# CNS Institute for Physics Teachers

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| **Title:** | **2-D Scattering – An analog to Rutherford backscattering** |
| **Version:** | July 1, 2006 |
| **Authors:** | Greg Fuchs, Walt Peck |
| **Appropriate Level:** | Regent Physics or Chemistry |
| **Abstract:** | This is lab is a 2-D analog to the materials characterization technique of Rutherford backscattering (RBS). It introduces the concept of looking at the angular distribution of scattered particles to measure/characterize the scattering target. In RBS, the scattering targets are the atoms, and the scattered particles are alpha-particles. In this experiment, we instead use a metal target with ball-bearings that scatter. Students repeatedly launch the ball bearings down the grooves of a ramp to simulate a uniform flux of alpha particles. The data is collected by the mark it leaves on a carbon-paper strip. By plotting and analyzing the data, students can learn about 2-D scattering (and by analogy, 3-D scattering) as well as calculate the size of the target. |
| **Time Required:** | One 40-minute period |
| **NY Standards Met:** | S3.1 Use various means of representing and organizing observations and insightfully interpret the organized data.<br>S3.2 Apply statistical analysis techniques when appropriate to test if chance alone explains the result.<br>S3.3 Assess correspondence between the predicted result contained in the hypothesis and the actual result, and reach a conclusion as to whether or not the explanation on which the prediction was based is supported.<br>S3.4 Based on the results of the test and through public discussion, revise the explanation and contemplate additional research. |
| **Special Notes:** | **Rutherford Scattering** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/ (cannot be shipped – must be picked up at Cornell, Ithaca, NY). |

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## Objectives:

- To explore the mechanism of scattering, and how this mechanism can be extended to make measurements at the atomic scale.
- To use graphical and numerical data analysis techniques to study scattering.

## Class Time required:

One or two 40-minute periods, depending on how much of the lab is used.

## Teacher preparation time:

10-20 minutes to set-up equipment, as well as, if necessary, obtaining equipment from CNS lending library

## Materials:

2-D Scattering kit from the Equipment Lending Library

## Assumed Prior Knowledge of Students:

Data plotting. A historical background is included.

## Background Information for Teachers:

Rutherford back-scattering (RBS) is a powerful materials characterization technique in which alpha-particles (nucleus of He) are fired at a target material (that you want to analyze) and the angular position, along with the energy of the scattered particles is analyzed to gain information about the atoms in the target. This was first done by Ernest Rutherford in 1911, when he fired alpha-particles at a gold foil, and by studying the angular distribution of the scattered particles, was able to determine the mass and size of the scattering agents in his target. To his great surprise, it was much smaller than the estimated size of the atom, and thus he discovered the nucleus.

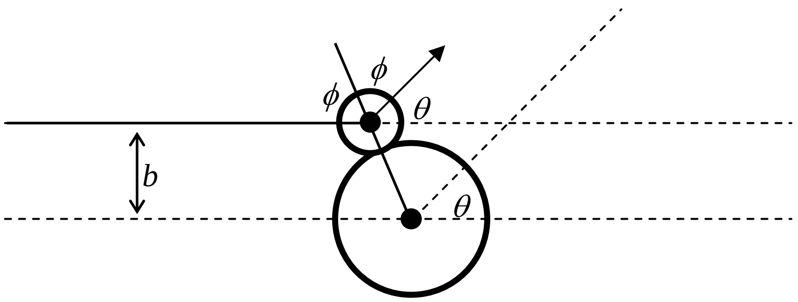
RBS is still used today as a thin-film characterization technique. In modern implementations, data is collected as a function of energy at a fixed target angle. In addition, since most of the alphas are not scattered by any given lattice plane, they can probe significantly beyond the surface (up to microns deep) which allows the technique to be used for compositional analysis of thin-film multilayers.

In this experiment, we are exploring a 2-D analog of RBS. In place of alpha-particles, we use steel ball-bearings. The scatterer, rather than a lattice of nuclei, is a single, round, metal target, or an array of targets to simulate the nucleus.

*Some background on how the pros do it:*

There are two important terms that are associated with scattering (used for various spectroscopy techniques, such as Rutherford backscattering (RBS) and other scattering based spectroscopies).

Scattering Parameter ($b$) – the perpendicular distance between the center of the target and the incident path of the projectile, as seen in the geometry below:



Scattering Cross-section $(\sigma(\theta)) = \dfrac{Number\ of\ \ scattering\ events\, that\ scatter\ to\ an\ angle\ \theta\ /\ t\ \arg\ et}{Number\ of\ \ incident\ \ particles\ /\ length}$

This is also known as the "differential cross-section." If we integrate over all scattering angles (count up all the scattering events we collect) then we get the "total cross-section." The reason for the name cross section is that this has units of length (for 3-D scattering, it is an area).

The description of scattering processes using these terms allows us to generalize the concepts of scattering independent of the specific interaction between the target and the scattered particle. In Rutherford's case, it is the inverse-square law coulomb force that acts between the alpha-particle and the target nuclei, but in this experiment, we can simply assume the ball bearings reflect off the target at equal angles ($\phi$). This is the "hard-sphere" approximation.

The cross section for our geometry is:

$$\sigma(\theta) = (R_1 + R_2)\left|Sin(\theta / 2)\right| / 2 \qquad , (1)$$

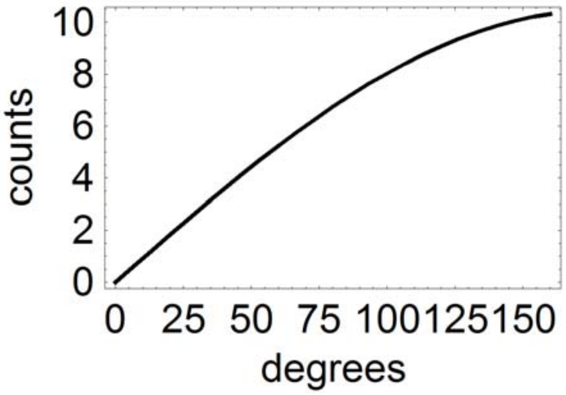
where $R_1$ is the radius of the incident particle, and $R_2$ is the radius of the target. This formula simply states that for uniform, incident flux of particles, the magnitude of scattering is determined by the sum of the radii, and that the majority of the particles that strike the target are back-scattered. Also, this formula is only fully correct in the case when the detector is very far away from the target. For shorter detector distances like we have, the formula is not very accurate for small values of $\theta$. This is particularly true in the target's "shadow" where particles cannot be scattered.

In the data analysis section of the lab, it is helpful to use a spreadsheet to make plots and do calculations. These can also be done, however, either by hand or with a graphics calculator.

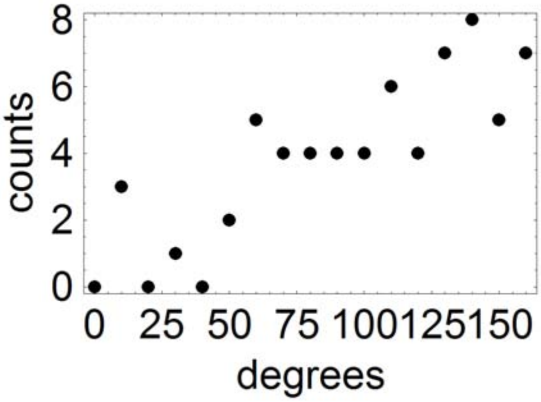
Some important numbers (for the protype)

- Diameter of steel ball-bearing = 0.25 inches
- Radius of smaller target = 1 inch
- Radius of larger target = 1.4 inches
- Diameter of detector = 36 inches

While this is certainly optional, a good choice of the incoming flux is to launch 10-20 times for every groove. The more times they launch, the better the data will be. There are also a number if ways in which this physical model doesn't do a good job of reproducing even the prediction of equation 1. Since the ramp has discrete grooves, there isn't really a uniform incident flux, which is one of the assumptions that goes into equation 1. This introduces a systematic error that causes an oscillation in the histogram. Furthermore, uneven surfaces, errors in the release, level being off, and even the rotational momentum of the balls are all factors that introduce additional sources of error, both systematic and random. Given this, equation 1 predicts "ideal world" data that would look something like this:



Taking random error into account, data might look more like this: (generated numerically, this is not real data)



Systematic errors will throw things off even more. Given that this apparatus is not a perfect model, the focus of the experiment is to help conceptualize the Rutherford experiment as well as being an opportunity for an inquiry-based lab. If students don't get quantitatively (or even qualitatively) accurate data, it is due to these errors, but that can also be part of the discussion.

When the students think about what other experiments can be done with the lab, equipment, using tacks (included, they are short with a large head) and tape, additional small scatterers can be added to model a lattice. Simply put the tacks head-side down on the board, and puncture a small piece of scotch tape to go over the sharp part in a cross pattern to hold it in place.

When running the experiment, 5-7 students can be occupied on a single apparatus. Roles can include: person to roll the balls, person to feed balls, person to count the balls in each bin, two “sweepers” in case the balls don’t quite make it to the bins, a person to enter the data in a computer/calculator, etc.

Included in the Student Section are some questions that may work as discussion questions.

**References:**

J. B. Marion and S. T. Thornton, Classical Dynamics of Particles and Systems, Harcourt College Publishers, 4th ed.1995.

Leonard C. Feldman and James W. Mayer, Fundamentals of Surface and Thin Film Analysis, P. T. R. Prentice Hall, Inc.1986.

http://www.lbl.gov/msd/Internal/Facilities/MSD_Ion_Beam.html

http://www.almaden.ibm.com/st/scientific_services/materials_analysis/ib_surface/rbs/

http://www.research.philips.com/technologies/misc/matanalysis/downloads/rutherford.pdf

# 2-D SCATTERING
# AN ANALOG TO RUTHERFORD BACKSCATTERING

Name ____________________________

**Background:**

Rutherford backscattering (RBS) is a powerful materials characterization technique in which alpha-particles (nucleus of Helium) are fired at a target material (that you want to analyze) and the angular position, along with the energy of the scattered particles is analyzed to gain information about the atoms in the target. This was first done by Ernest Rutherford in 1911, when he fired alpha-particles at a very thin gold foil (only a few layers of gold atoms in thickness). To his great surprise, nearly all of the alpha-particles when straight through with no scattering. So where was all the mass? Gold is, after all, much heavier than helium, it should deflect the path of the alpha particles. Since Rutherford knew that the alpha-particles are much more massive than electrons (they had already been discovered by Rutherford's former mentor, J. J. Thompson in 1897) they would have little or no effect on the path of the alpha-particles. This told Rutherford immediately that electrons took up most of the volume of the gold atoms. The very few alpha-particles that did scatter held the key to measuring the size of the rest of the mass (which was eventually named the nucleus). By studying the angular distribution of the scattered alphas, Rutherford was able to calculate the size accurately.

We are going to be looking at a 2-D model of Rutherford's experiment. In order to simulate a uniform stream of alpha-particles (the width of the stream is much wider than the individual nuclei) we are going to roll ball-bearings down a ramp at various size targets. The angular distribution of the scattered ball bearings will be related to the size of the target.

**Procedure:**

1. Line up the ramp with the opening on the apparatus.
2. Practice releasing the balls so the roll down evenly in the groove.
3. Empty all the pockets and begin taking data. Drop an equal number of balls down each groove, then shift the ramp over by half a groove width and repeat. The more dropped, the better the data set.
4. Count the number of balls that are collected in each pocket and record the result on the data table. When counting, add together the balls for each of the two nets on each side that have the same angle.
5. Repeat the experiment for both targets and the bare post.

Trial 1

| Angle (degrees) | Counts |
|---|---|
| 0-10 | |
| 10-20 | |
| 20-30 | |
| 30-40 | |
| 40-50 | |
| 50-60 | |
| 60-70 | |
| 70-80 | |
| 80-90 | |
| 90-100 | |
| 100-110 | |
| 110-120 | |
| 120-130 | |
| 130-140 | |
| 140-150 | |
| 150-160 | |
| 160-170 | |
| over 170 | |

Trial 2

| Angle (degrees) | Counts |
|---|---|
| 0-10 | |
| 10-20 | |
| 20-30 | |
| 30-40 | |
| 40-50 | |
| 50-60 | |
| 60-70 | |
| 70-80 | |
| 80-90 | |
| 90-100 | |
| 100-110 | |
| 110-120 | |
| 120-130 | |
| 130-140 | |
| 140-150 | |
| 150-160 | |
| 160-170 | |
| over 170 | |

Trial 3

| Angle (degrees) | Counts |
|---|---|
| 0-10 | |
| 10-20 | |
| 20-30 | |
| 30-40 | |
| 40-50 | |
| 50-60 | |
| 60-70 | |
| 70-80 | |
| 80-90 | |
| 90-100 | |
| 100-110 | |
| 110-120 | |
| 120-130 | |
| 130-140 | |
| 140-150 | |
| 150-160 | |
| 160-170 | |
| over 170 | |

Trial 4

| Angle (degrees) | Counts |
|---|---|
| 0-10 | |
| 10-20 | |
| 20-30 | |
| 30-40 | |
| 40-50 | |
| 50-60 | |
| 60-70 | |
| 70-80 | |
| 80-90 | |
| 90-100 | |
| 100-110 | |
| 110-120 | |
| 120-130 | |
| 130-140 | |
| 140-150 | |
| 150-160 | |
| 160-170 | |
| over 170 | |

**Questions:**

1. What is the relationship between angle and number of counts?  How does the pattern of scattering angles vary with the size of the target?

2. What would be the effect on the angular pattern of scattered balls if the balls were larger?  Smaller?  What if the balls were the same size as the target?

3. Are there any points that you should exclude from your analysis?  Why?  How would Rutherford have known which particles scattered and which didn't?

4. How would your analysis change if you couldn't detect the unscattered balls?

5. What kind of information could be gathered if you could only use 1 detector (net) and couldn't see balls scattered into other angles?  Where would you put the net (and why)?

6. What are some differences between our model and the Rutherford experiment?
7. How could we improve the accuracy of this model experiment? (Consider both the apparatus and the procedure; explain why each suggestion would improve things.)
8. What are the sources of systematic error? Random error?
9. What other experiments can be done with this apparatus? How would you model a lattice of nuclei? How would you make the “foil” thicker/thinner?