Rutherford Scattering

Kirsten A. Juhl *[1], Henriette Ravn †[1], and Laurits N. Stokholm ‡[1]

[1] *Department of Physics and Astronomy, Aarhus University*

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Abstract

These experiments studies the Rutherford scattering of protons on atomic nuclei. Energetic 400 keV protons were generated using a Van de Graaff accelerator and directed onto thin metal foils of Au/C, LiF, B, and Al and the scattering cross section of the target atoms was measured as a function of the scattering angle in the range xx to 160 degrees. The cross section showed a clear angular dependency as ....., as expected. The thickness of the target layers Au/C were determined from the stopping power of the layers to be ..... The nuclear reactions of protons with boron were demonstrated by ... Mere is den dur bla bla bla ... In conclusion ...

1 Introduction

Almost all of our knowledge in the field of nuclear and atomic physics has been discovered by scattering experiments. Scattering theory underpins one of the most ubiquitous tools in physics.

This paper has a limited extend, and to keep our discussion simple and relevant, we will only examine elastic collisions in the semi-classical regime, governed by the Sommerfeld criterion for classical scattering.

This is usually fine for low energy physics, in which internal energies remain constant and no further particles are created or annihilated.

Our experiment involves a single Van-de-Graaff accelerator and the energy is in the order of 400 keV.

In low energy physics, scattering phenomena provide the standard tool to explore solid state systems, and historically this was used as a first step towards our current understanding of the atom.

2 Materials and Methods

Experimental Setup

The energetic incident protons were generated using a Van de Graff accelerator as shown in Figures **??**, **??** and **??**. The variety of incoming particles were limited by the source, which was a flask of hydrogen gas connected to the accelerator tank. The flask was not changed, and thus this experiment only concerns the ions H^+ and H^{2+}, in particular pro-

*201606487@post.au.dk
†20116112@post.au.dk
‡201605496@post.au.dk

tons. The accelerator ionized a hydrogen gas which could escape in a narrow beam. The particles were accelerated to an energy up to 400 keV controllable on the accelerator. The particles entered a big electromagnet which makes a magnetic field that controls the angle of deflection of the beam. By adjusting the field one could control which particles, depending on the mass and charge, could enter the beamline and thus interact with the target.

From the beamline the particles were directed toward a chosen target material, where they got scattered on atomic nuclei of the target. A detector was placed at a movable position around the target, such that scattering angles up 160 degrees could be measured. The detector was coupled to a digitizer with a time resolution of xx s and connected to a computer. During measurements the digitizer started a clock inside it. When the detector was hit by a particle, the digitizer translated the measured energy into a digital number and sent the number and the corresponding time stamp to the computer. The program Mc2Analyzer was used to handle the data. The digital number is an arbitrary number called a channel number. It is translatable to the actual energy by a linear factor plus an offset. In order to convert these channel numbers to correct energies of the scattered particles a calibration was done.

Calibration

The measured energy of a scattered particle is given as a digital output called a channel number. A calibration is necessary to convert these channel numbers to the actual particle scattering energies. Assuming a linear relationship between the energy and the channel number the energy can be found as

$$E = \alpha(k - k_0),$$

where k is the channel and k_0 and α are constants. The constants in the relation is determined by varying the incoming energy and writing down the corresponding values of energy and channel number. The constants are determined from a linear fit of the energies as function of channel numbers. With the Van de Graff accelerator the magnetic field can be adjusted to deflect either H^+ or ${H_2}^+$ into the beamline. For each of these a data point of energy related to channel number can be found. By considering energy and momentum conservation for elastic scattering in two dimensions the energy of the scattered particles E_f can be found from the incident proton energy and the scattering angle as:

$$E_f = \left(\frac{m_p \cos\theta + \sqrt{{m_t}^2 - {m_p}^2 \sin^2\theta}}{m_p + m_t} \right)^2 E_i,$$

where E_i is the energy of the incident beam particles, m_p and m_t are the masses of the incident protons and the target particles, respectively, and θ is the angle between the direct outgoing non-scattered beam and the scattered particles - also called the scattering angle.

Unfortunately, this only give two data points one from H^+ and one from ${H_2}^+$. The incline from the linear fit to these data points is still useful. However, another method is used to determine the zero-amplitude constant k_0. Different energies are generated using a pulse generator by changing the amplitude (corresponding to a change of resistance). For each fixed amplitude, a normal distribution of counts around a certain mean channel is obtained. The mean channel (also called the centroid) is determined from a Gaussian fit to the distribution.

TABLE WITH CORRESPONDING VALUES OF AMPLITUDE AND MEAN CHANNEL (AND THEIR UNCERTAINTIES)!

FIGURE WITH AN EXAMPLE OF A GAUSSIAN FIT.

Figure X shows the count distribution as function of channels for the amplitude X fitted with gaussian function. The data clearly follows a gaussian distribution and the data points are, within uncertainty, well described by a gauusian distribution.

From the fit the coefficient k_0 is ....

Targets

Something about the different targets... Rettes til når vi ved noget mere.

The targets and their corresponding thickness and areal density are noted in Table ...

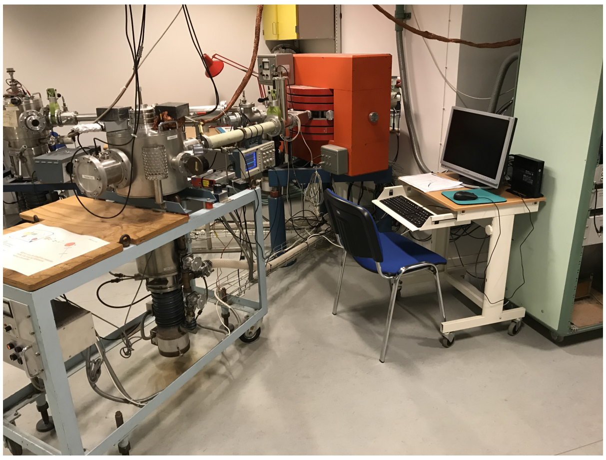

Figure 1: Experimental setup 1: The detector and a computer for the data analysis.

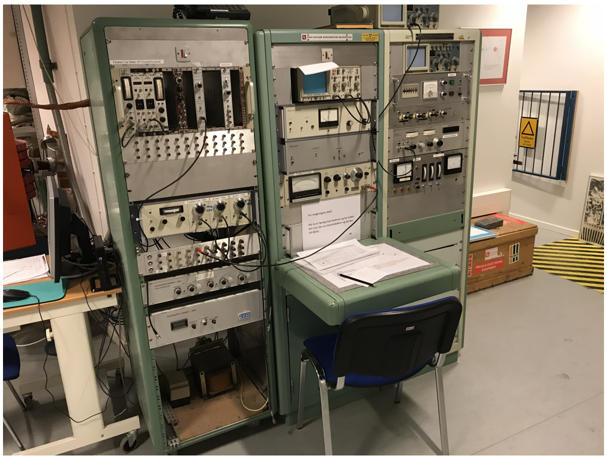

Figure 2: Experimental setup 2: All components with variables.

Figure 3: Experimental setup 3: The single Van-de-Graaf accelerator.

Scattering on atomic nuclei

The aim of this experiment was to use a particle accelerator to test certain dependencies of Rutherford scattering. Numerically, the Rutherford scattering differential cross section per target atom for any target atom is

$$\frac{d\sigma}{d\Omega} = 1.296 \left(\frac{Z_1 Z_2}{E_\infty [MeV] \sin^2\left(\frac{\theta}{2}\right)} \right)^2 \left[\frac{mb}{sr}\right],$$

where θ is the scattering angle, Z_1 is the atomic number of the incident particles, Z_2 is the atomic number of the target nuclei, and E_∞ is their kinetic energy HUSK CITE!. In order to test these dependencies a relation between the cross section and the count rate (number of scattered particles per time) is found as

$$dN = N\, n_{\text{tar}}\, dx\, d\Omega\, \frac{d\sigma(\theta, \phi)}{d\Omega},$$

where N is the number of incoming particles per time, n_{tar} is the particle density of the target, dx is the thickness of the target, and $d\Omega$ is the solid angle of the detector.

3 Angular dependency of the Rutherford cross section

4 Angular dependency of the proton energy

5 Target dependency of the Rutherford cross section

6 Thickness of the target layers

7 Nuclear reactions of protons with boron

8 Discussion

9 Conclusion

References

Griffiths, David J. *Introduction to Electrodynamics.* Cambridge, 2017. ISBN: 978-1-108-42041-9.

Jensen, Jens Ledet. *Statistik viden fra data.* Aarhus Universitetsforlag, 2012. ISBN: 978-87-7124-0245.

10 Appendix

Logbook

Anne Kirstine Knudsen*[1] and Laurits N. Stokholm†[1]

[1] *Department of Physics and Astronomy, Aarhus University*

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1 Overview

On this page, the reader will find the whole experiment summed up on a single page. It should be used to get an overview before the reader moves on to the rest of the lab script. It does not tell the reader why you need to do these procedures, but this can be found in the following pages. It is suggested that you have this page at hand, while you are doing the experiment.

2 Calibration

The calibration relates the channelnumbers, which is the output of the detector program, to measured photon energy.

1. Measure the activity of the calibration sources with a Geiger-counter.
2. Choose fitting calibration sources, measure these with the NaI detector. Measure the Cs-137 radiation source with the BGO detector. 30-60 minutes should be enough for these measurements.
3. Identify and read the channel number of the calibration sources photopeaks of the calibration sources, for both the BGO detector and the NaI detector.
4. Find the relation between channel number and photon energy, in each detector.

*anne839i97@gmail.com
†laurits.stokholm@post.au.dk

3 Coincidence measurement

The measurement of coincidence between the two detectors is where the effects of Compton-scattering can be seen.

1. Set up the program for coincidence measurements. Choose an angle to measure at.
2. Let the measurement run for preferably more than 10 hours.
3. Use the calibration values to merge the datafiles from the two detectors with ROOT-script TTree- Builder.c.
4. Use the given scripts to plot the cloudplot for the measurement.
5. Identify the area of the cloudplot where Compton-scattering has happened in the BGO-detector, and the Photoelectric effect has happened in the NaI-detector. Read the scattered-photon energy.
6. repeat steps 1 through 5 for differing angles.
7. Compare the measured shift in energy with the theoretical value given by the Compton effect. Results

4 Results

1. Plot the coincidence measurements as cloudplots, and identify the overlap between Compton- scattering in the first detector (BGO), and photoelet-ric effect in the second detector (NaI).
2. Interpret the movement of this area at varying angles.

5 Experimental Procedure

Before you begin

You should find the characteristic energy diagrams for those atoms you have chosen to investigate. It is the γ–peaks of theese atoms you later will have to compare with. When we did the experiment, we found the energy diagrams for $Cs - 137$ (1 peak), $Na - 22$ (2 peaks) and $Co - 60$ (2 peaks). All information can be found at `http://www.nndc.bnl.gov/`.

Calibration

The scintillators do not themselves measure the energy of the photons, but the power supply converts the signals to a channel number, which corresponds to a discrete energy. The purpose of the calibration is to convert the given channelnumbers from the AC–converter to a specific energy. To do so, it is necesary to compare the data of measurements, with the known energies at a given photopeak. You can find an illustrated review of the following description in the appendix.

Hardware

1. Check that both detectors are linked to the power supply, and make sure to note which channel each of their cabels are connected to. The power supply should also be connected to the computer.
2. Extend the arm between the BGO and the NaI in an angle relative to the BGO.

Software

1. To set up the software for the calibration, open MC2Analyser.
2. Go to “Acquisition Setup”, make sure the Online Spectrum is ticked, click “New Board Connection”.
3. “Device Conection” will open in a new window. Click “connect”.
4. Now turn “PWR” on.
5. Go to “Acquisition Setup”, click “Coincidences”, and make sure that all spaces are unticked and the drop downs are all on “NONE”. Press “Apply”. Go to output, and fill in a directory and the name of the filename to save data.
6. At last, click “RUN”. Let it run for as long as possible, a couple of hours or more.

The calibration has to be done for both the BGO and the NaI–detector. For the calibration of the BGO–detector, use the $Cs - 137$ source encaptured within the lead enclosement. DO NOT start fiddling with the lead enclosement! For the calibration of the NaI–detector, place a radioactive source on top of it. The γ-radiation source can be varied. Ask your lab-instructor for the other sources. It is recommended to use a Geiger–counter to find the most active radiation sources. From our experience, the $Co-60$ was great as opposed to the $Na - 22$, which could barely show any photopeak with the background effects of a $Cs - 137$ radiation source. Let the calibration run for at least 30 minutes.

Nonetheless, the longer it runs, the more precise. When the calibration is done, click “Stop” and remember to reset curve before continuing with the rest of the experiment. Now it is time to open the “Histogram” script in MatLab – you will find the instructions for the script written in MatLab. To convert the arbitary unit to a unit of energy, it is necesary to calculate the linear proportionality constant, κ.

$$E_{\text{source}} = \kappa E_{\text{Channel}}$$

The conversion factor should not be material dependent, but this might be a point of interest to investigate further. To find κ, you should first find the γ–peaks for each radiation source and then use then use the matlabcaliscript. When calculated, the κ–factor is constant for all measurements.

Practical/ Technical notes

One should be aware of the following:

I The optical breadboard with all its components is very heavy, so take care when taking it out of the cabinet and back again.

II Remember laser light can be harmful, so be careful also with parasitical beams!

III Remember not to touch any optics on the surfaces on which light in impinging!

IV Do only apply voltages in the range 0-10V to the control input of the piezodriver, and do not drive it at a frequency of more than 200 Hz. Hence, check and adjust the output of the function generator with the Pico Scope before connecting it to the piezo-driver. The voltage delivered to the piezo should be a factor of 10 higher than the control voltage (check backside of the piezo-driver).

V Remember to take clear pictures of you various setups, including the electronic wiring.

VI At the end of each experimental session, remember to safely fix all the optical elements to the breadboard in positions similar to those on Fig. 1., and bring everything back in good order in the cabinets!