Episode 521: Rutherford’s experiment

In this episode, students look in detail at Rutherford’s experiment and relate it to a mechanical analogue.

**Lesson Summary**

* Discussion: Recollecting the significance of Rutherford’s experiment (10 minutes)
* Discussion: Rutherford’s experiment (20 minutes)
* Demonstration: Collisions and momentum (10 minutes)
* Discussion: Rutherford scattering and Coulomb’s law (10 minutes)
* Student experiment or demonstration: The Gravitational model (30 minutes)
* Student questions: Rutherford experiment and atomic structure (optional) (20 minutes)
* Question: Rutherford’s results (optional)
* Discussion: Models in physics (10 minutes)

#### Discussion: Recollecting the significance of Rutherford’s experiment

As a preparatory task, ask your students to revise what they have previously learned about Rutherford’s α-scattering experiment. What idea of the atom did it suggest? (The nuclear model.) What model of the atom did this replace? (Thomson’s plum pudding model, in which atoms are seen as essentially small balls composed of a mixture of positive and negative electric charge, with no concentration of charge at any particular position.)

Is plum pudding a good name for the model? (Yes, if you see the negative electrons dispersed throughout a spherical lump of continuous positive charge, not so good if the volume of the atom has both positive and negative particles continuously distributed through it – students may well be recalling different pictures from different sources.)

#### Discussion: Rutherford’s experiment

Now you can present a more advanced exposition of the experiment. Why did Rutherford ask for the experiment to be done? Experiments on the absorption of β particles had also shown that sometimes the β particles were back scattered. Rutherford suggested that Geiger and Marsden should try looking for similar behaviour with α particles. Rutherford thought it was highly unlikely; because α particles are relatively massive compared with electrons, it was predicted that the αs would simply suffer a series of small deflections. They were expected to travel more or less straight through the absorber. However, Rutherford’s main concern was to give Geiger and Marsden something to do that would occupy them and get them some useful hands-on experience, rather than expecting them to get any very exciting results.

Show a diagram of the apparatus. The absorber was a thin gold metal foil. Why use gold? (Thin gold foils, typically 250 atoms thick, were easy to make and readily available.) Why thin? (as are easily absorbed.)

As expected , virtually all the αs went straight through, but about 1:8000 were turned through large angles (reflected or back-scattered). An 8 kBq a source gives one large-angle scattering per second.

The chance of a series of small deflections resulting in a reflection is far too small to account for what was observed.

Rutherford was astonished at the result: It was quite the most incredible event that ever happened to me in my life. It was as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you! (You may find other versions of this quote, because Rutherford described his experience on many different occasions.)

[Episode 521-1: Rutherford scattering (Word, 27 KB)](https://spark.iop.org/sites/default/files/media/documents/episode-521-1-rutherford-scattering.doc) - see end of document

[Episode 521-2: Alpha particle scattering experiment (Word, 48 KB)](https://spark.iop.org/sites/default/files/media/documents/episode-521-2-alpha-particle-scattering-experiment.doc) - see end of document

#### Demonstration: Collisions and momentum

Use colliding balls to show what happens to a projectile particle hitting a target particle; as the target ball mass gets bigger, the follow through by the projectile gets less. Use a selection of ball bearings, marbles etc on some curtain track, or trolleys loaded with different weights. When the target mass is small relative to the projectile mass, the missile follows through. For equal masses the projectile stops and the target sets off with the speed of the projectile. If the target mass is large, the projectile rebounds. (If your students have already studied momentum, they should be able to predict the outcome of each of these demonstrations.)

The back scattering of αs through large angles implies (i) all the positive charge is concentrated together, and (ii) the mass of the concentrated positive charge must be quite a bit larger than of an α particle.



#### Discussion: Rutherford scattering and Coulomb’s Law

Rutherford assumed that (i) Coulomb’s Law was obeyed down to very small distances, and that (ii) most of the mass of the nucleus was concentrated into a very small volume – the nuclear atom that resembles a miniature solar system. (Because the analysis works, we can take this as proof that Coulomb’s Law is valid down to distances about the size of a nucleus.)

Show a diagram to explain how the terms impact parameter p and scattering angle f are defined. Ask: how would you expect the number of αs scattered through angle f to depend upon (i) the impact parameter p, (ii) the charge on the target nucleus Z, and (iii) the energy of the α particles? (As *p* increases f decreases (force weaker); as Z increases f increases (greater repulsive force); as energy increases, f decreases (less interaction time).)

[Episode 521-3: Rutherford’s picture of alpha particle scattering (Word, 298 KB)](https://spark.iop.org/sites/default/files/media/documents/episode-521-3-rutherfords-picture-of-alpha-particle-scattering.doc) - see end of document



#### Student experiment or demonstration: The Gravitational model

The gravitational model provides a practical way for students to get a feel for the physics of alpha-scattering. Roll a marble past the hat to see it deflected. You can change the speed and impact parameter. Students can change these parameters systematically and observe the effects.

The hat is designed so that, as the slope of the hat gets steeper, the component of gravity parallel to the slope opposing the motion of the ball also gets larger. The actual shape is such that at any position on the slope a distance *r* from the centre of the hill, the component of a particle’s weight parallel to the slope ~ 1*r*2. (Revision of the relationship between 1*r* potential and 1*r*2 force can be done here if desired.)

If possible, it’s worth getting several gravitational models so that students can work with them in small groups. (The model can also be used when studying gravity. Turn it upside down to become a potential well so that you can demonstrate orbits, and discuss the difference between bound and unbound particles.)

[Episode 521-4: The 1/r hill: Slope and force](https://spark.iop.org/sites/default/files/media/documents/episode-521-4-the-1-r-hill-slope-and-force_0.doc) - see end of document

[Episode 521-5: A model for Rutherford scattering (Word, 37 KB)](https://spark.iop.org/sites/default/files/media/documents/episode-521-5-a-model-for-rutherford-scattering_0.doc) - see end of document

A good simulation of alpha particle scattering could be used if desired.

#### Student questions (optional): Rutherford experiment and atomic structure

[Episode 521-6: Rutherford experiment and atomic structure (Word, 28 KB)](https://spark.iop.org/sites/default/files/media/documents/episode-521-6-rutherford-experiment-and-atomic-structure.doc) - see end of document

#### Question: Rutherford’s results (optional)

Some actual results are given. Students may plot a graph to test Rutherford’s relation for α -scattering

[Episode 521-7: Rutherford scattering data (Word, 41 KB)](https://spark.iop.org/sites/default/files/media/documents/episode-521-7-rutherford-scattering-data.doc) - see end of document

#### Discussion: Models in physics

If time permits, you might have a discussion on the role of models (physical and mathematical) in physics. In what ways is the gravitational model similar to Rutherford scattering? In what ways does it differ? In which ways is the solar system a good model for the nuclear atom? What other models do your students know?

Episode 521-1: Rutherford scattering

Alpha source

very few

some

Many particles

gold foil

Most  particles travel straight through the gold foil but about 1:8000 were turned through a large angle. The experiment takes place in a vacuum to avoid problems of absorption by air.

Practical advice

This diagram is here so that you can discuss it with your class.

External reference

This activity is taken from Resourceful Physics

Episode 521-2: Alpha particle scattering experiment



The experiment takes place in a vacuum to avoid problems of absorption by air

Practical advice

This diagram is here so that you can discuss it with your class.

External reference

This activity is taken from Advancing Physics chapter 17, 100O

Episode 521-3: Rutherford’s picture of alpha particle scattering









Practical advice

These diagrams are here so that you can discuss them with your class.

External reference

This activity is taken from Advancing Physics chapter 17, 120O

Episode 521- 4: The 1/r hill: Slope and force

Mapping potential

The 1/r hill is a gravitational model showing how the electrical potential varies round a charged particle. One way up for the variation round a positively charged sphere, invert it for a model of the variation round a negatively charged sphere.

As the elevation of the hill above the bench top represents the potential, so the steepness of the hill represents the field.

Remember



You can investigate these field values by looking at the accelerations of a suitably chosen probe - a ball bearing.

You will need:

* 1/r hill
* ball bearing

Potential varies radially



Move across the surface, staying at a fixed gravitational potential energy. What does this correspond to in the electrical case? What shape do you make, as you move across the surface following this rule?

Now try moving across the surface so that the gravitational potential energy changes as much as possible in as small a distance as possible. What shape do you make now, as you move across the surface?

Field is potential gradient



Hold a ball bearing on the surface. Release it and compare the potential gradient with the acceleration. Repeat for several different positions. How does the steepness of the slope fix the acceleration? Why is the acceleration a good measure of the field? Remember that this is just a gravitational model. Can you sketch the corresponding situation for the electrical case?

You have

1. Looked at 1/rvariation in potential.
2. Compared a model with the thing being modelled.
3. Thought about the connection between field and potential.

Practical advice

Handling a 1/r hill in the way suggested allows students to show their understanding of some of the more subtle ideas in this chapter physically. Students might usefully have one hill between four and use the questions as a basis to present a mini-lesson on the 1/r hill to their peers, each section being repeated twice.

External reference

This activity is taken from Advancing Physics chapter 16, 210P

Episode 521-5: A model for Rutherford scattering

Use a model such as the one shown below to investigate Rutherford scattering. A marble runs down a ramp, and then past a plastic or metal ‘hill’. The closer it gets to the hill, the more it is deflected.



You will need:

* alpha scattering analogue apparatus
* talcum powder
* large sheets of white paper (A3 or larger)

What to do:

* Sprinkle some powder so that the track of the marble shows up.
* Start by investigating how much the marble is deflected when it is aimed at different distances from the hill. You need to measure two quantities, as shown below, d, the distance of the line of the original track from the centre of the hill and  the angle through which it is scattered.



* Make sure that you always release the marble from the same point on the ramp.
* How could you make the marble travel more slowly? How will this affect its track? Test your ideas.
* Why does the marble never go over the top of the hill? Use the idea of energy conservation to explain your answer

Practical advice

The ‘hill’ is shaped to reflect an inverse square law of repulsion (its height varies inversely with radius, as required for gravitational potential energy in an inverse square law field). You might refer back to this and remind students about studying Coulomb’s law. Talcum powder is useful for showing up the tracks of the marbles.

Students should appreciate that, provided the marble never starts higher than the top of the ramp, it will never reach the top of the hill.

If possible, it’s worth getting several gravitational model demos so students can work with them in small groups of three or four. [The ‘models’ can also be used when studying gravity. Turned upside down to become a ‘potential well’ you can demonstrate ‘orbits’ and bound or unbound ‘particles’.]

Technicians note

The apparatus consists of a plastic or aluminium ‘hill’, a ramp and a steel ball bearing or glass marble (see, for example, Philip Harris item Q88290/4).

External reference

This activity is taken from Salters Horners Advanced Physics, section PRO, activity 11

Episode 521- 6: Rutherford experiment and atomic structure

1. Describe briefly the two conflicting theories of the structure of the atom.

2. Why was the nuclear model of Rutherford accepted as correct?

3. What would have happened if neutrons had been used in Rutherford’s experiment? Explain your answer.

4. What would have happened if aluminium had been used instead of gold in the alpha scattering experiment? Explain your answer.

5. What three properties of the nucleus can be deduced from the Rutherford scattering experiment? Explain your answer.

Practical advice

These questions are to help your students to think about the Rutherford ideas.

Answers and worked solutions

1 The English scientist Thomson suggested that the atom, which is a neutral particle, was made of positive charge with ‘lumps’ of negative charge inset in it - rather like the plums in a pudding. For this reason it was known as the Plum Pudding theory of the atom.

 Rutherford explained it this way. He knew that the alpha particles carried a positive charge so he said that the positive charge of the atom was concentrated in one place that he called the nucleus, and that the negatively charged particles, the electrons, were in orbit around the nucleus. Most of the mass was in the nucleus

2 Rutherford’s prediction using the idea of Coulomb law repulsion was verified by experiment. It also enables experimental values of nuclear charge to be obtained, ie atomic number.

3 They would not have been repelled so it is unlikely that any would ‘bounce back’. Some could be absorbed by the nucleus.

4 The charge on the nucleus is much smaller so deflection would be smaller.

See the equation

[TAP 521-7: Rutherford scattering data](file:///Users/danjosman/Downloads/TAP521-7-Rutherfords-experiment.doc)

5 Small, massive and positive.

External reference

This activity is taken from Resourceful Physics

Episode 521-7: Rutherford scattering data

The idea of scattering using Coulomb’s law and a small central positive charge for the atom was communicated to the Manchester Literary and Philosophical Society in February 1911. His ideas require that “the scattering due to a single atomic encounter is small” and that “it be supposed that the diameter of the sphere of positive electricity is minute compared with the diameter and sphere of influence of the atom”.

The table below shows some of Geiger and Marsden’s results

Counting was carried out for the same time at each angle

|  |  |
| --- | --- |
| deflected angle degrees | number scattered |
| 15.0 | 132,000 |
| 22.5 | 27,300 |
| 30.0 | 7,800 |
| 37.5 | 3,300 |
| 45.0 | 1,457 |
| 60.0 | 477 |
| 75.0 | 211 |
| 105 | 70 |
| 120 | 52 |
| 135 | 43 |
| 150 | 33 |

The actual formula

Number of  particles y falling on unit area deflected by angle is given by: -

,

where *Q* is the total number of particles falling on the scattering material, *t* is the thickness of the material, *n* the number of atoms within unit volume of the material, and *b* given by the formula below. *N* is the number of positive charges, *e* the size of the positive charge, *m* the mass of an  particle, *u* their velocity and *E* the charge of the  particle.



One of Rutherford’s conclusions was that the number of scintillations per unit area of zinc sulphide screen is proportional to 

Maths note cosec ( 1/sin (

What to do

Add extra columns to the table as needed to enable you to draw a graph to test Rutherford’s conclusion that the number of scintillations per unit area of zinc sulphide screen is proportional to 

As an extension you might like to plot number scattered against 1/4

Write down you conclusions from the graph(s)

Practical advice

Some students might like to see Rutherford’s equation and try a test to see how the results come out. This activity is considered optional. Some websites with papers of the time are given below for interest

Alternative approaches

A spreadsheet could be used for this activity.

You should find:

* To a reasonable degree y proportional to 
* number scattered against 1/4 is only proportional at small angles.

External references

This activity is based on “The Scattering of and Particles By Matter and the Structure of the Atom. By Professor E RUTHERFORD F.R.S., University of Manchester.“ from which the equation is quoted and the section in quotation marks at the top of the page.

An abstract of the paper is at: -

<http://dbhs.wvusd.k12.ca.us/webdocs/Chem-History/Rutherford-atom-abstract.html>

see also:

*Philosophical Magazine*, Series 6, Volume 27 March 1914, p. 488 - 498

<http://dbhs.wvusd.k12.ca.us/webdocs/Chem-History/Rutherford-1914.html>

The paper can also be found in Foundations of Nuclear Physics, Beyer, Robert T (Ed), New York 1949 Dover Publications Inc. pp 111-130. The book also contains papers by Chadwick, Lawrence, Cockcroft, Gamow and Yukawa amongst others.

Of interest might also be:

On a Diffuse Reflection of the -Particles, *Proc. Roy. Soc.* 1909 A vol. 82, p. 495-500 By H. GEIGER, Ph.D., John Harling Fellow, and E. MARSDEN, Hatfield Scholar, University of Manchester

<http://dbhs.wvusd.k12.ca.us/webdocs/Chem-History/GM-1909.html>

and

The Scattering of the -Particles by Matter by H. GEIGER, Ph.D. Proceedings of the Royal Society vol. A83, p. 492-504

<http://dbhs.wvusd.k12.ca.us/webdocs/Chem-History/Geiger-1910.html>