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Abstract

We investigated the Rutherford theorem that atoms consist of the heavy nucleus in the middle and light electrons around the nucleus. We passed the alpha particles through the thin gold foil and measured how many alpha particles scattered on the different angles. From this data, we calculated the count rate, and plotted that count rate versus the scattering angles. We compared how our data fits the predicted Rutherford scattering formula. Most of our data fit very well on the graph, therefore the Rutherford atom structure theorem was proved.

Introduction

In early 20 century, many scientists were working towards exploring the structure of an atom. J.J. Thompson, physicist from England, discovered the electron [1].Since then scientists were thinking of an atom as a “plum pudding” model: uniform sphere of positively charged “pudding” with negatively charged electrons being inside that “pudding”. Such a model gives explanation to the presence of electrons that J.J. Thompson discovered as well as idea that atom itself is neutral.

As we know nowadays, the atom actually has positively charged nucleus in the middle and electrons are orbiting around the nucleus. The nucleus is bigger than electron and depending on the material; nucleus often has more charge than the electron has. Rutherford experiment is the key to proving that “plum pudding” model is wrong and that there is charge concentrated nucleus in the middle and electrons are around it.

The idea of the experiment is to pass alpha particles through the thin foil and study their scattering. Alpha particles are positively charged particles and they are identical to the helium nuclei, so alpha particles are much heavier than electrons. The theory of the experiment is that if the atom is like a “plum pudding” then when the alpha particle goes through the foil it would be scattered only to a very small angles (super small). This is because electrons are too small to affect the movement of the particle (big particle would kick it off the way) and the electric field from the neutral atom would not affect the positive particle as well.

If there we consider atom as a nucleus in the middle and electrons around it, then nucleus has sufficient amount of charge to create electric field around it strong enough to deflect alpha particles. Some particles will go gar from nucleus and would not be affected by the electric field of the nucleus. The particles that will go near nucleus will be deflected to various angles, depending on how close the particle goes to the nucleus.

In this experiment, we count how many particles deflect to specific angles. Rutherford calculated the angular distribution of the scattering rate. The result is “Rutherford scattering formula” [2], which is shown in figure 1. In the same figure there is also shown what each letter of the equation represents.

$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 KE^2 \sin^4(\theta/2)} \qquad \begin{aligned} N_i &= \textit{number of incident alpha particles} \\ n &= \textit{atoms per unit volume in target} \\ L &= \textit{thickness of target} \\ Z &= \textit{atomic number of target} \\ e &= \textit{electron charge} \\ k &= \textit{Coulomb's constant} \\ r &= \textit{target-to-detector distance} \\ KE &= \textit{kinetic energy of alpha} \\ \theta &= \textit{scattering angle} \end{aligned} \tag{1}$$

In this Eq.1, we can see how various parameters affect the count rate. If I use more dense material, there is a higher probability that particle will go near nucleus, so more particles would be deflected. Materials with bigger atomic number have bigger nucleus, so it has a stronger electric field around it as well as there is a bigger probability that particle will pass near that bigger nucleus. If the foil is thicker, then there is more chance that particle will hit the nucleus or pass near it as it goes through it, so there will be more particles deflected. However, if we release the particles with the higher kinetic energy, they will be less affected by the electric field of the nucleus, so the deflection angle of the particles will be smaller. The most important parameter for this experiment: as we increase the angle, the count rate decreases fast, because sin(θ/2) is to the fourth power.

We plot our data of the count rate versus the scattering angle and we compare it to the Rutherford scattering formula graph shape, to prove that there is indeed the total positive charge is concentrated in a nucleus and electrons are around it.

Procedure

To perform the Rutherford scattering experiment, I used Leybold 559.56 Rutherford scattering chamber, Leybold 575.471 counter, Leybold 559.931 discriminator preamplifier, Terranova 906A convection gauge controller (pressure reader) and Ulvac G-20DA rotary two-stage vacuum pump equipment. I used BNC cables to connect the equipment. The equipment should be setup and connected with cables as shown in the Figure 1 [3].

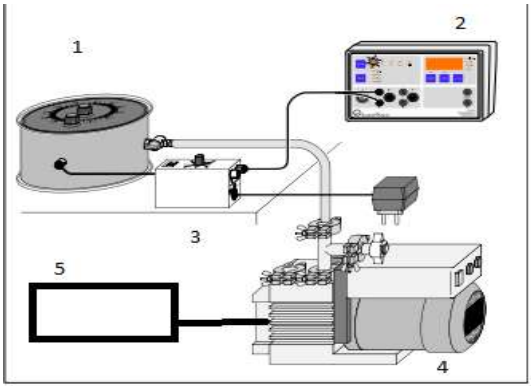

Figure 1: The setup for the Rutherford experiment. 1-scattering chamber, 2-counter,3-discriminator preamplifier, 4-vacuum pump, 5-Pressure controller

The scattering chamber consists of the following components: gold foil in frame, 5-mm slit aperture, BNC cables and the black cloth to cover the scattering chamber. For the source, I used Leybold 559.82 Am-241 preparation. Figure 2 represents the construction and components of the scattering chamber [3].

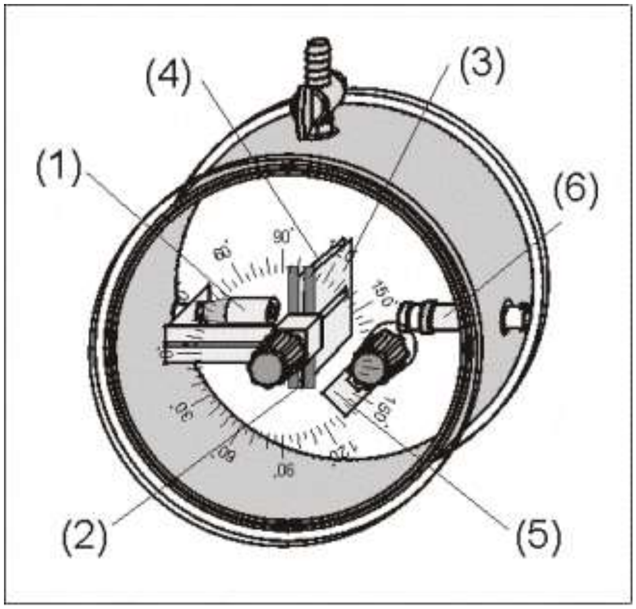

Figure 2: The diagram of the scattering chamber where: 1-Am241 preparation source, 2-holder, 3-gold foil in frame, 4-5mm slit aperture, 5-swivel arm, 6-semiconductor particle detector.

As we can observe on the Figure 2, the gold foil is right in front of the slit aperture. To make any adjustments in the chamber, the lid has to be removed. The plastic frame with the gold foil and the slit aperture should be placed on top of each other, so that the gold foil is in the middle. The preparation source should be fully insert in the socket so it stays stable. I had to make sure that the preparation source is pointing right towards the slit, so I get the precise results. After all the chamber setup is done, I just close the lid tight, making sure that positioning hole lines up with the pin of the wall.

When all the equipment setup is done and cables connected, I can setup the vacuum system. To evacuate the vacuum chamber I had to follow the following steps in order.

1. I closed the vent valve (not extremely tight, but tight enough).
2. I powered the pressure controller where I read the pressure around 700 Torr.
3. I powered the vacuum pump. The pressure started to drop. I had to wait for about 10 minutes for the pressure to drop below 100 mTorr, which meant that vacuum chamber is ready. My pressure reading was 11 Torr.

The vacuum pump keeps running throughout the whole experiment. After evacuating the vacuum chamber, I had to adjust the discriminator level. On the discriminator, there is the potentiometer knob that controls the discriminator level. When the level is set to zero (fully counterclockwise), the discriminator does not discriminate anything and all the noise signal passes through. To find the right level I had to find the average of the following two positions. Position 1: With the holder moved to the 30° angle, I turn the knob by a quarter. After that, I adjust it both directions to find the position at which the noise count is zero. Position 1 that I got was -0.3 V. Position 2: With the holder moved to the 0° angle, I observed that counter was reading 10-100 counts per second. I turned increased the discriminator level until the count rate starts to drop. Position 2 that I got was -0.9 V. The average of these two knob positions is the discriminator level I needed for this experiment, to get data that will be easy and comfortable to work with. Therefore, I was working with the discriminator level set to -0.6 V. At this point, I was done setting up the experiment.

To start counting I press start button and to reset counting I press ->0<- button. To change gate time I used GATE button. I set the $N_{A,E}$ pulse counting mode by using the MODE button. To set high gate times (like 600 and 900) I had to press GATE and MODE buttons simultaneously and then choose the desired gate time. I took the data for the angles from 5° to 30°. For the angles from 5° to 15°, I used 100s gate time, and increased the angles by the increments of 2.5°. For the angles 17.5° and 20°, I used 200s gate time, for 25° - 600s and for 30° - 900s.

I had to adjust the gate time for different angles because that it makes data gathering more convenient. For the bigger angles, I had to put much longer gate time, so I get a bigger number of counts that allows me to get a better accuracy in my calculations. I took data for both positive and negative angles. The main reason for this is that even if the source is not perfectly aligned with the slit, we can clearly see the shift on the graph. When I was taking data, I had to cover the chamber with the black cloth, so the light in the room does not affect the readings, because the detector in sensitive from light.

After I was done taking data, I had to follow the following steps (in order), to bring the chamber back to atmospheric pressure:

1. I turned off the vacuum pump.
2. Immediately after I opened the vent valve until I hear a rushing of air. I observed that pressure reading started to drop quickly.
3. I waited until the pressure reading reached about 700 Torr.

Results

The raw data I gathered for this experiment consists of the angles, gate times and pulse counts. As I increase the angle, I get smaller pulse counts because less particles are scattered to the bigger angles. The uncertainty for the all angles is 0.5°. The uncertainties for the pulse count are determined by the square-root rule [4] because I am just counting the pulses.

The numbers for the count rate for the positive angles were always bigger than count rates for the negative angles. This indicates that there was a slight shift, about 2-3 degrees, in the setup – the preparation was not aligned with the slit. Such a shift is very small and hard to avoid.

Since I have different gate times for different angles, I need to calculate count rate, so I can see a clear relationship between the count rate and the angle. To do so I simply divide the pulse count by the corresponding gate times, and I get the count rate (number of pulses per one second) – $N_d(\theta)$. For the small angles the scattering rate does not differ much. That happens because there are limitations for the small angles. According to the Rutherford formula Eq.1, as angle goes to zero, the count rate goes to infinity. Such a result is physically impossible. So when we have very small angles we do not get as high count rates as we expect, because of that limitation.

The count rates that I measured are in the plane geometry but Rutherford's formula is related the three-dimensional geometry. To convert my count rate $N_d(\theta)$ to the spatial scattering rate $N(\theta)$ I used the Eq.2, which relates two different geometries [3].

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

To get the uncertainty for the spatial scattering rate, I propagate the uncertainty of the count rate and the angle according to the uncertainty propagation rule. Since count rate depends on the angle, these two quantities are not independent. Such an observation means that I cannot add their relative uncertainties in quadrature, which increases the final uncertainty of the spatial scattering rate. It is important to mention, that even though the angle data I took is in degrees, I do all my calculations in radians.

Now I have variables I needed to compare my data with the Rutherford formula (Eq.1). The best way to compare result is graphing. If my data fits the Rutherford formula graph, then my experimental data prove the Rutherford calculations. Rutherford formula has many constants that do not affect the shape of the graph so we can combine then in parameter A. This parameter represents a vertical shift of the graph. In addition, since I can already see that I have some misalignments in the setup, I introduce parameter B that represents the horizontal shift on the angular scale. After putting the parameters in the Rutherford formula, I get Eq.3, which is a function that Rutherford formula represents [3].

$$f(\theta) = \frac{A}{\cdot \sin^4(\frac{\theta - B}{2})} \tag{3}$$

I plot my data of spatial scattering rate versus the angles (in radians) and I fit it to the Eq.3 function. On the graph, that is shown in Figure 4, we can clearly see that the data fort the first few small angles does not fit the Rutherford function graph. For that reason, I did the fit only for the angles starting from 10°, so we can see how good all the rest data fits on the Rutherford function graph. To do so I used "cursor fit" in IgorPro software.

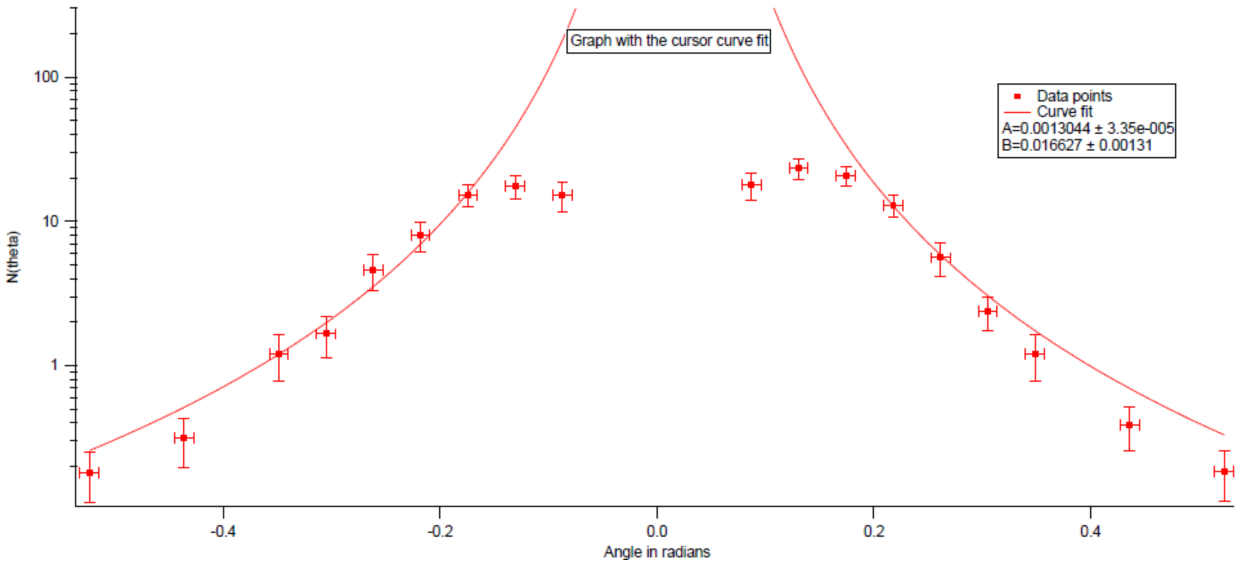

Figure 4: Rutherford function "cursor" fit over my data.

To make my graph look nice I had to do several adjustments. I set the count rate scale to logarithmic scale. As well as I had to play with A and B constant, so I can get the best fit, and these constant are very sensitive. My constants are shown in the legend of the graph in the Figure 4.

Conclusion

My data fits the graph I expect it to fit pretty well, except the small angles. The reason for the small angles data to off the expected fit is the limitation discussed in the result section. As we look at the graph, we can see that the uncertainty is relatively big for the data points. One of main reasons is the propagation of uncertainty in Eq.2, because the quantities from which the uncertainty propagates are not independent, so I cannot add them in quadrature. Another reason for a big uncertainty, especially on the big angles, is the small pulse count number. The more numbers we count, the smaller the uncertainty is. However, so few particles deflect on the big angle, that it would take us a very long time to get a big count number.

Rutherford did his calculation with the idea that atom consists of a heavy nucleus in the middle and light electrons are orbiting around it [3]. The fact that my experimental data fit the Rutherford function formula proves that his calculations are right and are consistent with the nature of atom structure. That means that my experiment proves Rutherford's theory of the atom structure.

References

[1] J.J. Thompson, Philosophical Magazine, **44**, 293 (1897).

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[4] J. R. Taylor, *An Introduction to Error Analysis, 2e*, (University Science Books, 1997).