Rutherford Scattering

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In this experiment, we perform gamma ray spectroscopy using two detectors simultaneously and employing the use of correlation or coincidence to obtain better registration of radioactive events. We first understand the principles of nuclear physics involved, how the gammas are being produced in the radioactive source and what are the expected results in accordance with conservation of momentum and energy. The primary aim remains the verification of the same. The apparatus used is an important part of the experiment along with the software which provides the results in form of spectrum acquisition plots and summation of regions enclosed by the histograms. Finally, we discuss and draw conclusions based on the experiment, exploring its scope beyond the laboratory.

I. INTRODUCTION

In 1909, Hans Geiger and Ernest Marsden performed the gold foil experiment in collaboration with Ernest Rutherford, in which they fired a beam of alpha particles (helium nuclei) at foils of gold leaf only a few atoms thick. At the time of the experiment, the atom was thought to be analogous to a plum pudding (as proposed by J. J. Thomson), with the negatively-charged electrons (the plums) studded throughout a positive spherical matrix (the pudding). If the plum-pudding model were correct, the positive "pudding", being more spread out than in the correct model of a concentrated nucleus, would not be able to exert such large coulombic forces, and the alpha particles should only be deflected by small angles as they pass through.

However, the intriguing results showed that around 1 in 20,000 alpha particles were deflected by very large angles (over 90°), while the rest passed through with little deflection. From this, 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 outlined below, that the size of the nucleus was less than about 10^{-14} m (how much less than this size, Rutherford could not tell from this experiment alone; see more below on this problem of lowest possible size). As a visual example, figure (1) shows the deflection of an alpha particle by a nucleus in the gas of a cloud chamber.

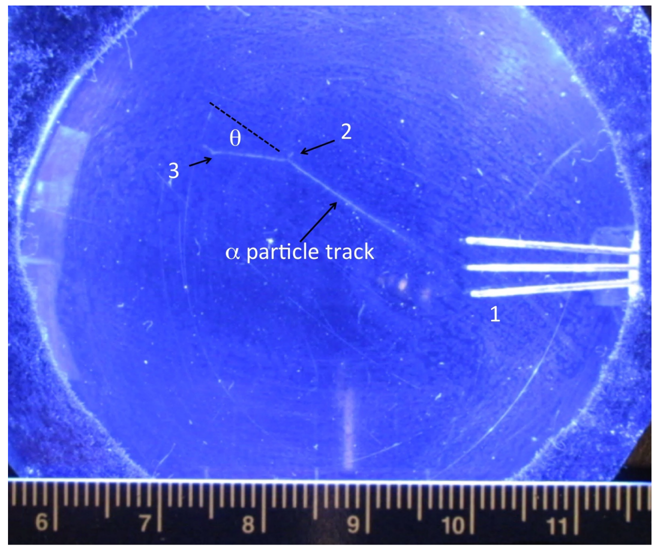

FIG. 1: In a cloud chamber, a 5.3 MeV alpha particle track from a lead-210 pin source near point 1 undergoes Rutherford scattering near point 2, deflecting by an angle of about 30°. It scatters once again near point 3, and finally comes to rest in the gas. The target nucleus in the chamber gas could have been a nitrogen, oxygen, carbon, or hydrogen nucleus. It received enough kinetic energy in the elastic collision to cause a short visible recoiling track near point 2. (The scale is in centimeters.)

Rutherford scattering is the elastic scattering of charged particles by the Coulomb interaction. It led to the development of the planetary Rutherford model of the atom and eventually the Bohr model. Rutherford scattering was first referred to as Coulomb scattering because it relies only upon the static electric (Coulomb) potential, and the minimum distance between particles is set entirely by this potential. The classical Rutherford scattering process of alpha particles against gold nuclei is an example of *elastic scattering* because neither the alpha particles nor the gold nuclei are internally excited.

II. APPARATUS

1. Scattering chamber after Rutherford
2. Aluminium and Gold foil in frame
3. Vacuum pump

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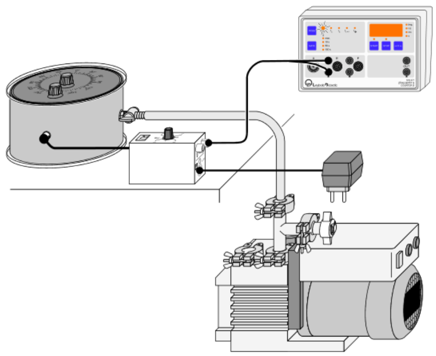

FIG. 2: Experimental setup schematically for the Rutherford Scattering Experiment.

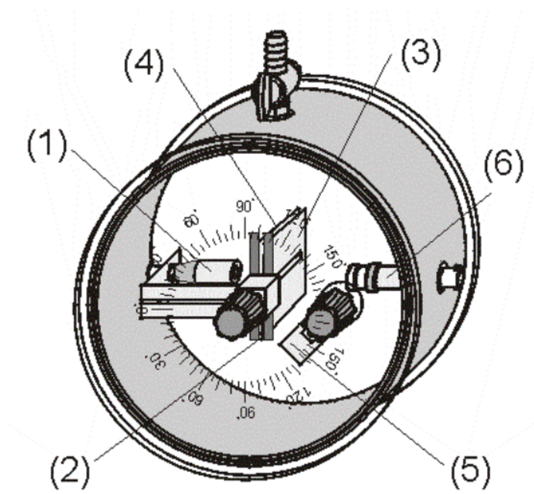

FIG. 3: The scattering chamber (1) Preparation (2) Holder (3) Gold foil (4) Slit (5) swivel arm (6) detector

4. Discriminator preamplifier
5. Counter
6. Plug-in power supply unit
7. Am-241 preparation

III. EXPERIMENT DESCRIPTION

The experimental appratues is given in figure (2) The detailed diagram of the scattering chamber is given in figure (3). The scattering geometry is given in figure (4).

IV. THEORY

If α-particles are allowed to strike a thin gold foil, they are deflected from their path (*scattering*), each by an

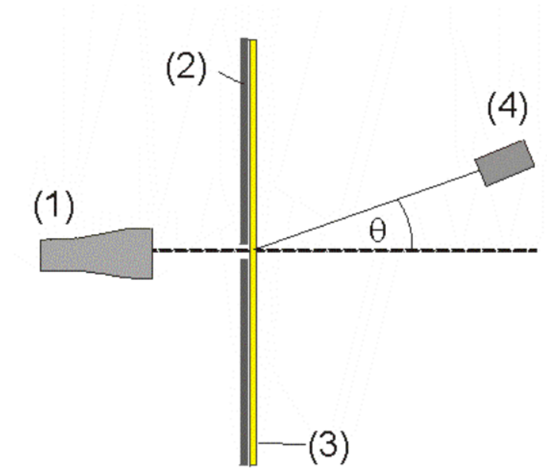

FIG. 4: The scattering geometry (1) preparation (2) collimator slit (3) gold foi (4) detector

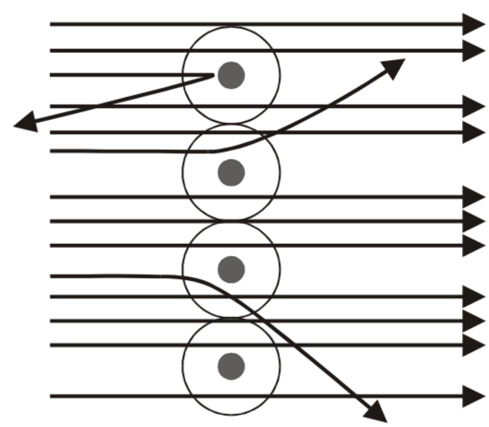

FIG. 5: Scattering of α-particles on a monolayer of atoms.

angle θ. The majority of α-particles is scattered by angles less than 1° (figure (5)).

A few particles, however, show substantially large scattering angles θ, in the extreme case up to 180° (*back scattering*). These initially qualitative observations can only be explained by assuming that the gold atoms have a very small nucleus, containing practically the whole atomic mass, and being positively charged.

On the basis of this idea Rutherford calculated the angular distribution of the scattering rate $N(\theta)$. The scattering rate is the number of particles which are scattered during the time unit in a determined interval $d\theta$ around an average angle θ. The result of this calculation is *Rutherford's scattering formula*:

$$N(\theta) = N_0 \cdot c_F \cdot d_F \frac{Z^2 \cdot d^4}{(8\pi\epsilon_0 E_\alpha)^2 \cdot \sin^4(\theta/2)} \tag{1}$$

where N_0 is the particle rate in the foil; c_F is the atomic concentration in the foil; d_F is the thickness of the foil; Z

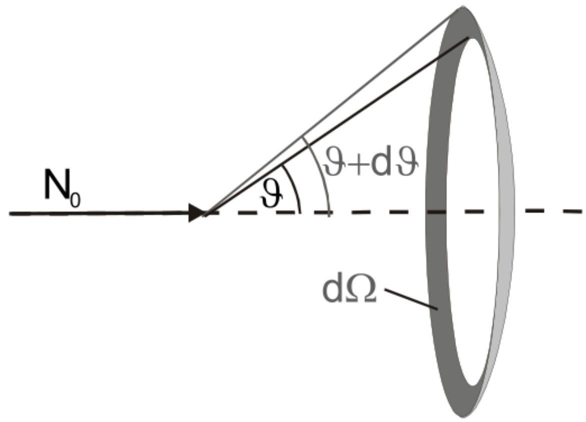

FIG. 6: The α-particles are scattered into the angular region $\vartheta + d\vartheta$.

is the nuclear charge number of the scattering material; E_α is the energy of the α-particles; e is the elementary charge ($e = 1.6021 \times 10^{-19}\,\mathrm{A\,s}$); ϵ_0 is the dielectric constant in vacuum ($\epsilon_0 = 8.8524 \times 10^{-12}\,\mathrm{A\,s\,V^{-1}\,m^{-1}}$).

The α-particles emitted from the Am-241 preparation fall through a slit aperture of 5 mm width onto the gold foil and leave this gold foil with various scattering angles. The scattered α-particles are identified with a semiconductor detector.

If we compare the scattering rates between two different foil materials (e.g. Au and Al) at the same angle θ, we can derive from the scattering formula (1):

$$\frac{N_{Au}}{N_{Al}} = \frac{c_{Au} d_{Au} Z_{Au}^2}{c_{Al} d_{Al} Z_{Al}^2} \tag{2}$$

and thus

$$Z_{Al} = \sqrt{\frac{N_{Al}(\theta) c_{Au} d_{Au} Z_{Au}^2}{N_{Au}(\theta) c_{Al} d_{Al}}} \tag{3}$$

V. EVALUATION AND RESULTS

After recording the pulse counts $n(\theta)$ the mean values $n_m(\theta)$ can be determined. Using the mean values $n_m(\theta)$ the scattering rates $N_d(\theta)$ are calculated by

$$N_d(\theta) = \frac{n_m(\theta)}{t(\theta)} \tag{4}$$

These measuring results $N_d(\theta)$ are typical for a plane scattering geometry which is given by the transparent construction of the chamber used in this experiment. The theoretical function (according to Rutherford's formula), however, is related to a three-dimensional geometry. The relation between these different aspects can considered by the following concept (figure (6)).

Each plane angle θ corresponds in space to a cone with an aperture of $2 \cdot \theta$ (produced by rotation of the plane structure around the incident beam axis). In the same way the plane angular differential $d\theta$ corresponds in three dimensions to a spatial angular differential $d\Omega$ given by

$$d\Omega = 2 \cdot \pi \cdot \sin(\theta) d\theta \tag{5}$$

This geometrical corrections allows to derive a relation between the plane scattering rate $N_d(\theta)$ and the spatial scattering rate $N(\theta)$:

$$N(\theta) = 2 \cdot \pi \cdot \sin(\theta) \cdot N d\theta \tag{6}$$

Finally, the corresponding spatial values $N(\theta)$ are calculated (II) and the space corrected values plotted in a diagram (7).

The measuring value pairs $\{\theta/N(\theta)\}$ can be compared with the shape of the theoretical curve of equation:

$$f(\theta) = \frac{A}{\sin^4\left(\frac{\theta - b}{2}\right)} \tag{7}$$

The proportionality factor A represents a vertical shift (at logarithmic scale). The coefficient B is representing a small displacement along the horizontal angular scale.

Now we have for $N_{Au}(15^\circ) = 18.701\,\mathrm{s}^{-1}$ and $N_{Al}(15^\circ) = 3.402\,\mathrm{s}^{-1}$ with $d_{Au} = 2\,\mu\mathrm{m}$, $d_{Al} = 8\,\mu\mathrm{m}$, $c_{Au} \approx c_{Al}$ and $Z_{Au} = 79$, we obtain from equation (3):

$$Z_{Al} = 16.8 \tag{8}$$

and for $N_{Au}(-15^\circ) = 4.011\,\mathrm{s}^{-1}$ and $N_{Al}(-15^\circ) = 0.285\,\mathrm{s}^{-1}$ and rest of the parameters same as before, we get

$$Z_{Al} = 10.5 \tag{9}$$

Taking mean Z_{Al}, we obtain $Z_{Al} = 13.7$ which is close to the actual value of $Z_{Al} = 13$.

The data recorded is tabulated in table (II). The corresponding plot between scattering angle θ and $N(\theta)$ is given in figure (7).

VI. DISCUSSIONS

1. A small inaccuracy of the collimator-slit adjustment or non-centric distribution of the radiation, coming from the preparation in the holder, may cause a shift of the curve along the horizontal axis (angle shift $< 3^\circ$).

2. Due to such effects it is useful to record scattering rates as well in the positive as in the negative angular range, to get information of both branches with respect to an accurate determination of the symmetry-axis displacement.

TABLE I: Measured values for Gold foil and slit width $d = 5\,\mathrm{mm}$

Angle, θ (degrees)	**Angle**, θ (radians)	**Gate time** $t(\theta)$ (s)	**Pulse counts** $n(\theta)$	**Mean Pulse counts** $n_m(\theta)$	**Counting rate** *(directly)* $N_d(\theta)$ (s^{-1})	**Counting rate** *(space corrected)* $N(\theta)$ (s^{-1})
-30	-0.524	900	148 151 157	152	0.169	0.531
-25	-0.436	600	227 241 221	230	0.383	1.016
-20	-0.349	200	572 597 613	594	2.970	6.382
-15	-0.262	100	1181 1126 1143	1150	11.500	18.701
-10	-0.175	100	2797 2771 2884	2817	28.173	30.739
-5	-0.087	100	3558	3558	35.580	19.484
5	0.087	100	2787	2787	27.870	15.262
10	0.175	100	1204 1265 1269	1246	12.460	13.595
15	0.262	100	246 255 239	247	2.467	4.011
20	0.349	200	86 71 68	75	0.375	0.806
25	0.436	600	104 128 113	115	0.192	0.509
30	0.524	900	77 72 69	73	0.081	0.254

TABLE II: Measured values for Aluminium foil and slit width $d = 5\,\mathrm{mm}$

Angle, θ (degrees)	**Angle**, θ (radians)	**Gate time** $t(\theta)$ (s)	**Pulse counts** $n(\theta)$	**Mean Pulse counts** $n_m(\theta)$	**Counting rate** *(directly)* $N_d(\theta)$ (s^{-1})	**Counting rate** *(space corrected)* $N(\theta)$ (s^{-1})
-15	-0.262	1000	2092	2092	2.092	3.402
15	0.262	1000	175	175	0.175	0.285

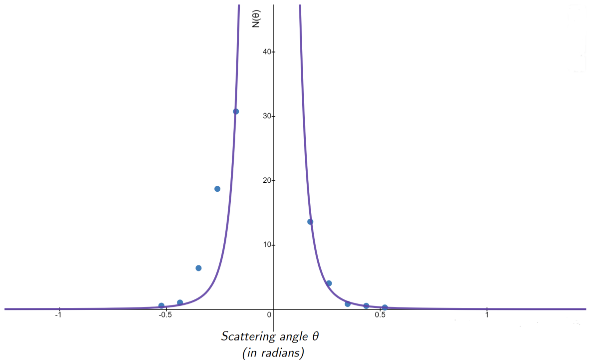

FIG. 7: The plot of scattering angle θ against $N(\theta)$ and the corresponding fitted curve according to equation (1)

VII. PRECAUTIONS

1. The radioactive sources should be held with utmost care.
2. Never touch the gold or aluminium foil.
3. Venting of the chamber after the experiment has to be done very carefully.

VIII. CONCLUSIONS

The results obtained through the experiment were satisfactory and as expected.