Rutherford scattering – Experiment 6b

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INTRODUCTION:

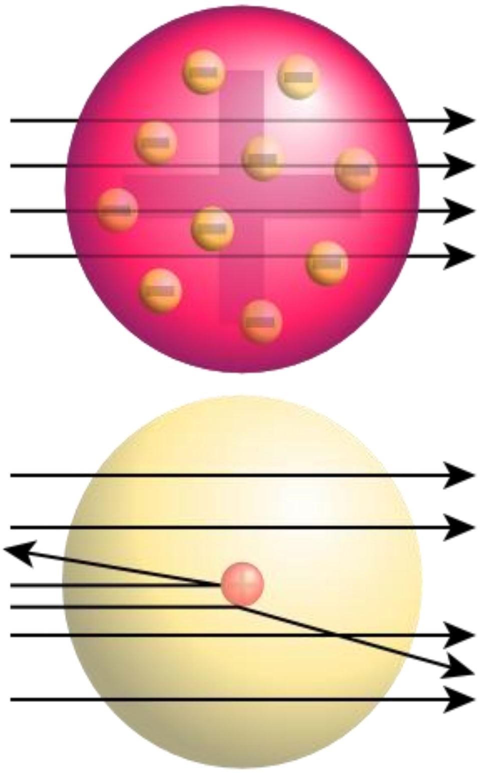


Figure 1: Rutherford gold foil experiment results (1)

Historically, there was no generally accepted model of the atom at the end of the 19th century. Most physicists believed that the atom was the most basic building block and was indivisible. However, the English physicist J.J. Thompson discovered the electron in 1897. After that, J.J. Thomson and Niels Bohr proposed two very different atomic models to fit data collected through spectroscopy. J.J. Thomson created the so called “plum pudding model of the atom”, where the negatively charged electrons are embedded in a fluid of positive charge. Niels Bohr introduced his so called “Bohr model of the atom”, where negatively charged electrons moving in circular orbits around the positive nucleus. After E. Rutherford’s scattering experiment it was clear that the “plum pudding model of the atom” could not explain Rutherford`s findings and Bohr´s model of the atom was widely accepted.

THEORETICAL BACKGROUND:

α-particle emission from a source is a coulomb repulsion effect. As the proton number (Z) of an element increases the coulomb repulsive force within the nucleus increases at a rate proportional to Z^2. The nuclear binding force acting against the Coulomb repulsion only increases at a rate proportional to its mass number, A. The α-particle (Helium nucleus) consist of two protons and two neutrons, making it a doubly magic nucleus and very stable. This stability means it is favoured as an emitted particle. The α-particle has a relative atomic charge of +2.

When the α-particle is fired at gold foil they are deflected from their original path. For many of the particles the deflection is very small, however some have much larger scattering angles.

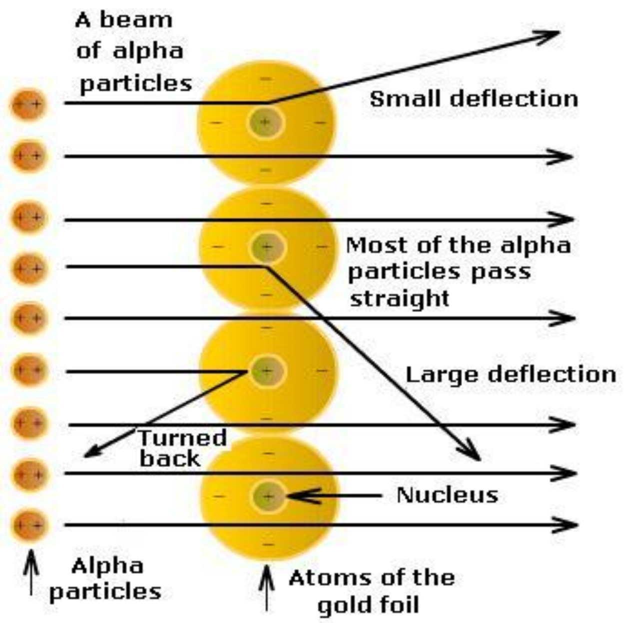


Figure 2: α-particle scattering in a dense target (2)

The distribution of scattered α-particles for a given angle θ, N(θ) is described by Rutherford´s scattering formula

$$N(\theta) = N_0\, C_f\, d_f \frac{Z^2\, e^5}{(8\pi\varepsilon_0 E_\alpha)^2 sin^4\left(\frac{\theta}{2}\right)} \qquad \text{(Eq.1)}$$

N_0 = number of incident α-particles
C_f = atomic concentration of the foil
d_f = foil thickness
Z = atomic number of foil

E_α = energy of the α-particle
e = elementary charge
ε_0 = dielectric constant

Since the coefficients in Eq.1 are all constant in this experiment, the scattering as a function of angle can be described by

$$f\,(\theta) = \frac{1}{sin^4\left(\frac{\theta}{2}\right)} \qquad \text{(Eq.2)}$$

In the case scattering rates between two different metal foils (for example Au and Al) at the same angle θ are compared, the following can be derived from Eq.1

$$\frac{N_{Au}}{N_{Al}} = \frac{C_{Au} d_{Au} Z_{Au}^2}{C_{Al} d_{Al} Z_{Al}^2} \qquad \text{(Eq.3)}$$

EXPERIMENTAL DESIGN AND PROCEDURE:

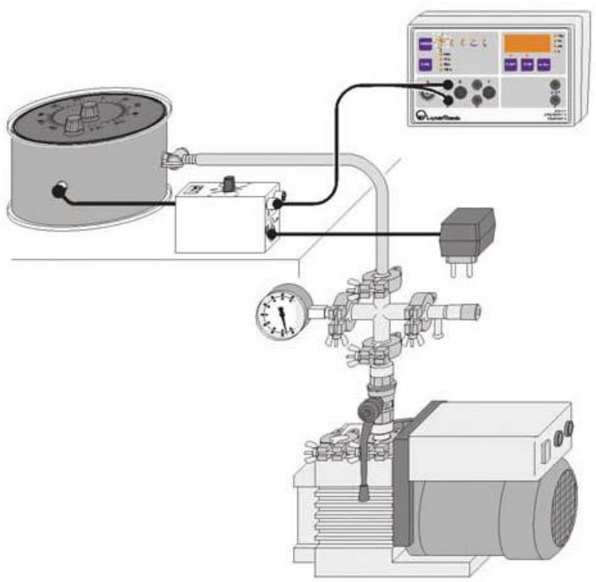


Figure 3: Experimental Setup (3)

In order to record the scattering angles of α-particles an α-particle source (Americium) was placed into a chamber. Gold foil of 2μm thickness was placed between a holder with a 5mm slit in it and positioned in the chamber such that the α-particles from the source would be incident on the exposed foil. To ensure the only scattering observed was due to deflection from the Gold nuclei the chamber was sealed and evacuated. The experiment was also covered with a thick dark cloth to minimise interference from the overhead light sources. The detector was moved to record any α-particles with scattering angles greater than 150˚ (a very large scattering angle) and the discriminator voltage was increased until no counts had been detected for 3 minutes. The detector was orientated to record scattering angles of 30˚, 25˚, 20˚, 15˚, 10˚ and 5˚ either side of the foil target.

In order to experimentally verify the proton number of Aluminium the same experimental procedure was repeated using a 1mm slit. The count rate for Gold foil was recorded for scattering angles of 5˚, 10˚ and 15˚. The Gold foil was then replaced with Aluminium foil with a thickness of 7μm and the experimental procedure repeated at the same angles, again using the 1mm slit.

ANALYSIS:

The uncertainty in angle in angle measurement was estimated at ± 2 degrees as the marked increments were 5 degree. For the first part the number of samples taken varied with each scattering angle, for the smaller angles with the fast count rates, a greater number of events were recorded to minimise the uncertainties. Since the last Laboratory session was cancelled due to weather conditions the data collected for the second part of the experiment is rather low. The uncertainty in time measurement was ± 0,05s, however as shown by the plot for the gold foil there is an additional source of error in that the data logger was not registering events from the whole beam width. The data logger would require a clearing time, i.e. the time from one event being registered to the next event being registered. The results imply that the data logger could not log more than approximately 45 counts per second. This was taken into account when choosing values for the variables A and B and it was ensured that the line of the best fit correlated well with the results at angles $\theta \geq 15^{\circ}$.

The experimental results relate to the scattering of α-particles in a plane. In order to relate the results to Rutherford´s formula a correction factor must be introduced to account for the fact that the scattering is actually in 3D.

It should be noted that the length of a segment of a circle, can be expressed as shown in Figure 4 if the change in angle dθ is suitably small.

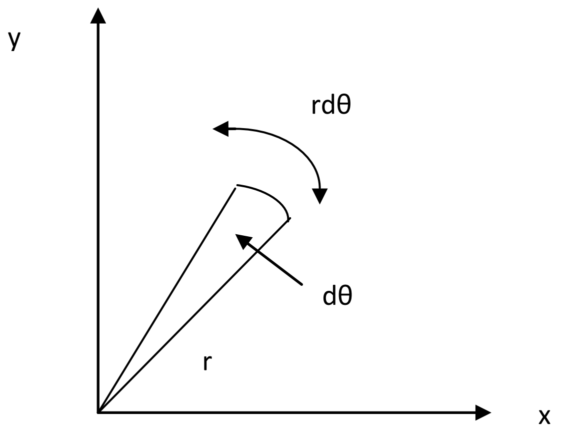


Figure 4: Small angle approximation to obtain the length of the side of a segment (4)

In order to match the Rutherford formula the results are taken to be representative of a small section of a cone as illustrated in Figure 5

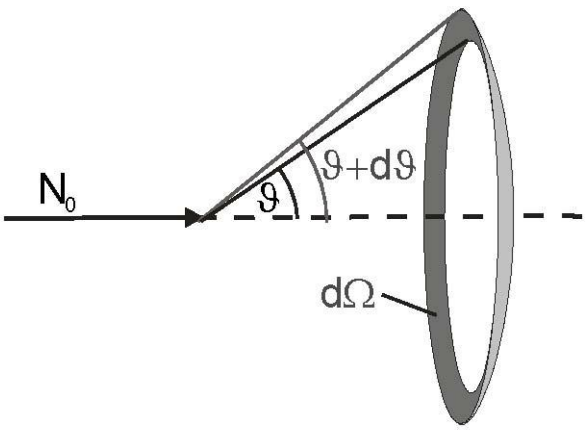


Figure 5: Diagram of the volume, the correction refers to (3)

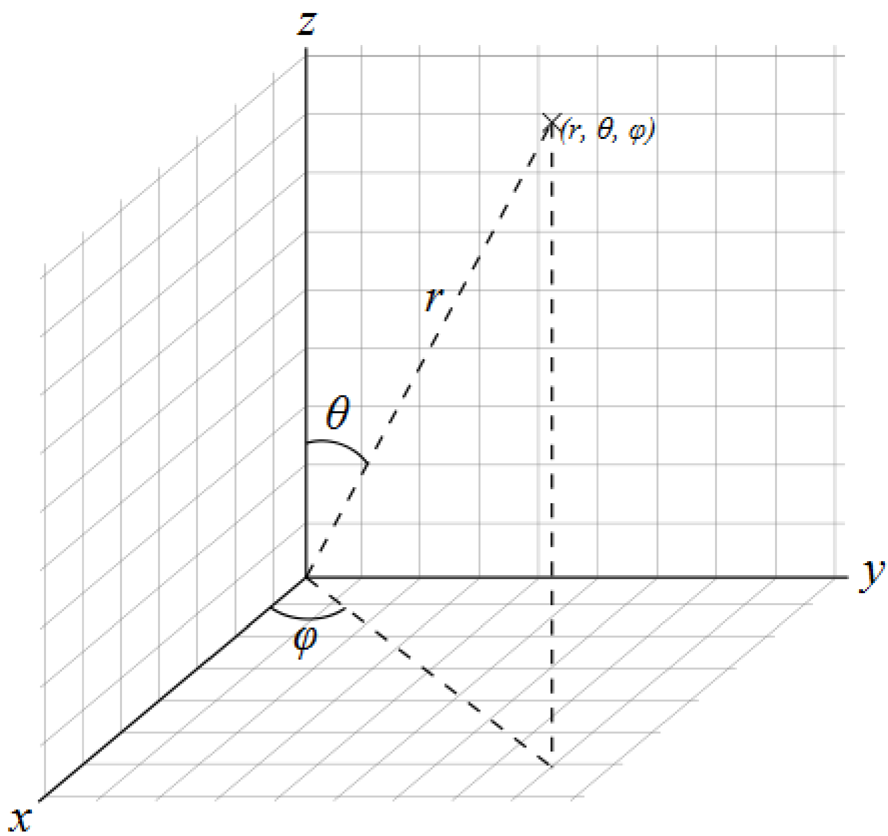


Figure 6: Converting Cartesian co-ordinates into spherical polar co-ordinates (5)

By converting into 3D polar coordinates it can be seen that there is a projection on the x-y plane. The length from the origin making the angle ϕ will have the length of rsinθ. For a small change in angle ϕ, the length a will be given by r sinθ dϕ. The height above the x-y plane depends purely of the angle θ, so for a small change dθ the length b can be expressed as r dθ.

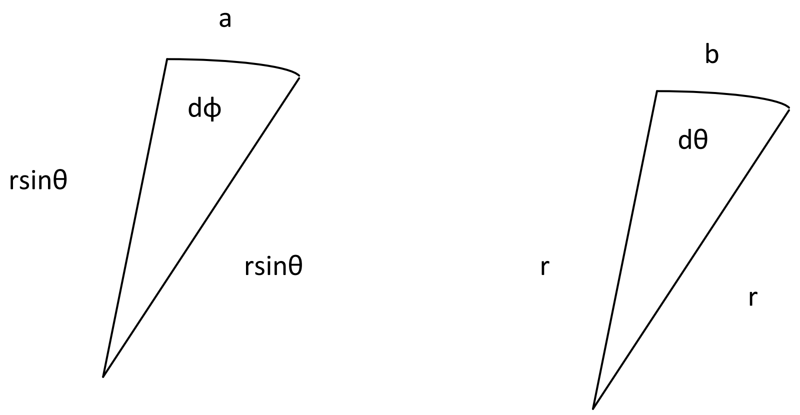


Figure 7: Segments used to calculate the area axb for the correction factor

The area axb is an infinitesimal section of the cone which surrounds the source of scattering (at the Origin in the diagram) i.e. 0 ≤ ϕ ≤ 2π. (axb = rsinθ dϕxrdθ)

$$\int_0^{2\pi} r^2 sin\theta \; d\theta \; d\,\varphi$$ (Eq.4)

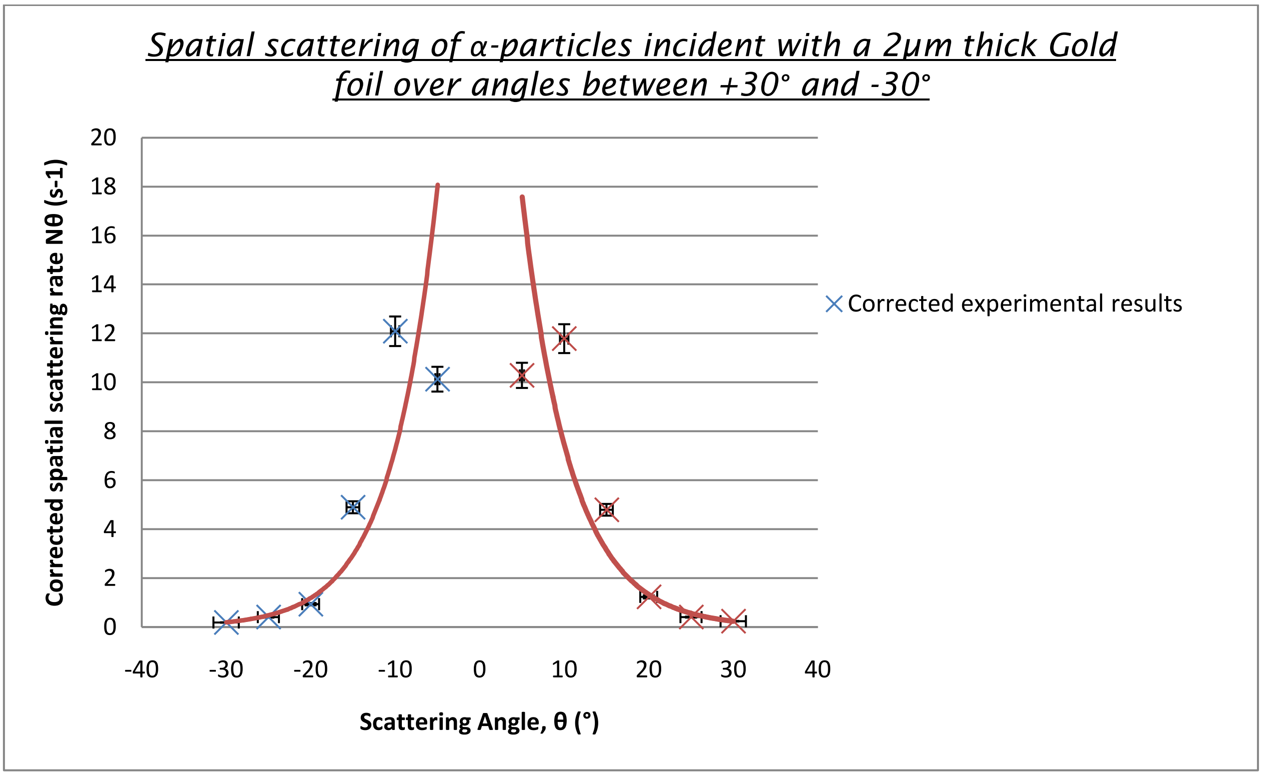
By making the test area a unit sphere i.e. r = 1 the correction factor is 2πsinθ dθ.

$$\mathrm{N}(\theta) = N_d \; 2\pi \; \sin\theta \; \mathrm{d}\theta$$ (Eq.5)

Multiplying the direct counting rate by this correction gives the spatial scattering rate Nθ. Ideally the plot of count rate Nθ vs. angle will have the form of

$$\mathrm{N}\;(\theta) = \frac{A}{sin^4\left(\frac{\theta - B}{2}\right)}$$ (Eq.6)

Where A and B are constants, A shifts the ideal plot vertically and B is a small change in angle shifting the graph horizontally. By plotting the results and the ideal and experimental results and altering A and B until the ideal results and experimental results matched, a was estimated to be 0,0005 and B with an estimated magnitude of 5.5˚. As the horizontal plot had both negative and positive points, chosen arbitrarily to ensure the detector was properly aligned, when the angle was negative the correction factor was negative and when the angle was positive the correction factor was also positive.



Graph 1: Corrected spatial scattering rate vs. scattering angle

The plot of the results is symmetric about the axis, indicating that the detector and source were properly aligned. In order to calculate the Proton number of Aluminium, the Gold foil was replaced with Aluminium and the experiment repeated. Because of reason stated in the beginning, only few data points were collected. Rearranging Eq.3 the number of protons for Aluminium can be obtained if the proton number of Gold is known.

$$Z_{Al} = \sqrt{\frac{C_{Au} d_{Au} Z_{Au}^2 \, N_{Al}}{C_{Al} d_{Al} N_{Au}}} \qquad \text{(Eq.3.1)}$$

Based on this equation and the result obtained for 10° the proton number of Al was calculated as 13,2. As the proton number has integer values only the result should be rounded to 13. It came as a surprise that with just one data set the correct result was obtained.

CONCLUSION:

This experiment was conducted in an attempt to recreate Ernest Rutherford´s famous scattering experiment. From the data obtained we can conclude that the positive matter in atoms are concentrated in a very small volume, the nucleus. This ruled out the atomic model of J.J. Thompson. If this experiment was to be repeated a more sensitive counter might be used to counteract the limited count rate of the equipment used in this experiment.

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