogen atom and positive charge two times than that of the proton. On the basis of this experiment Rutherford came with his new atomic model overcoming the defects of previously hailed Thomson's atomic model.

Theoretical Description

The minimum distance for an α-particle to approach the target nucleus known as impact parameter denoted by 'b' and the scattering angle 'θ' were studied by Rutherford.
For head on collision obviously b=0,
And as the distance of closest approach 'D', the repulsive force of the nucleus would stop the approaching α-particles and all the K.E. of it is transferred to P.E, given by the relation, $D = \frac{1}{4\pi\varepsilon_0}\frac{2Ze^2}{K}$
Where, $\frac{1}{4\pi\varepsilon_0}$ is the coulomb's constant
Z is the Atomic Number of nucleus,
K is the Kinetic Energy of the particle,
e is the charge of the electron,
The α-particle on moving away along the radius vector $\vec{r}$ under the central force,

$$\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{2Ze^2}{\vec{r}}$$

results in making the angular momentum of the α-particles constant as no torque acts on the force $\vec{F}$, along the radius vector $\vec{r}$.
From geometry, the value of cot angle made by the α-particles to the nucleus was found to be $\frac{2b}{D}$, and on mathematical calculation on the force $\vec{F}$, the relation between the impact parameter 'b' and scattering angle 'θ' was found to be $b = \frac{Ze^2}{4\pi\varepsilon_0 K}\cot\frac{\theta}{2}$

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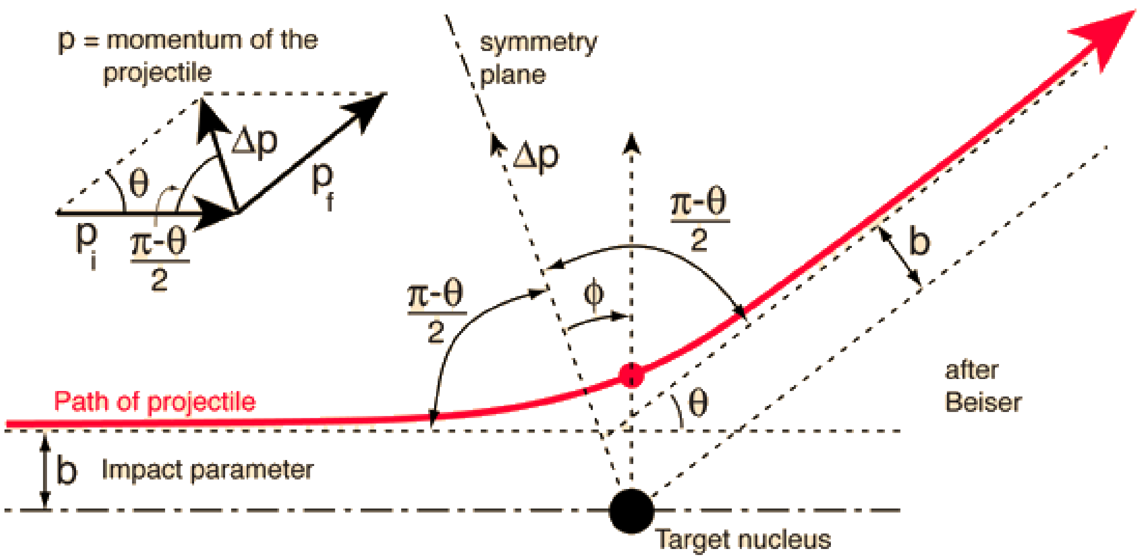
Which showed that, the value of scattering angle decreased with the increasing impact parameter. The differential cross section for the cross sectional area ($\sigma = \pi b^2$) of the nucleus was found to be

df= $-\pi n t \left(\frac{Ze^2}{4\pi\varepsilon_0 K}\right)^2 \cot\frac{\theta}{2}\ \ cosec^2\frac{\theta}{2}\ d\theta$

Where, 't' is the thickness of gold foil
'n' is the no. of target nuclei per unit volume
f is the fraction of α-particles experiencing scattering angle θ or more
Here, '-ve' sign indicates that the value of f decreases with the increasing value of θ.
Fig: Rutherford's Theoretical Description
Image Source [3]



The scattered α-particles were detected by the means of scintillation they caused and Rutherford found the relation for total 'N_i' no. of particles striking the gold foil over the course of experiment and further striking the screen at θ, to be

$$N(\theta) = \frac{N_i n t Z^2 e^4}{(8\pi\varepsilon_0)^2 r^2 K^2 sin^4\left(\frac{\theta}{2}\right)}$$

This equation is known as Rutherford's Scattering Formula

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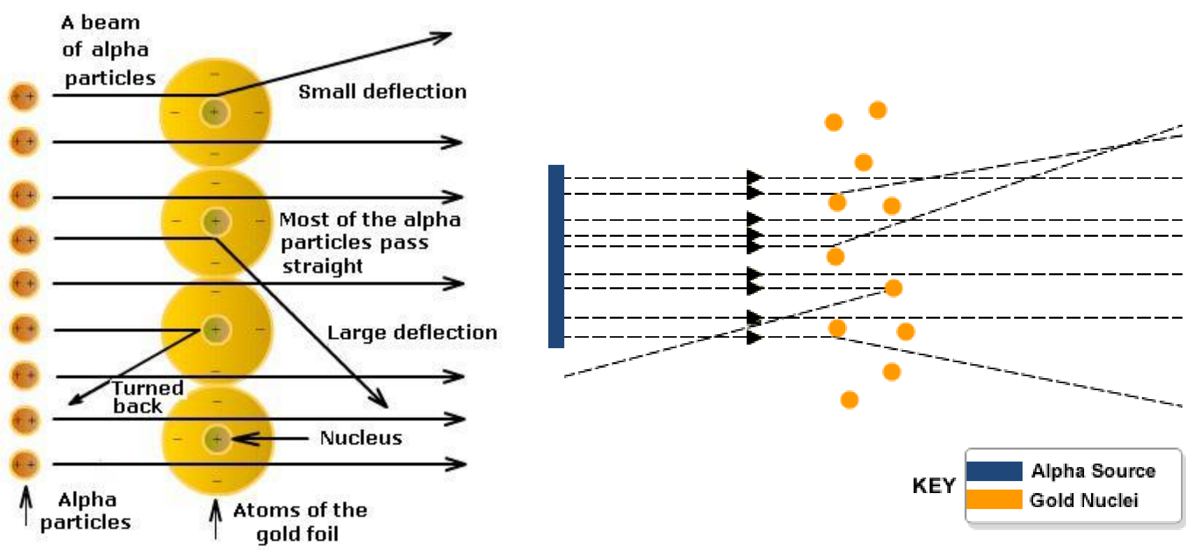

Image Source: [3] and [4]

Rutherford observed the α-particles scattered with the varying angles from 0^0 to 180^0 producing the flashes of light at ZnS screen detected by the microscope.

Results

The result he found was simply astonishing, as most of the α-particles passed straight along the gold foils, predicting that most of the space inside the atom was vacant. Some of the α-particles scattered through the acute angles predicting the presence of other particles inside the nucleus. Few of the α-particles scattered by angle greater than 90^0 and only occasionally the α-particles retraced their path making an angle of $180^{0,}$ which predicted the existence of nucleus inside the atom.

On the basis of this experiment, Rutherford postulated that most of the mass of the atom was concentrated in the nucleus predicting the size of the atom to be of 10^{-10} m and the size of the nucleus to be 10^{-15}m. For the stability of the atom, he stated that like the gravitational force, centrifugal force arised due to the rotation of electron was balanced by the electrostatic force of attraction, between the nucleus and the electron.

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For an electron revolving around the nucleus, the energy required for it to be dynamically stable in the orbit of radius r is given by $E = \frac{-e^2}{8\pi\varepsilon_0 r}$

Similarly, when an atomic gas is excited at low pressure by providing an external electric field, it emits radiation in a spectrum containing certain specific wavelengths only. Every element has their very own unique line of spectrum. Hence, by the means of spectroscopy, composition of any unknown substances can be found out.

If the gas is subjected to the white light, then the absorption spectrum formed consists of a bright background crossed over by the dark lines. These dark lines correspond to the missing spectrum, whereas the absorption spectrum consists of bright lines on dark background.

Temperature, pressure, presence of external electric and magnetic field, motion of the source, all are responsible for the intensity, number and exact wavelength of the lines in the spectrum of any element. Thus by observing spectrum, the elements present in the radiation/light as well as the information on their physical state can be known.

Failures and Conclusion

Though Rutherford's model provided a better insight to the composition of the atom, it failed to reconcile with the laws of electrodynamics, as a revolving charged particle must emit radiation continuously, which would result in, the electron vanishing in the nucleus after losing all the energy. But such thing seldom happens. Another failure was electrons could revolve in any orbit of any radius, thus, they should emit radiations in all frequencies, but experimental observations showed that atoms like Hydrogen emit line spectrum for fixed frequencies only. Hence, it failed to explain the Hydrogen spectrum.

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Despite of above mentioned failures in the Rutherford's model, it provided an fine insight to the fundamental composition of an atom, predicting that there must be other sub-atomic particles in the nucleus. Further, it predicted the importance of studying the line spectrum of the elements for the more detailed structure of the atom.

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