Astronomy, Space Science and Astrophysics

Exp.6 Rutherford Scattering

PH520 - Stage 2

Physics Laboratory A

Date: 11th Nov 2019 - 13th Jan 2020

Report Author: Lukasz R Tomaszewski

Lab Partner: Thomas O'Sullivan

Word Count: 2397

Contents

1 Abstract

By scattering α-particles at different it's proved Rutherford's "scattering formula" eq. (1) given an error of θ=$\pm$1.5°. Shown in fig. 5 and fig. 6 a strong correlation within the data points relevant error margins is given between the experimental data and the theoretical data, this was done by valuing the coefficients A and B in eq. (7) to be 0.00035 and 0.01 respectively. The experimental data was also corrected as the experiment measured values in a 2D horizontal plane whereas in fact it is a 3D cone, therefore a correction factor of $\sin(\theta)$ was deduced and multiplied with the experimentally α rate/s. The atomic number of aluminium and eq. (3) proven by finding a strong correlated data angle i.e. -15°and its α-particle Rate/s used in eq. (3) to give a value of 12.88 which is just outside of the $\pm$0.1 error margin as the atomic number of aluminium is 13 [2]. It was also proven that the ratio of Rate/s and the total number of α-particles is physically dimensionless by associating the physical dimension with each parameters SI Units.

2 Introduction

"In 1911, Ernest Rutherford discovered the nucleus of the atom and kick started the age of nuclear physics. Since this, the Thompson model of the atom pioneered the understanding of the atom as it was discovered that the atom composed of very small electrons surrounded by a sea of positive charge to counter the electrons negative charge. Rutherford projected alpha particles at thin metal foils, while observing their deflection he noticed that the highly charged alpha particles went straight through the metal foils, where some scattered up to 180 degrees and a few deflected backwards, thus disproving the Thompson model. [3] [4]

In this experiment, Rutherford's well known scattering experiment will be repeated as to find the following objectives: [3]

- To record the direct count rate N_d of α-particles scattered by a gold foil as a function of the scattering angle θ.
- To correct the count rates measured in one plane for the fact that the foil scatters in a 3D cone.
- To validate "Rutherford's scattering formula".
- To determine the atomic number of aluminium experimentally.

3 Methodology

3.1 Background

Within this experiment α-particles collide with and penetrate a thin gold foil, at small angles a majority of the α-particles scatter less than 1°, at large angles up to 180°only a few particle are scattered, this is called back scattering. With this observation, Rutherford formulated his "scattering formula":

$$N(\theta) = N_0 \, c_f \, d_f \, \frac{Z^2 \, e^4}{(8\pi \, \epsilon_0 \, E_\alpha)^2 \, \sin^4(\theta/2)} \tag{1}$$

With the parameters set as:

N_0 Number of incident α-particles
d_f Foil thickness
E_α Energy of α-particles
ϵ_0 Dielectric constant (table 7)
c_f Atomic concentration of foil
Z Atomic number of the foil
e elementary charge (table 7)

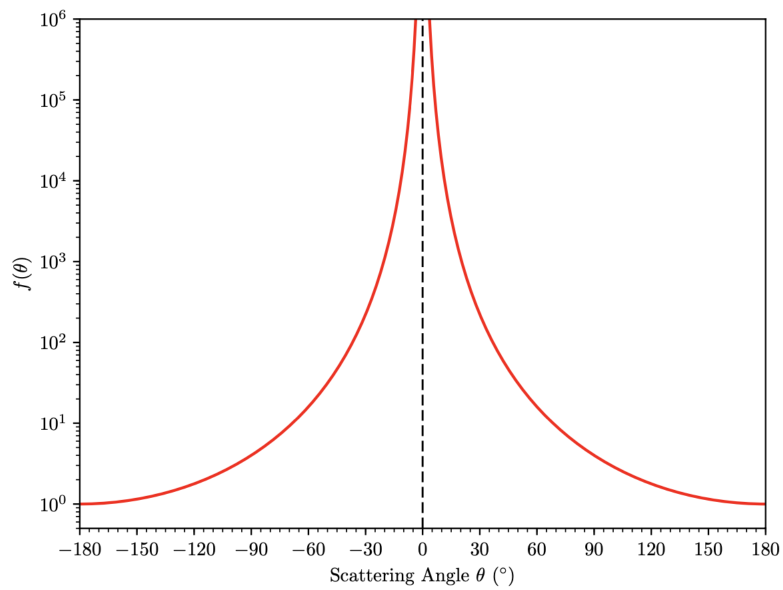


Figure 1: Theoretical scattering rate as a function of angle eq. (2). From [3].

Rutherford's "scattering formula" can be simplified as the coefficients are constant, so the formula equates to the scattering of the scattering of α-particles as a function of angle:

$$f(\theta) = \frac{1}{\sin^4(\theta/2)} \tag{2}$$

As f(θ) tends to infinity as a singularity occurs as the angle approaches very small angles, this can be view by graphical representation in fig. 1. Due to this, the experimental data recorded will only be compared to the theoretical data of angles $|\theta| \leq \pm 5°$, on the other hand its clear that the scattering rate become very small at larger angles therefore a limit is set to $|\theta| \leq \pm 30°$. These limits ensure a significant amount of high quality experimental data so that it can be compared theoretically.

By being able to change the gold foil with aluminium foil and by keeping the induced angle the same the atomic number of aluminium can be computed, by using the scattering angles:

$$\frac{N_{Au}}{N_{A1}} = \frac{c_{Au}\, d_{Au}\, {Z_{Au}}^2}{c_{A1}\, d_{A1}\, {Z_{A1}}^2} \tag{3}$$

With the parameters set as:

N_{Au} Scattering rate of gold
c_{Au} Atomic concentration of gold
d_{Au} Foil thickness of gold
Z_{Au} Atomic number of gold

N_{A1} Scattering rate of aluminium
c_{A1} Atomic concentration of aluminium
d_{A1} Foil thickness of aluminium
Z_{A1} Atomic number of aluminum

3.2 Experimental Setup

3.2.1 Recording the scattering rate as a function of angle

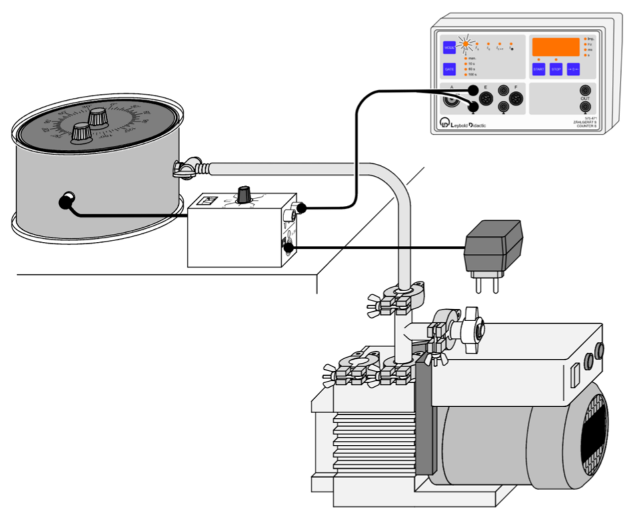
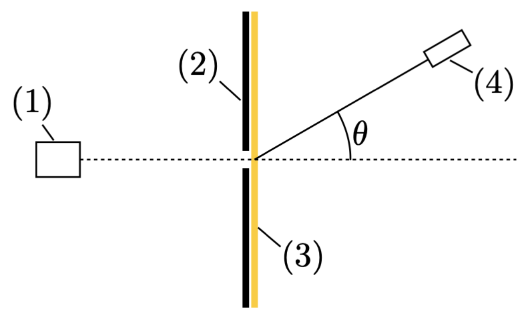


Figure 2: Setup of apparatus. From [3][1].

By setting up the apparatus depicted in fig. 2, the vacuum within the chamber is created by using the vacuum pump to extract the air, thus improving the quality of the experiment so that the α-particles aren't affected by the air molecules when being fired at the gold foil. Inside the chamber the α-particles are fired form an Am-241 source, through a 5mm wide slit in front of the gold foil and thus scattered, by changing the angle of the detector on the other side of the foil, the scattering rate as a function of the angle can be observed. The detector measures how many α-particles it detects and feeds the data through a discriminator preamplifier so that the data can organised and any external "noise" discarded, the quality data shows onto a piece of computer software called CASSY. Within this program the "gate time" can be inputted which collects data per the specified gate time (counts per second) thus collating the results so that the number of αparticles can be divided by the gate time to give rate per second, this allows more control on the quality of the data sourced.



(1) = Am-241 source
(2) = 5mm/1mm slit
(3) = Gold/ Aluminium foil
(4) = Detector

Figure 3: Inside the chamber. From [3][1].

Setting the discriminator preamplifier to -0.2v at the start of the experiment tills the counts per seconds holds steady (falls to zero), this in effect gives a zero point to which the detector collects the data. By turning the angle of the detector by $\pm 5°$shown in fig. 3, the program can start and measurements are taken over every 10 seconds for 60 seconds. This allows the experiment to be unbiased as the time is unchanged. Increasing the angle from $\pm 5°$and recording the amount of scattered α-particles until $\pm 30°$is reached. The total amount of particles are then averaged then divided by the gate time to give α-particle rate per second.

Further exploring this, increasing the gate time to 30 seconds, but instead of keeping the total elapsed time the same, en-devouring to allow more than a total of 100+ particles to be detected over the elapsed time to reduce statistical error when calculating the rate per second.

3.2.2 Measuring the atomic number of Aluminium

By changing the 5mm slit with a 1mm slit (fig. 3) to give a smaller target area for the α-particles to collide with the foil, the foil is also changeable so that measurements for the rate of particles scattered is obtained for both gold and aluminium foils. Instead of utilizing a large difference in angle as before with the limits being $\pm 5° \geq |\theta| \leq \pm 30°$, a suitable angle with a reasonable count rate such as -15°will be used for both types of foils when using the scattering rates of both materials in eq. (3) when calculating the atomic number of aluminium. The measurements can be repeated for other angles such as -10°, -5°and +5°to validate and compare the value of the atomic number of aluminium with each angle.

3.3 Evaluation & Results

3.3.1 Recording the scattering rate as a function of angle

When the α-particles are fired from the Am-241 source and passes through the 1mm/5mm slit the α-particles scatter only in a horizontal plane due to the shape of the slit, whereas in the theoretical data is scattered in a 3D cone as seen in fig. 4. Due to this a mathematical correction must be applied to the experimental data to compare with the theoretical data.

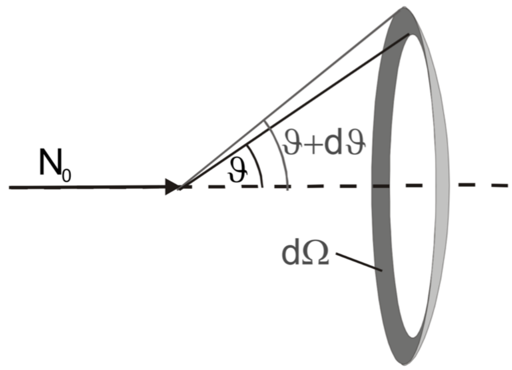


Figure 4: α-particles scattering into a 3D cone. From [3][1].

This correction is calculated as follows;

If the end of the cone in laid flat into rectangular strip (area in grey in fig. 4) and say the diameter equals to 'h' then the area of the end and the circle can be determined;

$$A_A = 2\pi r h \tag{4}$$

$$A_d = \pi r^2 \rightarrow \pi (h/2)^2 \rightarrow \frac{\pi h^2}{4} \tag{5}$$

$$\frac{A_A}{A_d} = \frac{2\pi r h}{(\pi h^2)/4} \rightarrow \frac{8r}{h} \tag{6}$$

By changing this equation into 3D polar coordinates as the *alpha*-particles scatter into a circle, r now becomes $r = \sin\theta$. This correction factor is then multiplied by the experimental data fit the theoretical curve of;

$$f(\theta) = \frac{A}{\sin^4((\theta - B)/2)} \tag{7}$$

Where A and B are coefficients that represents the vertical shift and horizontal drift respectively of the theoretical curve. These coefficients are to be altered to align itself with the experimental data so that a true comparison can be made and any and all visible discrepancies of the experimental data can been recorded.

3.3.2 Determining the atomic number of aluminium

To determine the atomic number of aluminium, rearrange eq. (3) to find Z_{A1};

$$\frac{N_{Au}}{N_{A1}} = \frac{c_{Au}\, d_{Au}\, {Z_{Au}}^2}{c_{A1}\, d_{A1}\, {Z_{A1}}^2} \rightarrow Z_{A1} = \sqrt{\frac{N_{A1}\, c_{Au}\, d_{Au}\, {Z_{Au}}^2}{N_{Au}\, c_{A1}\, d_{A1}}} \tag{8}$$

Z_{Au} is known in table 7, the scattering rates Z_{Au} and Z_{A1} are found in the experimental data then corrected with the correction factor. The atomic concentration needs to be calculated via;

$$c = \frac{MassDensity}{AtomicWeight} \times Avogadro'sConstant \tag{9}$$

Thus filling the parameters with their values will calculate an approximated value for the atomic number of aluminium.

3.4 Error Analysis

The errors throughout this experiment there are 3 main errors to consider and are the same throughout, though using computer software where errors are fairly accurate, it still produces a margin for error though very small.

Angle (θ) =	$\pm 1.5°$
Time (s) =	± 0.1s
Na_1 =	± 1

Table 1: Error Analysis.

Standard Error for section 2.1.1 in [3]:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{10}$$

$$\sigma = 174.88 \tag{11}$$

Standard Error for section 2.1.2 in [3]:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{12}$$

$$\sigma = 3397.22 \tag{13}$$

Standard Error for section 2.2 in [3]:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{14}$$

$$\sigma_{Au} = 2508.17\sigma_{A1} = 1876.23 \tag{15}$$

4 Results & Findings

4.1 Recording scattering rate as a function of angle

When applying the correction factor of $\sin(\theta)$ and determining the theoretical data (eq. (7)), the value for θ is in radians;

Converting angles into radians												
θ	-30	-25	-20	-15	-10	-5	+5	+10	+15	+20	+25	+30
Radians	-0.52	-0.44	-0.35	-0.26	-0.17	-0.09	0.09	0.17	0.26	0.35	0.44	0.52

Table 2: Angles into Radians

By obtaining the experimental results from table 3, the correction factor can be applied and the theoretical data derived from section 3.3. A correlation can be seen with in the limits specified in section 3.1, proving that as θ tends to zero the rate of scattering increases. The theoretical data coefficients in eq. (7) were proven to equal A = 0.00035 and B = 0.01.

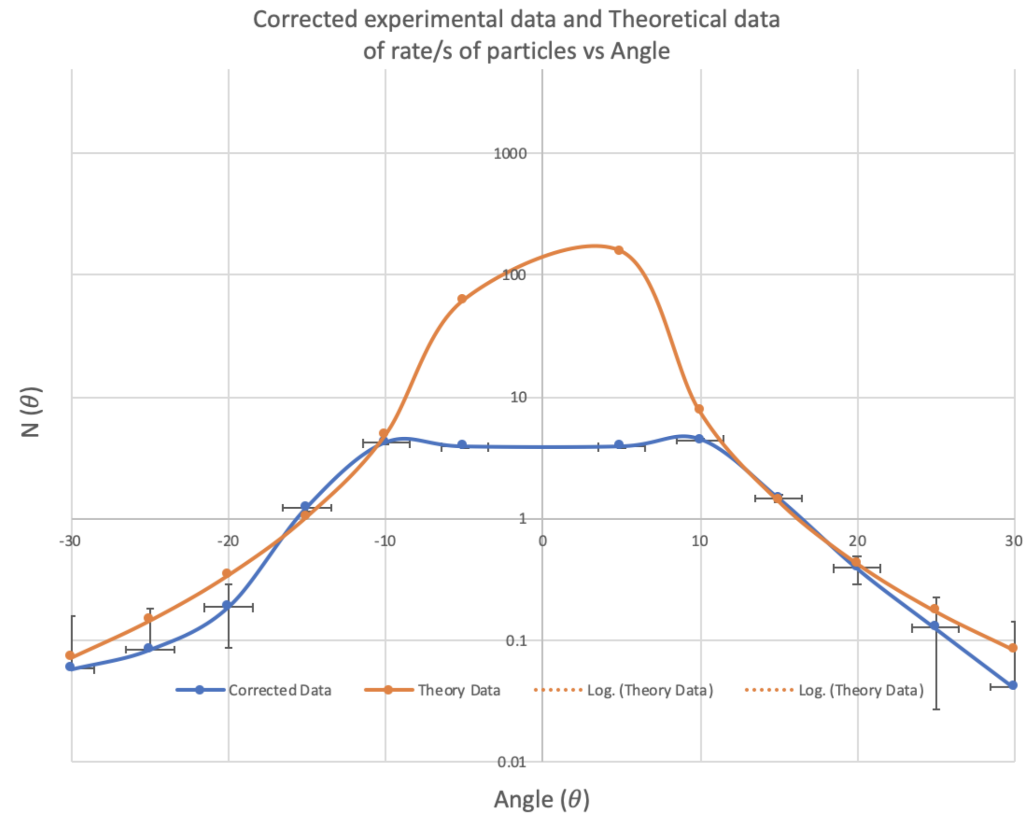


Figure 5: Corrected experimental and theoretical data of $rate/s$ vs angle withing a gate time of 10s over 60s. From (table 3).

Rate of particles entering the chamber within a gate time of 10s over 60s												
θ	-30	-25	-20	-15	-10	-5	+5	+10	+15	+20	+25	+30
Time (s)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
*Avg.Na_1	1.17	2.00	5.50	47.67	241.17	446.17	447.00	257.67	57.00	11.50	3.00	0.08
*$Rate/s$	0.12	0.20	0.55	4.77	24.12	44.62	44.70	25.77	5.70	1.15	0.30	0.08
*$C - Rate/s$	0.06	0.08	0.19	1.23	4.19	3.89	3.90	4.47	1.48	0.39	0.13	0.04
*$T - Rate/s$	0.08	0.15	0.33	0.90	3.51	28.61	1301.50	21.26	2.93	0.79	0.30	0.14

*Avg.Na_1 = Average number of particle in time (s).
*$Rate/s$ = Rate of particles per second.
*$C - Rate/s$ = Corrected rate of particles per second.
*$T - Rate/s$ = Theoretical rate of particles per second.

Table 3: Rate of particles within a gate time of 10s over 60s

From fig. 5 the experimental data correlates with the theoretical data, it can be seen that between +20°and +10°both sets of data match, with some variations in the comparison in the negative axis. But apart from -20°all the experimental data points are within their individual error margin with the theoretical data. These results were attained by keeping the overall time fixed with fluctuating amount of particles, on the other hand while making sure 100+ α-particles were detected and total time is the variable.

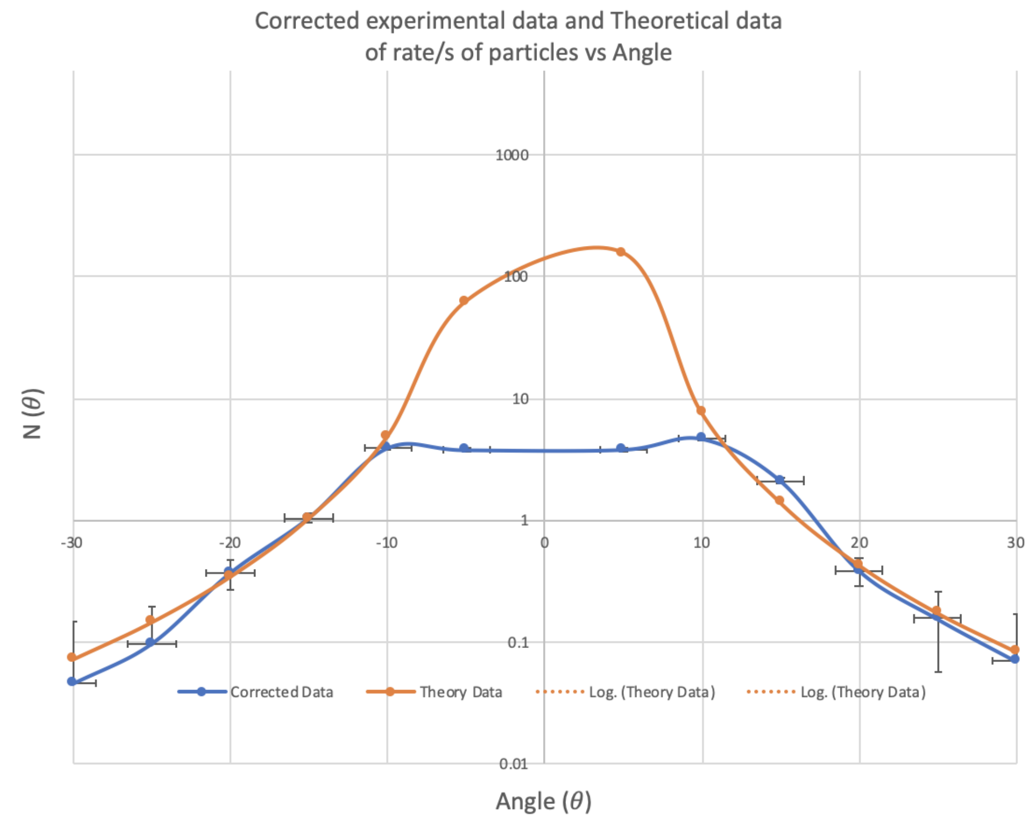


Figure 6: Corrected experimental and theoretical data of $rate/s$ vs angle withing a gate time of 40s ensuring 100+ particles. From (table 4

Rate of particles entering the chamber within a gate time of 40s ensuring 100+ particles												
θ	-30	-25	-20	-15	-10	-5	+5	+10	+15	+20	+25	+30
Time (s)	1120.8	480.3	200.1	200.1	200.1	200.1	200.1	200.1	200.1	200.1	280.2	840.6
*Total Na_1	103	111	217	812	4518	8703	8762	5402	1648	229	104	118
*$Rate/s$	0.09	0.23	1.09	4.060	22.59	43.52	43.81	27.01	8.24	1.15	0.37	0.14
*$C - Rate/s$	0.05	0.10	0.37	1.05	3.92	3.79	3.82	4.69	2.13	0.39	0.16	0.07
*$T - Rate/s$	0.08	0.15	0.33	0.90	3.51	28.61	1301.50	21.26	2.93	0.79	0.30	0.14

*Avg.Na_1 = Average number of particle in time (s).
*$Rate/s$ = Rate of particles per second.
*$C - Rate/s$ = Corrected rate of particles per second.
*$T - Rate/s$ = Theoretical rate of particles per second.

Table 4: Rate of particles within a gate time of 40s ensuring 100+ particles

By allowing at least 100+ α-particles to be detected and allowing the total time to fluctuate the correlation in fig. 6 the mirror image to fig. 6. While the negative axis shows a strong relationship between the angles -20°to -10°, the positive doesn't show the same relationship as in fig. 5 instead a relationship between +20°to +30°emerges.

This part of the experiment shows more correlation to the theoretical data than in fig. 5, this is mostly due to allowing more particles enter the chamber and be scattered instead of the total time being fixed. The gate time was also increased to 40 seconds instead of 10 seconds to allow more α-particle to be detected, by increasing the gate time also increase the average amount of α-particles though irrelevant as the average number of α-particles are divided by their gate time, giving rate per second.

4.2 Measuring the atomic number of Aluminium

Rate of particles within a gate time of 30s of both Gold & Aluminium foils									
Material	Aluminium Foil				Gold Foil				
θ	-15	-10	-5	+5	-15	-10	-5	+5	Error
Time (s)	600.2	300.2	300.2	300.2	300.2	300.2	300.2	300.2	$\pm 0.1s$
*Total Na_1	13	29	816	5246	70	338	1872	4160	± 1.0
*$Rate/s$	0.022	0.097	2.720	17.487	0.233	1.127	6.240	13.867	$\pm 1.0s$
*$C - Rate/s$	0.036	0.106	1.489	9.576	0.379	1.229	3.417	7.594	$\pm 1.0s$

*Total Na_1 = Total number of particles in the chamber in time (s).
*$Rate/s$ = Rate of particles entering the chamber per second.
*$C - Rate/s$ = Corrected rate of particles entering the chamber per second.

Table 5: Rate of particles on Gold & Aluminium foils

By observing the difference of α-particle detected through the aluminium foil the at angles -15°and -10°are significantly less than its golden counter-part. This is due to the fact the larger the angle the closer the α-particle gets to striking the aluminium nuclei, which has happened here. This observation can make use of using the scattering angle to determine the materials nuclei diameter.

There are still two parameter that need to be calculated, the atomic concentration of the gold and aluminium foils, using [2]:

$$c = \frac{Massdensity}{AtomicWeight} \times Avogadro'sConstant \tag{16}$$

$Md_{Au} = 0.193\ g/m^3$
$Aw_{Au} = 196.966569$ kg
$Md_{A1} = 0.027\ g/m^3$

Avogadros Constant $= 6.022_{x10}{}^{23}\ mol^{-1}$
$Aw_{A1} = 26.9815386$

Gold:

$$c = \frac{0.193}{196.966569} \times 6.022_{x10}{}^{23} = 5.9_{x10}{}^{20} mol/m^3 \tag{17}$$

Aluminium:

$$c = \frac{0.0270}{26.9815386} \times 6.022_{x10}{}^{23} = 6.02_{x10}{}^{20} mol/m^3 \tag{18}$$

Atomic number of Aluminum:

$$Z_{A1} = \sqrt{\frac{N_{A1}\, c_{Au}\, d_{Au}\, {Z_{Au}}^2}{N_{Au}\, c_{A1}\, d_{A1}}} \tag{19}$$

With the parameters set as:

N_{Au} Scattering rate of gold = (table 5)
c_{Au} Atomic concentration of gold = $5.9_{10}{}^{20}$ mol/m^3
d_{Au} Foil thickness of gold = $2_{x10}{}^{-6}$m [3]
Z_{Au} Atomic number of gold = 79 (table 7)

N_{A1} Scattering rate of aluminium = (table 5)
c_{A1} Atomic concentration of aluminium = $6.02_{10}{}^{20}$ mol/m^3
d_{A1} Foil thickness of aluminium = $7_{x10}{}^{-6}$m [3]
Z_{A1} Atomic number of aluminum = ?

By applying the corrected scattering rates of the Aluminium and Gold foils to eq. (19) we get:

$$Z_{Au}(\theta = -15) = \sqrt{\frac{0.036 \times 5.9_{\times 10^{20}} \times 2_{\times 10^{-6}} \times 79^2}{0.379 \times 6.02_{\times 10^{20}} \times 7_{\times 10^{-6}}}} = 12.88 \tag{20}$$

$$Z_{Au}(\theta = -10) = \sqrt{\frac{0.106 \times 5.9_{\times 10^{20}} \times 2_{\times 10^{-6}} \times 79^2}{1.229 \times 6.02_{\times 10^{20}} \times 7_{\times 10^{-6}}}} = 12.28 \tag{21}$$

$$Z_{Au}(\theta = -5) = \sqrt{\frac{1.489 \times 5.9_{\times 10^{20}} \times 2_{\times 10^{-6}} \times 79^2}{3.417 \times 6.02_{\times 10^{20}} \times 7_{\times 10^{-6}}}} = 27.60 \tag{22}$$

$$Z_{Au}(\theta = +5) = \sqrt{\frac{9.576 \times 5.9_{\times 10^{20}} \times 2_{\times 10^{-6}} \times 79^2}{7.594 \times 6.02_{\times 10^{20}} \times 7_{\times 10^{-6}}}} = 46.94 \tag{23}$$

The atomic number of Aluminium had the value 13 [2], as can been seen for the larger angles -15°and -10°the values ascertained by eq. (19) are fairly accurate more so for -15°as it had a stable α-particle count but for the smaller angle -5°and +5°as hypothesised in section 3.1, 0°tends to infinity due to a singularity occurring.

4.3 Question

The question in [3] states;

"In eq. (1) the ratio $\frac{N(\theta)}{N_0}$ should be dimensionless; show this?"

By utilizing each parameters individual SI units, their dimensions can be sourced. Simplifying Rutherford scattering formula eq. (1) into eq. (26) by removing all the constant with no SI units. The dimensions for each associated SI unit is sourced [2] and shown in table 6.

$$N(\theta) = N_0\, c_f\, d_f\, \frac{Z^2\, e^4}{(8\pi\, \epsilon_0\, E_\alpha)^2\, \sin^4(\theta/2)} \tag{24}$$

$$\frac{N\theta}{N_0} = \frac{Z^2\, C_f\, d_f\, e^4}{(8\pi\, \epsilon_0\, E_\alpha)^2} \tag{25}$$

$$\frac{N\theta}{N_0} = \frac{C_f\, d_f\, e^4}{\epsilon_0^2\, E_\alpha^2} \tag{26}$$

Nomenclature;

Symbol	SI Unit	Dimension
C_f	M^{-3}	L^{-3}
d_f	M	L
e	C	IT
e^4	C^4	I^4T^4
ϵ_0	C^2/NM^2	$(IT)^2/MLT^{-2}L^2$
ϵ_0^2	C^4/N^2M^4	$I^4T^4/M^2L^2T^{-4}L^4$
E_α	J	ML^2T^{-2}
E_α^2	J^2	$M^2L^4T^{-4}$

Table 6: Dimensions Nomenclature

Thus by trading the SI units for the associated dimensions in eq. (26), the dimensions cancel out and show that the ratio is truly dimensionless.

$$\frac{N\theta}{N_0} = \frac{(L^{-3})(L)(I^4T^4)}{(I^4T^4/M^2L^2T^{-4}L^4)(M^2L^4T^{-4})} = \frac{L^{-2}I^4T^4}{(I^4T^4M^{-2}L^{-2}T^4L^{-4})(M^2L^4T^{-4})} \tag{27}$$

$$\frac{N\theta}{N_0} = \frac{(L^{-2}I^4T^4)(T^4L^4M^2)}{(I^4T^4L^{-2}T^4)(M^2L^4)} = \frac{T^8I^4L^2M^2}{T^8I^4L^2M^2} = 0 \tag{28}$$

5 Discussion

The only variable error in this experiment was affecting the vacuum or detector, though these were prevented by not moving the detector only when changing the angle and not moving or removing the lid/ pipes of the vacuum chamber the small possibility of error could be to blame for the deviation of results between the experimental and theoretical data. This experiment was completed in 3 separate 2hr intervals thus the vacuum was destroyed and made live twice as well as the detector could have been hit thus affected its performance, this is taken into account as an error that affected the results as the experiments apparatus was not fair, this could've been avoided by completing the entire experiment in one session, thus not affecting or changing the apparatus.

6 Conclusion

Rutherford's scattering formula was proved as it was compared to physically collected experimental data which is corrected to account for the 3-dimensional cone scattering of the α-particles. fig. 6 shows a strong correlation as a total of 100+ α-particles were detected giving stronger quality results. But in both fig. 5 and fig. 6 shows a relationship between both sets of data at ±15°clearly indicates an angle where reasonable results occur, this observation foreshadowed using 15°to determine the atomic number of aluminium.

By determining a positive relationship with the experimental and theoretical data with the angle -15°, this angle was used as the reference point for which its rate/s was used to accurately prove eq. (3). Not only prove eq. (3) but prove the hypothesis section 3.1, the closer $\theta = 0$, a singularity occurs and the results become unstable. Therefore the angles -5°and +5°were dismissed, with -10°forming a value of 12 instead of -15°giving 13, which is the atomic number of aluminium [2]. While recording these results it was obvious to see by the difference of the count rate of α-particles per angle between both the aluminium and gold foils that the size of the nucleus can be determined by using the scattering angle.

7 Appendix

Parameter	Symbol	Value
Charge of an Electron	e	$1.6021x10^{-19}$
Permittivity of free space	e_0	8.8524 Fm^{-1}
Atomic number of Gold	Z_Au	79

Table 7: Useful Constants.[3]

Rate/s of Avg.Na_1 within a gate time of 10s over 60s								
θ	10s	20s	30s	40s	50s	60s	Avg.Na_1	$Rate/s$
-30	1	1	0	2	1	2	1.167	0.117
-25	0	2	0	4	4	2	2.000	0.200
-20	10	5	7	5	2	4	5.500	0.550
-15	44	43	47	59	48	45	47.670	4.767
-10	241	224	243	240	254	245	241.167	24.117
+10	267	236	235	282	275	251	257.670	25.767
+15	57	76	51	46	59	53	57.000	5.700
+20	16	7	10	17	9	10	11.500	1.150
+25	3	4	4	2	3	2	3.000	0.300
+30	1	2	1	1	0	0	0.834	0.083

Table 8: Table showing $Rate/s$ of particles with a gate time of 10s over 60s.

-5° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	1721	43.025
80.0	1801	45.025
120.1	1693	42.325
160.1	1769	42.975
200.1	1719	42.025
200.1	**8703**	**43.515**

-10° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	924	23.100
80.0	905	22.625
120.1	898	22.450
160.1	878	21.950
200.1	913	22.825
200.1	**4518**	**22.590**

-15° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	157	3.925
80.0	169	4.225
120.1	165	4.125
160.1	156	3.900
200.1	165	4.125
200.1	**812**	**4.060**

-20° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	46	1.150
80.0	44	1.100
120.1	42	1.050
160.1	38	0.950
200.1	47	1.175
200.1	**217**	**1.085**

-25° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	14	0.350
80.0	5	0.125
120.1	8	0.200
160.1	11	0.275
200.1	3	0.075
240.1	8	0.200
280.2	10	0.250
320.2	13	0.325
360.2	15	0.375
400.3	7	0.175
440.3	6	0.150
480.3	11	0.275
480.3	**111**	**0.231**

-30° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	3	0.075
80.0	4	0.100
120.1	7	0.175
160.1	5	0.125
200.1	3	0.075
240.1	3	0.075
280.2	3	0.075
320.2	3	0.075
360.2	5	0.125
400.3	7	0.175
440.3	2	0.050
480.3	5	0.125
520.4	4	0.100
560.4	4	0.100
600.4	6	0.150
640.5	1	0.025
680.5	5	0.125
720.5	4	0.100
760.5	4	0.100
800.6	2	0.050
840.6	7	0.175
880.6	2	0.050
920.6	3	0.075
960.7	3	0.075
1000.7	2	0.050
1040.7	2	0.050
1080.7	2	0.050
1120.7	2	0.050
1120.7	**8703**	**0.092**

Table 9: Negative angle table showing $Rate/s$ of particles with a gate time of 40s allowing 100+ particles.

+5° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	1718	42.950
80.0	1715	42.875
120.1	1754	43.850
160.1	1799	44.975
200.1	1776	44.400
200.1	**8772**	**43.810**

+10° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	1063	26.575
80.0	1118	27.950
120.1	1007	25.175
160.1	1068	26.700
200.1	1146	28.650
200.1	**5402**	**27.010**

+15° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	332	8.300
80.0	319	7.975
120.1	344	8.600
160.1	324	8.100
200.1	329	8.225
200.1	**1648**	**8.240**

+20° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	46	1.150
80.0	52	1.300
120.1	33	0.825
160.1	46	1.150
200.1	52	1.300
200.1	**229**	**1.145**

+25° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	9	0.225
80.0	18	0.450
120.1	12	0.300
160.1	16	0.400
200.1	13	0.325
240.1	19	0.475
280.2	17	0.425
280.2	**104**	**0.371**

+30° Deflection		
Time (s)	Total Na_1	$Rate/s$
40.0	4	0.100
80.0	5	0.125
120.1	5	0.125
160.1	4	0.100
200.1	2	0.050
240.1	5	0.125
280.2	3	0.075
320.2	3	0.075
360.2	9	0.225
400.3	6	0.150
440.3	4	0.100
480.3	7	0.175
520.4	2	0.050
560.4	2	0.050
600.4	5	0.125
640.5	2	0.050
680.5	8	0.125
720.5	4	0.050
760.5	8	0.200
800.6	5	0.125
840.6	25	0.625
840.6	**118**	**0.141**

Table 10: Positive angle table showing $Rate/s$ of particles with a gate time of 40s allowing 100+ particles.

-5° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	72	2.400
60.0	80	2.667
90.1	74	2.467
120.1	92	3.067
150.1	83	2.767
180.1	84	2.800
210.2	82	2.733
240.2	87	2.900
270.2	73	2.433
300.2	89	2.967
300.2	**816**	**2.720**

-15° Deflection		
Time (s)	Total Na_1	$Rate/s$
60.0	1	0.017
120.0	2	0.033
180.1	2	0.033
240.1	3	0.050
300.1	1	0.017
360.1	2	0.033
420.1	1	0.017
480.1	1	0.017
540.2	0	0.000
600.2	0	0.000
600.2	**13**	**0.022**

-10° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	4	0.133
60.0	1	0.033
90.1	2	0.067
120.1	4	0.133
150.1	4	0.133
180.1	1	0.033
210.2	5	0.167
240.2	0	0.000
270.2	3	0.100
300.2	5	0.167
300.2	**29**	**0.097**

+5° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	528	17.600
60.0	533	17.767
90.1	544	18.167
120.1	545	18.400
150.1	552	15.967
180.1	479	15.967
210.2	511	17.033
240.2	504	16.800
270.2	520	17.333
300.2	530	17.667
300.2	**5246**	**17.487**

Table 11: $Rate/s$ of particles upon Aluminium foil.

-5° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	173	5.767
60.0	167	5.567
90.1	186	6.200
120.1	179	5.967
150.1	204	6.800
180.1	201	6.700
210.2	186	6.200
240.2	196	6.533
270.2	189	6.300
300.2	191	6.3675
300.2	**1872**	**6.240**

-15° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	10	0.333
60.0	12	0.400
90.1	6	0.200
120.1	4	0.133
150.1	5	0.167
180.1	4	0.133
210.2	11	0.367
240.2	3	0.100
270.2	9	0.300
300.2	6	0.200
300.2	**70**	**0.233**

-10° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	43	1.433
60.0	33	1.100
90.1	39	1.300
120.1	35	1.167
150.1	39	1.300
180.1	29	0.967
210.2	36	1.200
240.2	25	0.833
270.2	36	1.200
300.2	23	0.767
300.2	**338**	**1.127**

+5° Deflection		
Time (s)	Total Na_1	$Rate/s$
30.0	419	13.967
60.0	370	12.333
90.1	393	13.100
120.1	413	13.767
150.1	397	13.233
180.1	425	14.167
210.2	419	13.967
240.2	419	13.967
270.2	472	15.733
300.2	433	43314.
300.2	**4160**	**13.867**

Table 12: $Rate/s$ of particles upon Gold foil.

References

[1] Leybold Didactic. 'rutherford scattering: measuring the scattering rate as a function of the scattering angle and the atomic number'. Leybold Physics Leaflet P6.5.6.2.1. Leybold Didactic GMBH, Germany.

[2] W. M. Haynes. Crc handbook of chemistry and physics: a ready-reference book of chemical and physical data 94th edition. Boca Raton, Florida: CRC Press 2013, 2013-2014. ISBN: 9781466571143.

[3] E. Pugh. Exp.6 rutherford scattering. University of Kent Moodle 2019, September 2018. PH520 Physics Labs A.

[4] L. R. Tomaszewski. Exp.6 lab book. University of Kent, November 2019. PH520 Physics Labs A.