

IIA4

Modul Atomic/Nuclear Physics

Rutherford Scattering

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1.1 Preliminary Questions

- Describe the scattering experiment of Rutherford in your own words.
- In this experiment, a so-called discriminator is used. What is it and why is it necessary?
- Why is the experiment done in a vacuum chamber and not in air?
- How does an oscilloscope function? What are its general settings?

1.2 Theory

1.2.1 Development of the Atomic Model

The first model of the atom was from the Greek philosophers *Leucippus* (around 440 BC) and his student *Democritus* (460-370 BC). They believed that all matter is made of small, indivisible particles. These particles were called atoms after the Greek word for indivisible. Between these atoms, in their view, only empty space is found. Therefore, all macroscopic bodies and their similar or different properties would, by their arrangement, be determined.

However, throughout the Middle Ages and up to the beginning of the modern era, this idea was again discarded because it was too materialistic and also disagreed with the doctrine of creation by the church.

From about the 17th century, the atomic model became more important again. Various chemists recognized by accurate weighing of reactants and reaction products, that integer ratios resulted in their masses. These mass ratios were described by molecules from individual atoms. Further evidence came from the development of the kinetic theory of gases by *Rudolf Julius Clausius* (1822-1888), *James Clerk Maxwell* (1831-1879), and *Ludwig Boltzmann* (1844-1906). They could attribute macroscopic properties of gases such as pressure, temperature and specific to heat movement and bumps of gas atoms.

At the end of the 19th century came the idea that the matter consists of atoms constructed, finally prevailed. Various experiments recorded a more accurate image of these atoms. Studies on the conductivity of different liquids, experiments with gas discharges and the discovery of radioactivity showed that in atoms, positive and negative charge carriers must be present. Thus, the atom was no longer "indivisible", but consisted of charged components. Mass spectrometry experiments showed that the positively charged components of the atom own a much larger mass than the negatively charged components. Also, thermodynamic experiments gave information about the atomic radius.

However, on one point, there was still uncertainty: how were the positive and negative charges distributed in the atom? The favored model at the time was the so-called *Raisin cake model*. It is named after its inventor *Joseph John Thomson* (1856-1940), also called *Thomson's Atomic Model*. It states that the positive and negative charges are evenly distributed in the atom. Therefore, outwardly, the atom seems electrically neutral.

1.2.2 Scattering Experiments

The question of the charge distribution in the atom could finally be clarified in 1911 by *Ernest Rutherford* (1871-1937) and his staff. They took advantage of the then novel technique of scattering experiments. These can be a beam of particles of type A with a volume that interacts with another particle of type B. Then we examine in how many particles of type A are scattered in solid angle $d\Omega$. From such experiments, one can draw conclusions about the interaction potential $V(r)$ between the particles A and B.

The most important concept in scattering experiments is the so-called cross-section. One distinguishes between the *total* σ_{tot} and the *differential cross section* $\frac{d\sigma}{d\Omega}$. The total cross-section is defined as follows:

$$\sigma_{tot} = \frac{\text{number of interactions per time}}{\text{number of incoming particles per time} \times \text{number of scatteringcenters per area}}.$$

The total cross section can also be specified as follows:

$$\sigma_{tot} = \frac{N_{tot}}{F \cdot A \cdot N \cdot \delta x}, \quad (1.1)$$

where N_{tot} is the number of scattered particles, F is the flow of incident particles, A is the area of the target, δx is the surface density of the scattering centers and its thickness N . The total cross section has the unit of an area. It is often in *barn*. The following applies:

$$1 \text{ barn} = 10^{-28} \text{ m}^2 \quad (1.2)$$

This surface is **not** the surface of the target and also **not** the surface of the individual scattering centers, but is a measure of the probability of the interaction between incident particles and the target.

The differential cross section indicates how many particles N in a particular solid angle $d\Omega$ are scattered in relation to all incident particles:

$$\frac{d\sigma}{d\Omega} = \frac{1}{F} \cdot \frac{dN_S}{d\Omega}, \quad (1.3)$$

where F is the flux. How many particles N_S into the solid angle $d\Omega$ scattered, will be illuminated as follows:

$$N_S = F \cdot A \cdot N \cdot \delta x \cdot \frac{d\sigma}{d\Omega} \quad (1.4)$$

The relationship between complete and differential cross section is given by:

$$\sigma_{tot} = \int \left(\frac{d\sigma}{d\Omega} \right) \cdot d\Omega \quad (1.5)$$

1.2.3 The Rutherford Experiment

Rutherford investigated the charge distribution in the atom with a scattering experiment as described above. In this experiment, in an evacuated chamber, he shot a very thin gold foil with a beam of α -particles. With a fluorescent screen, he then examined the count rate at different angles to the incident beam. The influence of electrons in the scattering can be neglected due to their small mass. The deflection of the incident α -particles really makes a difference by spreading the protons into existence. Due to Thomson's atomic model, Rutherford expected that the incident particles would exhibit only very small scattering angles. Back-scattering suspended this model entirely. His results showed that most incident α particles easily penetrated the film. However, some showed large scattering angles, except for back-scattering. Such a result was not compatible with the *Raisin Cake Model*. The most conclusive explanation was that the positive charges were together in a small core cluster, the electrons were surrounded, like a cloud. The question why the core is not broken of positively charged protons by the Coulomb repulsion, was only about 20 years later by the discovery of the neutron by *James Chadwick* (1891-1974) will be answered.

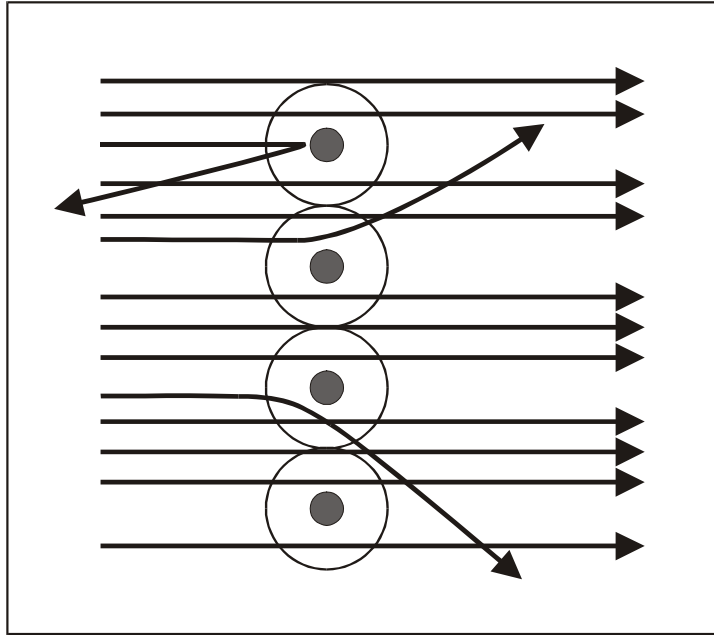


Figure 1.1: Scattering of a particles of a single layer of gold atoms

The differential cross section for the scattering of charged particles is thus called the *Rutherford Cross Section*

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{1}{4} \cdot \left(\frac{q \cdot Q}{4\pi\epsilon_0 \cdot E_{kin}}\right)^2 \cdot \frac{1}{\sin^4\left(\frac{\theta}{2}\right)} \quad (1.6)$$

Here Q is the charge from the target, q is the charge of the incident particles and E_{kin} is the energy, and θ indicates the angle between the incident beam and scattered particles. For α -particles, which scatter in a material with the charge number Z , using Eqs. (1.4) and (1.6) gives the following relationship:

$$N_S(\theta) = N_0 \cdot N \cdot \delta x \cdot \frac{Z^2 \cdot e^4}{(8\pi\epsilon_0 \cdot E_\alpha)^2} \cdot \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}, \quad (1.7)$$

where N_0 is the rate of incident α -particles, their kinetic energy E_α and e is the elementary charge.

$N_S(\theta)$ describes the number of particles per second which are scattered in a solid angle $d\Omega$. Due to the radial symmetry of the experiment, the solid angle $d\Omega$ corresponds to $\theta + d\theta$ spanned area on a sphere. This relationship is shown in Figure 1.2.

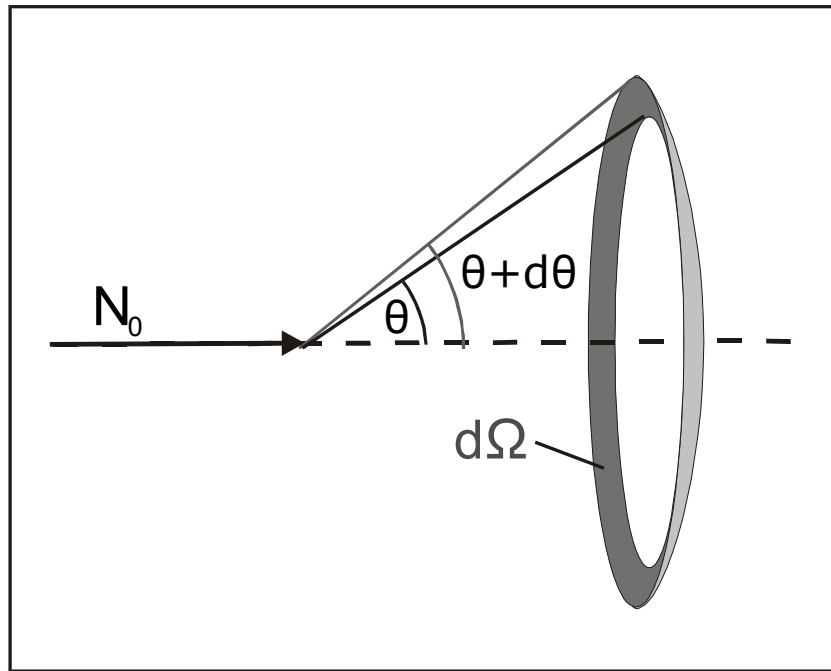


Figure 1.2: Solid angle $d\Omega$ in dependence of $\theta + d\theta$

1.3 Experiment

1.3.1 Equipment

Component	Number
Scattering chamber after Rutherford	1
Vacuum Pump	1
Gold foil with slit	1
Aluminum foil with slit	1
Am-241 source	1
Discriminator Preamp	1
Counter	1
Oscilloscope	1
BNC-to jack cable	1
BNC short cable	1
BNC long cable	2
BNC T-Piece	1
Cloth	1

1.3.2 Experimental Setup and Adjustments

1. Open the scattering chamber and place the Am-241 source in the sample holder (see Figure 1.3, (1)) and the gold foil of all screens in the corresponding holder (see Figure 1.3, (2)). The slit has a notch on one side that allows for center alignment. The side with the slot-shaped aperture should point at the source.
2. The detector has an aperture slit. Turn it such that their labeling is in line with the pen on the detector.

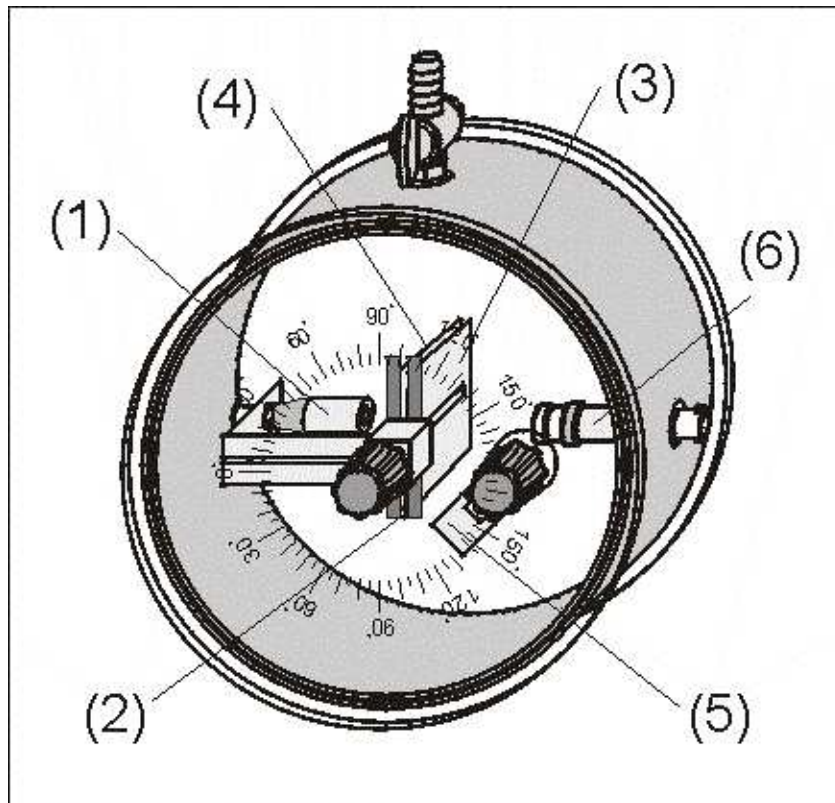


Figure 1.3: Scattering Chamber after Rutherford:

- (1) Sample holder
- (2) Support for the foil
- (3) Foil
- (4) Slit
- (5) small hinged arm
- (6) Detector

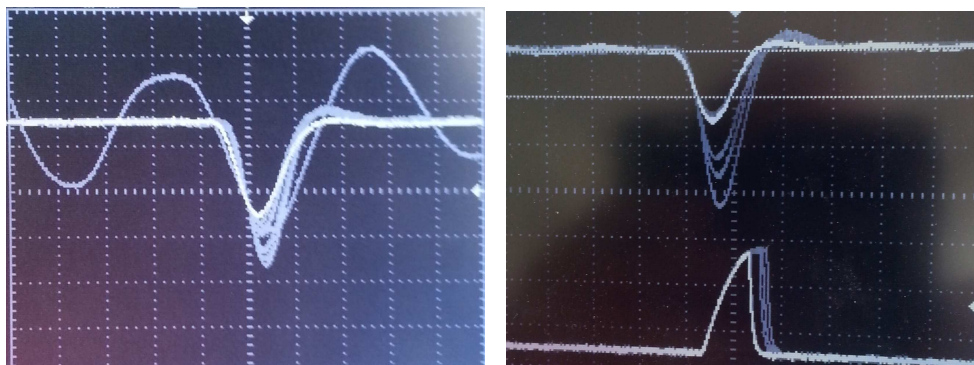


Figure 1.4: Left: Incorrect Measurement Right: Good Measurement

3. Buckle the chamber and turn the small hinged arm (see Figure 1.3, (5)), to the wall so that it is not in the way during the experiment.
4. Open the valve on the chamber and close the vent valve on the vacuum pump.
5. Start the pump and wait until the pressure in the chamber has fallen to at least 4 mbar. The pump is running throughout the experiment.

6. Connect the detector by the short BNC cable with the discriminator-preamplifier.
7. Attach the BNC T-Piece at the trigger output (rectangular pulse symbol) of the discriminator preamplifier. Make the trigger signal via the BNC-to-jack cable to the input E of the counter (short cable to ground). Now connect the oscilloscope using the BNC cable to the trigger output.
8. Connect also the signal output to the oscilloscope.
9. Point the trigger of the oscilloscope on the signal output of the discriminator preamplifier and turn the large arm with the source and the gold foil to 0° . Examine the signals of the α -particles and consider what the value of the discriminator should be. You may mark this position with the cursor function of the oscilloscope.
10. Put now the trigger of the oscilloscope on the trigger output of the discriminator preamplifier. Adjust the discriminator level so that only α -particles are detected, the position should be higher than the position you have previously marked.
11. Put the oscilloscope display in the Menu "persist, infinity" on. This will keep the old signals visible and you can check if incorrect (see Figure (1.4)) signals occurred.
12. The measurements can now be performed.
13. After completing the measurements: it is essential to do the following procedures to aerate the chamber:
14. Close the valve on the Rutherford scattering chamber.
15. Switch off the vacuum pump.
16. Open the vent valve on the pump. Make sure that you hear a hiss.
17. Open the valve of the scattering chamber slowly until a hiss audible.
18. Wait until the hissing has stopped.

1.3.3 Implementation

1. Measure the count rate all 5° ranging from $\pm 5^\circ$ to $\pm 30^\circ$, beginning with 30° . Go to as follows:
 - Place the large arm to the desired position.
 - Cover the scattering chamber with the cloth.
 - Choose on the counter a gate time of 100s.
 - Start the counter and watch the signals on the oscilloscope.
 - If no faulty signals occurred, note the number of hits.
 - If faulty signals occur, the measurement must be discarded and a new one performed.
 - Repeat 100s measurement repeatedly until a minimum total of 100 hits were counted. However, if this, after 6 measurements ($6 \cdot 100s = 600s = 10min$) is not yet the case, go on to the next position.
 - If you are still measuring at a single goal position after 3 measurements, go over to the next position.
2. Vent the scattering chamber and replace the gold foil to the aluminum foil. Repeat the experiment.

1.3.4 Tasks for Evaluation

1. Compute for gold and aluminum foil, the direct count rate N_d for each angle.
2. The determined N_d rates are a function of the angle $\theta + d\theta$ and calculated in the plane. To be able to compare them with the Rutherford scattering formula (Eq. 1.7), the rates must be corrected. The following applies:

$$d\Omega(\theta, \phi) = \sin(\theta)d\theta d\phi \quad (1.8)$$

Due to the radial symmetry, the ϕ dependence can be eliminated and Eq. (1.8) can be simplified to:

$$d\Omega(\theta) = \int_0^{2\pi} d\Omega(\theta, \phi) = \sin(\theta)d\theta \int_0^{2\pi} d\phi = 2\pi \cdot \sin(\theta)d\theta \quad (1.9)$$

The corrected rate N_S from Eq. (1.9) can be as follows:

$$N_S = 2\pi \cdot \sin(\theta) \cdot N_d \quad (1.10)$$

Compute now the corrected rate N_S for each angle.

3. Apply the rates $N_S(\theta)$ against θ . Choose a logarithmic representation of the axis with the rates. Interpret the plot. What do you notice?
4. Add error bars added to your plot. Use of the rate the statistical error from the Poisson statistics: $\Delta N = \sqrt{N}$. The statistical error in the measurement of time and angle measurement can be neglected. The angle itself provides a systematic error estimation to it.
5. Now fit the following function to your measurements:

$$f(\theta) = \frac{a}{\sin^4\left(\frac{\theta-b}{2}\right)} \quad (1.11)$$

Give the values of a and b . Which statement can you derive from them?

6. From the ratio of the rates between N_S and N_d of gold and aluminum, one can, with the help of Eq. (1.7), determine the thickness of the gold film. Take part to the fact that the areal densities for both films are equal. The number and energy of the incident particles are the same in both cases. The atomic number of gold and aluminum can be found by means of the periodic table. Furthermore, the following applies: $\delta x_{Aluminum} = 8\mu m$. Compute for all common angles θ , the thickness of the gold film. After the average, form and enter the statistical error.

1.4 Literature

- Povh, Rith, Scholz & Zetsche, *Teilchen und Kerne*, Springer
- Wolfgang Demtröder, *Experimentalphysik 3: Kern-, Teilchen- und Astrophysik*, Springer
- William R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer