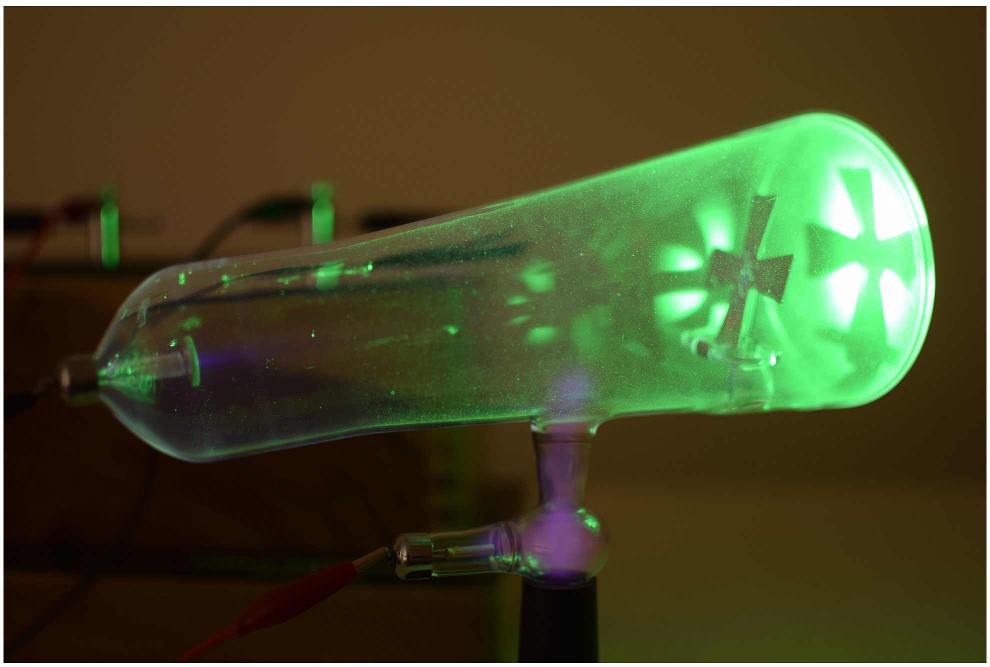
Module 8: From the Universe to the Atom

M8.2: Structure of the Atom



Tammy Humphrey

Contents

Cover photo credit: Own work

Syllabus content: From the Universe to the Atom

Structure of the Atom

Inquiry question: How is it known that atoms are made up of protons, neutrons and electrons?

Students:

- investigate, assess and model the experimental evidence supporting the existence and properties of the electron, including:
  - early experiments examining the nature of cathode rays
  - Thomson's charge-to-mass experiment
  - Millikan's oil drop experiment (ACSPH026)
- Investigate, assess and model the experimental evidence supporting the nuclear model of the atom, including:
  - the Geiger-Marsden experiment
  - Rutherford's atomic model
  - Chadwick's discovery of the neutron (ACSPH026)

Early experiments on Cathode Rays

Video: https://www.youtube.com/watch?v=A8gPoAwzhwk

Early technological advances

Three inventions laid the foundation for the early experiments on cathode rays and later, with improvements, the discovery of the electron.[1]

The first was the development of more effective vacuum pumps, first the Geissler pump in the mid-1850s and later the Sprengel vacuum pump in 1865.

The second innovation, also by Geissler, was the development of in-glass electrodes (prior to this a cork with an electrode passing through it was inserted into a glass tube). This greatly improved the ability of glass tubes to hold a vacuum. An electrical discharge across the electrodes through different types of gas could produce a variety of colours. Elaborate and intricately designed Geissler tubes were sold to the public as novelty entertainment.

The third innovation was the development of the Rühmkorff coil in the 1850s as a high voltage source to power these tubes. This device performs the function of a step up transformer, but is powered by a DC voltage source such as a battery. This is done using an "interrupter" switch that switches the input voltage on an off using the magnetic field generated by the coil [2].

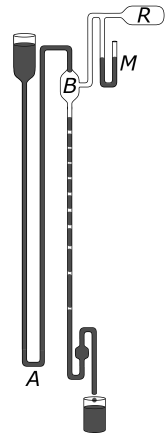


Figure 1: Sprengel vacuum pump. Mecury drops capture air in bulb B as they fall through it, so evacuating the connected vessel R. A manometer denoted M measures pressure. Image credit: By Vladsinger - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=56806025

[1] Abraham Pais, "Inward Bound: Of matter and forces in the Physical World" (1986).

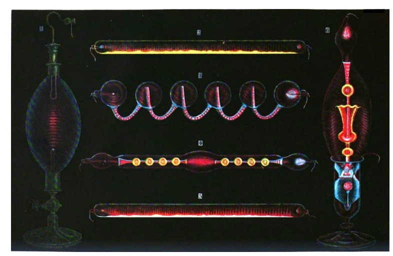


Figure 2: Decorative Geissler tubes. Image credit: Public Domain https://commons.wikimedia.org/w/index.php?curid=5605216

[2] Please see https://www.youtube.com/watch?v=A8gPoAwzhwk at 1:50min for more details and a demonstration

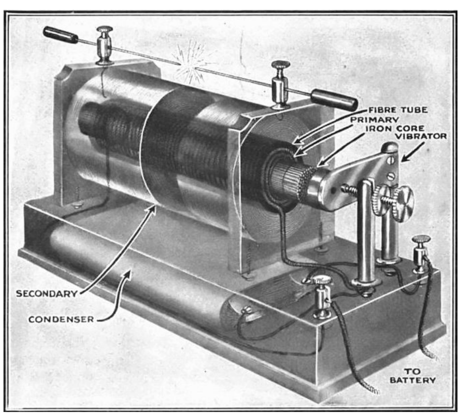


Figure 3: Rühmkorff Induction coil https://commons.wikimedia.org/wiki/File:Induction_coil_cutaway.jpg

Faraday and Crookes' early experiments

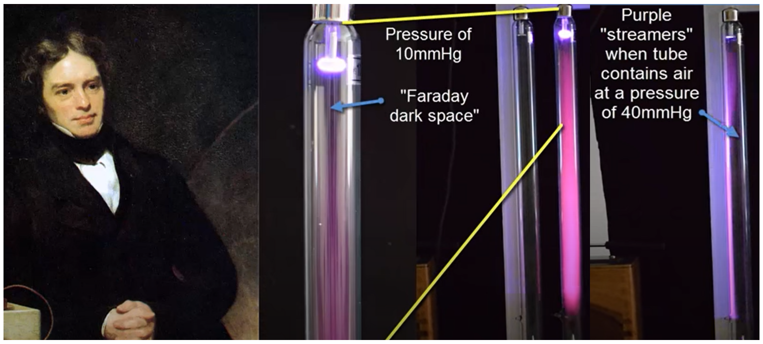


Figure 4: Michael Faraday (Public Domain, from `https://commons.wikimedia.org/wiki/File:M_Faraday_Th_Phillips_oil_1842.jpg` and a gas discharge tube showing Faraday's dark space and another showing purple streamers observed at higher gas pressures (Image credit: The author)

Faraday performed initial experiments on electrical discharges through gases. He established that as gas pressure in a glass discharge tube was lowered, the pattern of the discharge changed from purple "streamers" to a steady glow with a dark space (now known as "Faraday's dark space" at the cathode [3].

Using Sprengel's vacuum pump, William Crookes investigated gas discharges at lower pressures, discovering (along with other researchers) very complex behaviour (due to the formation of a plasma in the tube) such as striations, and further structure in the form of an additional dark space at the cathode ("Crookes dark space").

[3] Per F. Dahl "Flash of the cathode rays: A history of J.J. Thomson's electron" (1997), pg. 49

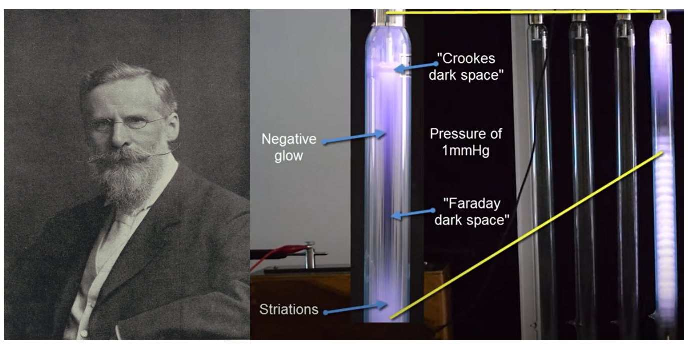


Figure 5: William Crookes (Public Domain, from `https://commons.wikimedia.org/w/index.php?curid=84675578` and a gas discharge tube showing Crookes' (and Faraday's) dark space and striations (Image credit: The author)

Plücker discovers cathode rays

Julius Plücker was also studying cathode rays using Geissler's tubes and in 1857 discovered that if the tube was evacuated further, until there was essentially no gas left in the tube, the glow was replaced by a green fluorescence in the glass of the tube opposite the cathode (we now know that this is due to uranium atoms fluorescing when stuck by high energy electrons). He also noticed that the position of the fluorescence moved in response to a magnet[4].

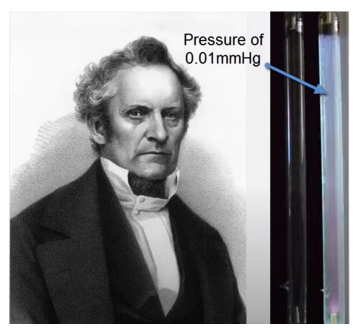


Figure 6: Julius Plücker. Image credit: Public Domain `https://commons.wikimedia.org/wiki/File:Julius_Pl%C3%BCcker.jpg` and a low pressure cathode ray tube showing the green phosphorescence characteristic of cathode rays. Image credit: The author.

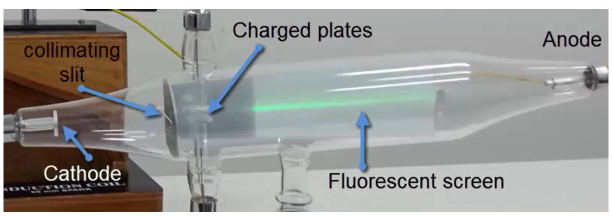
[4] Per F. Dahl "Flash of the cathode rays: A history of J.J. Thomson's electron" (1997), pg. 55

Hittorf's experiments - rectilinear propagation

In 1869 Johann Hittorf established that cathode rays are blocked by objects placed in front of the cathode, producing a sharp shadow opposite the cathode. This demonstration of rectilinear propagation convinced German scientists researching cathode rays that they were likely to be some kind of electromagnetic wave in the aether[5].

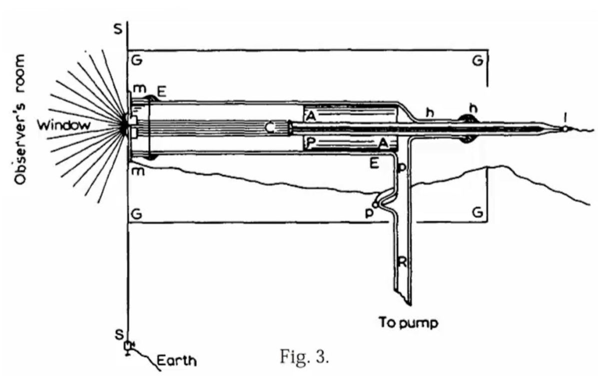
Hertz and Lenard's experiments

Heinrich Hertz investigated the deflection of cathode rays by electric fields. He was unable to detect any deflection when collimated cathode rays passed between charged electric plates. It would later be shown by J.J. Thomson that this was due to the tubes he used being insufficiently evacuated, so that the remaining gas was ionised by the electric field, gas ions then effectively screen the cathode rays from the electric field, so that they are undeflected. Thomson was later able to demonstrate deflection in electric fields at higher vacuums.



Hertz and Philip Lenard used thin foil windows that were expected to be impervious to atoms at the end of cathode ray tubes to show that the rays could pass through these windows and produce fluorescence on a screen external to the tube.

Both the above results, the (initial) inability of electric fields to deflect the electrons, and their ability to pass through metal foils and produce fluorescence were taken as further convincing evidence by German scientists that cathode rays were a type of light.



[5] Per F. Dahl "Flash of the cathode rays: A history of J.J. Thomson's electron" (1997), pg. 57

Figure 7: Heinrich Hertz. Image credit: Public Domain `https://commons.wikimedia.org/wiki/File:Heinrich_Rudolf_Hertz.jpg`

Figure 8: Cathode rays are shown penetrating a thin foil window in experiments by Hertz and Lenard.

Figure 9: Philip Lenard. Image credit: Public Domain `https://en.wikipedia.org/wiki/Philipp_Lenard#/media/File:Phillipp_Lenard_in_1900.jpg`

Figure 10: A cathode ray tube used in experiments by Hertz and Lenard, showing cathode rays passing through a thin metal foil window. Image credit: Per F. Dahl "Flash of the cathode rays: A history of J.J. Thomson's electron" (1997), pg. 86

Crookes' maltese cross and "paddlewheel" cathode ray tube experiments

Video: `https://www.youtube.com/watch?v=dkGTFhmC18g`

William Crookes continued to investigate cathode rays. In 1879, Crookes' assistant Gimingham created a tube with a "maltese cross" blocking the beam, and the anode at the base of the tube. This repeated Hittorf's demonstration of rectilinear propagation (as a clear shadow of the cross is seem on the far end of the tube) showed that at low pressures the cathode rays travel in straight lines regardless of the position of the anode.

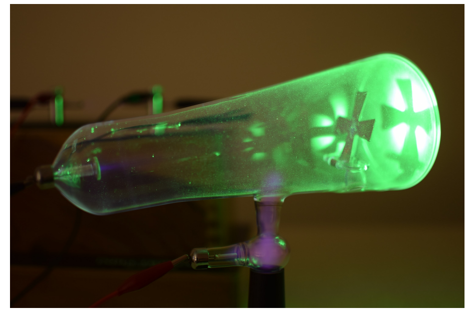


Figure 11: A maltese cross cathode ray tube. Note the position of the anode at the base of the tube. Image credit: The author

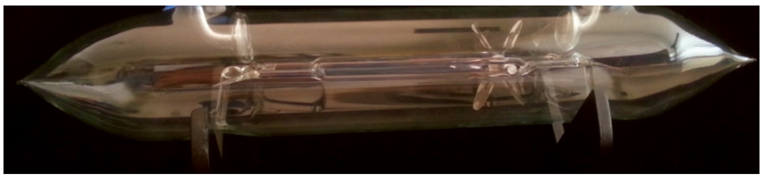


Figure 12: A paddle wheel cathode ray tube. Image credit: The author

Crookes also developed a number of "paddlewheel" cathode ray tubes that demonstrated that a light mica paddlewheel could be propelled along a rail by the cathode rays, in a direction away from the cathode. At the time, Crookes interpreted this effect as evidence that the rays carried momentum (i.e. were a stream of negatively charged particles). Later analysis by J.J. Thomson (after he had established the mass and charge of the electron) concluded that the cathode rays (which he knew to be a stream of electrons) had insufficient momentum to be responsible for the rotation. Instead it is likely that is is a radiometric effect causing this rotation[6].

[6] J. J. Thomson, Conduction of Electricity Through Gases (Cambridge University Press, 1903), pg 501.
See also: A Century-Old Question: Does a Crookes Paddle Wheel Cathode Ray Tube Demonstrate that Electrons Carry Momentum? T.E. Humphrey and V. Calisa, The Physics Teacher, **52**, 142 (2014).`https://fathomingphysics.nsw.edu.au/wp-content/uploads/2017/07/TEHumphrey_VCalisa_Phys_Teach_vol_52_iss_3_142_2014.pdf`

Perrin's experiment

In his 1895 paper, read to the Paris Academy of Sciences, Jean Perrin outlines the current state of understanding:

> Two hypothesis have been propounded to explain the properties of the cathode rays. Some physicists think with Goldstein, Hertz, and Lenard, that this phenomenon is like light, due to vibrations of the ether1 or even that it is light of short wavelength. It is easily understood that such rays may have a rectilinear path, excite phosphorescence, and effect photographic plates.
> Others think, with Crookes and J.J. Thomson, that these rays are formed by matter which is negatively charged and moving with great velocity, and on this hypothesis their mechanical properties, as well as the manner in which they become curved in a magnetic field, are readily explicable.

Perrin undertook to further test the hypothesis that the rays consisted of negatively charged particles by showing that the rays negatively charged electroscopes placed inside the tubes.

Summary: Early experiments examining the nature of cathode rays

- The development of the Rühmkoff induction coil, in-glass electrodes and new vacuum pump technology from the 1850s enabled the investigation of electrical discharges in evacuated cathode ray tubes.
- Initially, there was conflicting evidence for whether cathode rays were a type of light (vibration in the aether) or charged particles.
- German physicists, including Plücker, Hittorf, Hertz and Lenard believed that cathode rays were a type of light as they demonstrated rectilinear propagation (produced sharp shadows), produced phosphorescence, passed through thin metal films and were (initially) not observed to be deflected by electric fields.
- English and French physicists, including Crookes, Perrin and J.J. Thomson, believed they were negatively charged particles on the basis that they negatively charged electroscopes, could rotate a paddlewheel tube, and were deflected by a magnetic field.
- J.J. Thomson conclusively demonstrated in 1897 that cathode rays were negatively charged particles by demonstrating that they were in fact able to be deflected by electric fields if the cathode ray tube is sufficiently highly evacuated (as discussed in the next section).

Thomson discovers the electron

Video: `https://www.youtube.com/watch?v=dkGTFhmC18g`

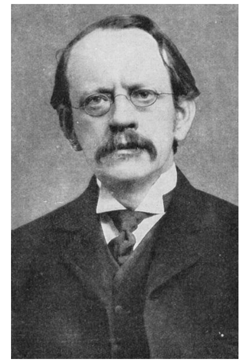


Figure 13: J.J. Thomson. Image credit: Public Domain `https://en.wikipedia.org/wiki/J._J._Thomson#/media/File:J.J_Thomson.jpg`

Thomson settles the debate: cathode rays are negatively charged particles

J.J. Thomson conducted experiments passing cathode rays between charged plates in tubes that were more highly evacuated than those used in earlier research by Hertz, and so established conclusively that cathode rays were in fact streams of charged particles.

Thomson discovers the electron: the measurement of q/m

In 1897 J.J. Thomson used the cathode ray tube shown below to experimentally determine the charge to mass ratio (q/m) for cathode rays, which later came to be understood to be electrons.

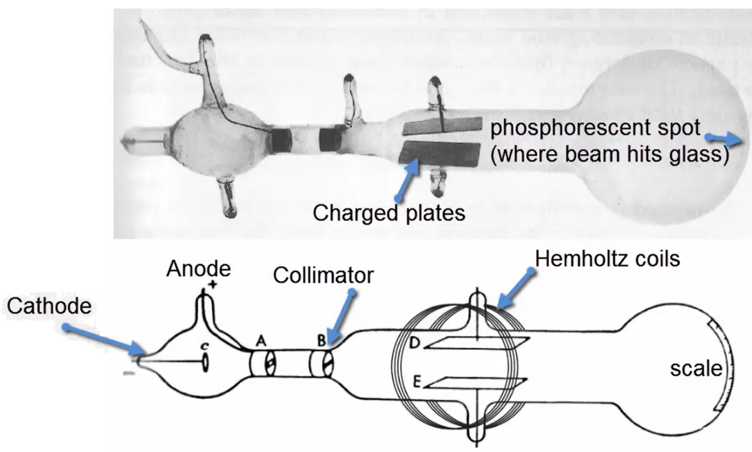


Figure 14: (Top) The cathode ray tube Thomson used for his experiment to measure q/m. Note that the Hemholtz coils used to produce the magnetic field are not present. (Bottom) A diagram of the equipment, including the Hemholtz coils.

In this tube, electrons are emitted from the cathode and accelerate towards the anode, due to an electric field applied between these. A small hole in the anode means that some electrons pass through and continue through a second collimator slit, which ensures that a narrow beam is produced. The beam may then be deflected by an electric field produced by charged plates and/or by a magnetic field produced by two Hemholtz coils on either side of the tube. The beam then produces a fluorescent spot where it hits the far end of the tube.

There are two parts to the experiment. In the first part *only* the magnetic field is switched on, and the beam deflects in the arc of a circle. Thomson could calculate the magnetic field strength due to the coils, and using geometry, Thomson could also measure the radius of the deflection. Using $\Sigma F = ma$, so that $qvB = m\frac{v^2}{r}$ and he could obtain q/m:

$$\frac{q}{m} = \frac{v}{rB}$$

The problem is that the velocity of the electrons is still undetermined.

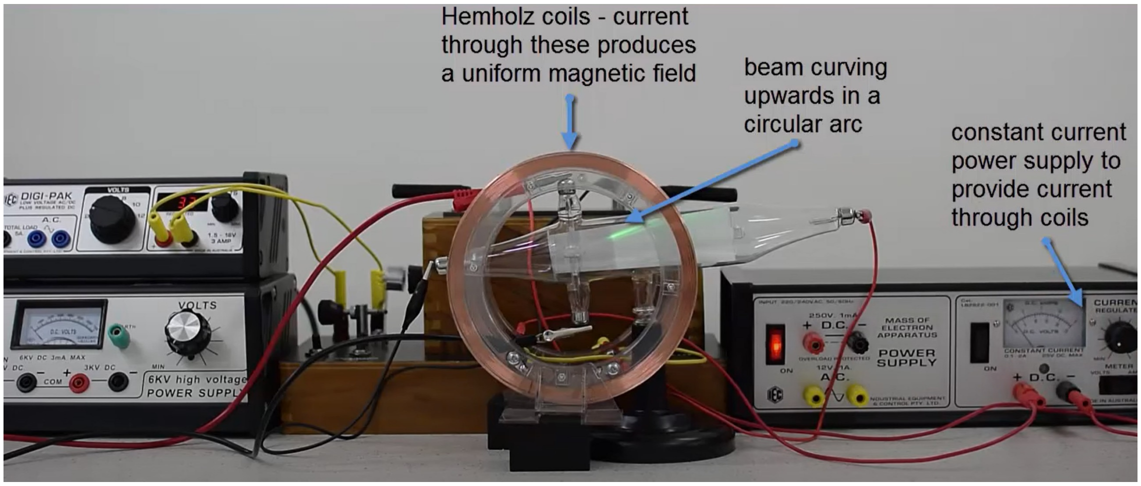


Figure 15: A setup demonstrating the deflection of cathode rays by a magnetic field produced by Hemholtz coils. Image credit: The author.

In the second part of the experiment, Thomson applied an electric field *as well* as a magnetic field by applying a voltage between parallel plates inside the cathode ray tube. By adjusting the voltage until there was no deflection of the beam, the force due to the electric field could exactly balance the force due to the magnetic field, so that:

$$qE = qvB$$

In this way Thomson could determine the velocity of the electrons as $v = \frac{E}{B}$, and substitute this into his previous expression for the charge to mass ratio to find:

$$\frac{q}{m} = \frac{E}{rB^2}$$

which consisted of values he could calculate and measure.

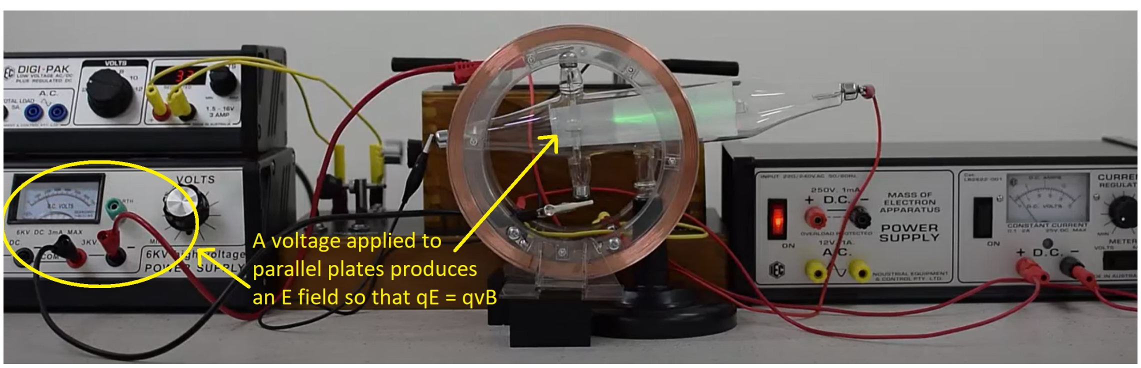


Figure 16: A setup demonstrating the cancellation of the forces due to both an electric and magnetic field acting on cathode rays. Image credit: The author.

Millikan's oil drop experiment

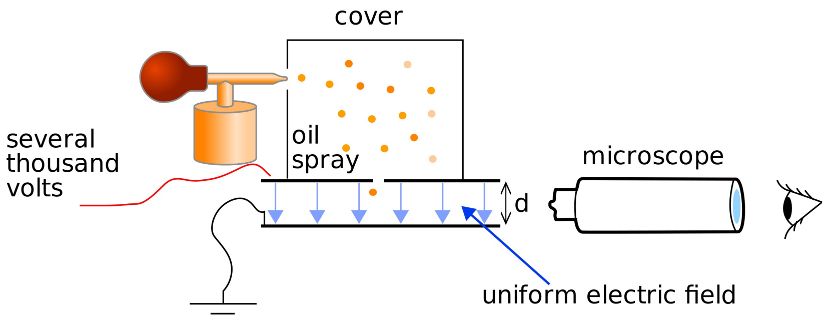


Figure 17: CA simplified diagram of Millikan's oil drop experiment. Image credit: `https://commons.wikimedia.org/w/index.php?curid=14695366`

Figure 18: Robert Millikan, circa 1923. Image credit: By Nobel foundation - `http://nobelprize.org/nobel_prizes/physics/laureates/1923/millikan-bio.html`, Public Domain, `https://commons.wikimedia.org/w/index.php?curid=6207477`

Between 1910 and 1913 Robert Millikan, assisted by Harvey Fletcher, conducted experiments to determine the charge on an electron by timing droplets of oil as they fell (or rose) in an electric field produced by two charged plates (see figure 17)[7].

Individual droplets of oil could accumulate positive or negative charges due to the ionisation of the air in the chamber by an X-ray source (see bottom right of figure 20). As the oil droplets were small, the drag force (modelled according to Stokes law) was sufficiently large that they fell downwards with a constant (terminal) velocity if the gravitational force on the droplet was larger than the upward electrical (and buoyant) force, or moved upwards with a constant (terminal) velocity if the electrical (and buoyant) force was larger than the gravitational force.

[7] References: Original paper: `https://journals.aps.org/pr/pdf/10.1103/PhysRev.2.109`, Review articles: `https://physics.aps.org/articles/v5/9`, `http://www.kcvs.ca/site/projects/physics_files/millikan/documents/chemEd.pdf`, `https://physicstoday.scitation.org/doi/pdf/10.1063/1.2743125`

Figure 19: Millikan's oil drop apparatus. Image Credit: Wikipedia [Public domain]

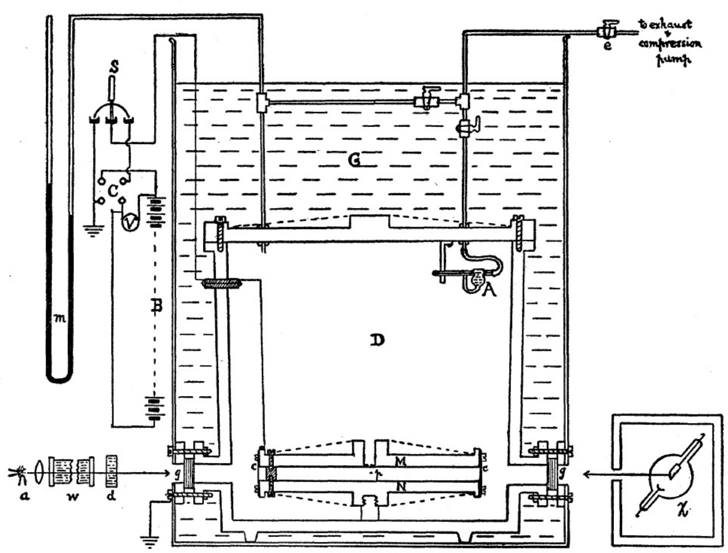


Fig. 1.

Figure 20: Diagram of the oil-drop experiment, from Millikan's 1913 paper. The water bath (to maintain constant temperature) and X-ray source (to ionise the air in the chamber) are shown.

In each measurement Millikan observed an individual droplet that was positioned in focus in the field of view of the telescope and repeatedly timed its movement up and down, switching the electric field on and off to ensure the same individual droplet remained in view for many measurements as it gained or lost charge.

In the introduction to his 1913 paper, Millikan says:

> The essential feature of the method consisted in repeatedly changing the charge on a given drop by the capture of ions from the air and in thus obtaining a series of charges with each drop. These charges showed a very exact multiple relationship under all circumstances - a fact which demonstrated very directly the atomic structure of the electric charge.

Summary: Millikan's oils drop experiment

Between 1910 and 1913, Robert Millikan:

- demonstrated that charge is quantised and
- measured the charge on individual electrons

In his experiment, a fine mist of tiny oil droplets was sprayed into a chamber where the droplets picked up charges from air ionised by X-rays. A voltage applied between two parallel plates could be used to switch an electric field on or off. By measuring the velocity of a very large number of individual droplets with the field on and with the field off, Millikan could establish that the droplets always carried an integer amount of a fundamental unit of charge, as well as accurately determining the value of this fundamental charge (the charge on an electron).

Models in Physics

The syllabus defines a model as:

> A representation that describes, simplifies, clarifies or provides an explanation of the workings, structure or relationships within an object, system or idea.

This definition could be elaborated upon a little to say that a physical model is an abstraction which captures the most important and relevant behaviour of the system, while ignoring aspects that are thought to be less significant or important for the particular scientific investigation.

Models can be tested by using them to make predictions that can be checked experimentally. If the results agree with the predictions of the model then it may be accepted as a good working representation of the system of interest - at least until any contradictory experimental results arise.

As an example we can consider Newtonian mechanics, which describes the relationship between the net external force acting on an object and its acceleration. This model yielded results in agreement with experiment up until physicists began to study particles moving at very high speeds, at which point the predictions of the model no longer agreed with the real behaviour of particles. A new model (special relativity) was adopted as it yields results which are in agreement with experiment.

Rather than abandon Newtonian mechanics, however, we continue to use it widely as a model as it describes very closely the behaviour of any physical system that does not involve relativistic speeds or atomic sizes. The difference is that we now recognise it to be an approximation to reality, rather than an exact description.

Modelling experiments on electrons

The syllabus asks us to "investigate, assess and model the experimental evidence supporting the existence and properties of the electron". To address the modelling component, we will look at an online simulation of Thomson's experiment. We will try to answer the following questions for our simulation:

- how well does the simulation model the *original experiment*?
- what are the advantages and disadvantages of the simulation in terms of promoting understanding of the original experiment?
- what simplifications of the *physics* have been made to allow for easier numerical implementation?

Modelling Thomson's experiment

We will use the model at Physlet Quantum Physics: `https://www.compadre.org/PQP/quantum-need/section4_4.cfm`

Follow the instructions to calculate a value for the change to mass ratio of the electron.

How does this model compare to the experiment Thomson actually performed? See `http://web.lemoyne.edu/~giunta/thomson1897.html` (or `http://www.ymambrini.com/My_World/History_files/JJThomson.pdf`) for a copy of his original paper.

Development of the nuclear model of the atom

Background: Thomson's "plum pudding" model of the atom

After his discovery of the electron, J.J. Thomson worked on an atomic model in which he proposed that all atoms are constituted by some number of fundamental particles - the corpuscles he discovered (now known as electrons) embedded within a region of diffuse positive charge[8].

Thomson refined his model between 1904 and 1909, calculating that stability could be achieved if large numbers of electrons (of the order of several thousand) rotated in concentric rings. For large numbers of electrons, Thomson could show that the emission of radiation due to their acceleration became very small and could effectively be neglected.

In the introduction to his 1904 paper, Thomson describes the model he is investigating:

> The view that the atoms of the elements consist of a number of negatively electrified corpuscles enclosed in a sphere of uniform positive, electrification, suggests... ...the motion of a ring of *n* negatively electrified particles placed inside a uniformly electrified sphere.

And in his summary at the end of his paper:

> We suppose that the atom consists of a number of corpuscles moving about in a sphere of uniform positive electrification: the problems we have to solve are:
> (1)what would be the structure of such an atom, i.e. how would the corpuscles arrange themselves in the sphere; and
> (2) what properties would this structure confer upon the atom.
> The solution of (1) when the corpuscles are constrained to move in one plane is indicated by the results we have just obtained – the corpuscles will arrange themselves in a series of concentric rings. This arrangement is necessitated by the fact that a large number of corpuscles cannot be in stable equilibrium when arranged as a single ring, while this ring can be made stable by placing inside it an appropriate number of corpuscles. When the corpuscles are not constrained to one plane, but can move about in all directions, they will arrange themselves in a series of concentric shells; for we can easily see that, as in the case of the ring, a number of corpuscles distributed over the surface of a shell will not be in stable equilibrium if the number of corpuscles is large, unless there are other corpuscles inside the shell, while the equilibrium can be made stable by introducing within the shell an appropriate number of other corpuscles.

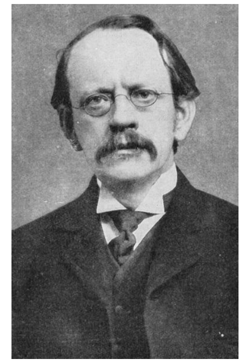


Figure 21: J.J. Thomson. [Public domain]

[8] References for this section: J.J. Thomson's 1897 and 1904 papers (`http://www.hep.princeton.edu/~mcdonald/examples/EP/thomson_pm_44_293_97.pdf` and `http://fizika.unios.hr/~ilukacevic/dokumenti/materijali_za_studente/qm1/Thomson_1904.pdf`), "Quantum Generations" by Helge Kragh, pg. 44, and "Inward Bound" by Abraham Pais, pg. 185

Difficulties with the model were:

- the vague nature of the positive charge in which the electrons were embedded
- the gradual accumulation of evidence after 1906 that the number of electrons in atoms was small - likely of the same magnitude as the ordering number of the atom in the periodic table
- the inability of the model to quantitatively predict the spectral lines of atoms
- by 1909, its inconsistency with the results of the α scattering experiments of Geiger and Marsden

The Geiger-Marsden experiment

Working at the University of Manchester under the guidance of Ernest Rutherford just prior to 1909, postdoctoral fellow Hans Geiger and undergraduate student Ernest Marsden conducted experiments to detect the scattering of α particles incident upon thin metal films[9].

Ernest Marsden described the genesis of the experiment as follows:

> One day Rutherford came into the room where we were counting... α-particles... turned to me and said "See if you can get some effect of α-particles directly reflected from a metal surface". I do not think he expected any such result, but it was one of those "hunches" that perhaps some effect might be observed... To my surprise I was able to observe the effect looked for... I well remember reporting the result to Rutherford a week after, when I met him on the steps leading to his private room"

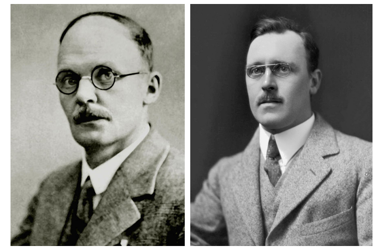


Figure 22: Hans Geiger (left) and Ernest Marsden (right). [Public domain]

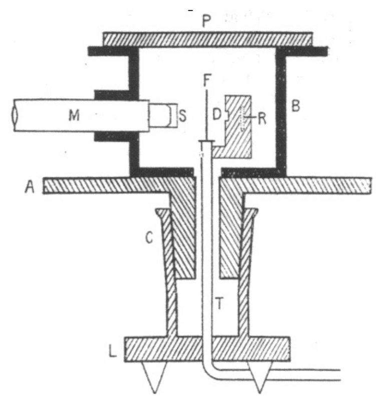


Figure 23: The diagram of the experimental setup from Geiger and Marsden's 1913 paper. M-microscope, F-metal film, S-ZnS screen, R-radon source (surrounded by Pb box to contain β emissions), D-diaphagm to allow narrow α-particle beam, P-glass plate to seal chamber, T-tube used to evacuate chamber, A-graduated circular platform on which the microscope and screen can be rotated.

[9] References for this section: Geiger and Marsden's 1909 and 1913 papers (`https://www.chemteam.info/Chem-History/GeigerMarsden-1913/GeigerMarsden-1913.html`, "Quantum Generations" by Helge Kragh, pg. 51, and "Inward Bound" by Abraham Pais, pg. 189

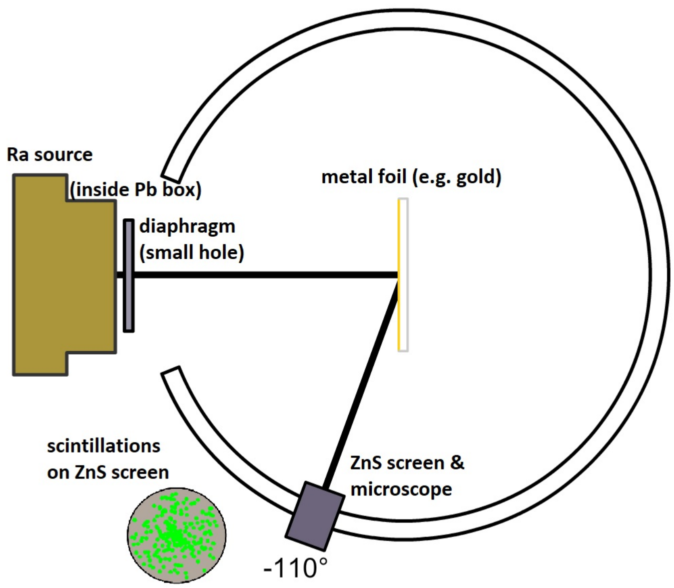


Figure 24: Diagram of Geiger and Marsden's 1913 experiment. Image credit: Applet created by the King's center for visualisation in science: `http://www.kcvs.ca/site/projects/physics_files/rutherford/historical_scattering2.swf`. Labelled according to the diagram in Geiger and Marsden's 1913 paper `https://www.chemteam.info/Chem-History/GeigerMarsden-1913/GeigerMarsden-1913.html`

In 1909 Geiger and Marsden reported their initial results that a small fraction (1/8000 in the case of platinium) α particles incident on thin metal experiences large angle α scattering. In a more complete paper in 1913 they reported results which showed agreement with detailed predictions of Rutherford's 1911 model of the atom. They concluded:

> The experiments described in the foregoing paper were carried out to test a theory of the atom proposed by Prof. Rutherford, the main feature of which is that there exists at the centre of the atom an intense highly concentrated electrical charge. The verification is based on the laws of scattering which were deduced from this theory.
> The following relations have been verified experimentally :

1. The number of a particles emerging from a scattering foil at an angle ϕ with the original beam varies as $\frac{1}{\sin^4 \phi/2}$, when the α particles are counted on a definite area at a constant distance from the foil. This relation has been tested for angles varying from 5° to 150°, and over this range the number of a particles varied from 1 to 250,000 in good agreement with the theory.
2. The number of a particles scattered in a definite direction is directly proportional to the thickness of the scattering foil for small thicknesses. For larger thicknesses the decrease of velocity of the a particles in the foil causes a somewhat more rapid increase in the amount of scattering.
3. The scattering per atom of foils of different materials varies approximately as the square of the atomic weight. This relation was tested for foils of atomic weight from that of carbon to that of gold.
4. The amount of scattering by a given foil is approximately proportional to the inverse fourth power of the velocity of the incident a particles. This relation was tested over a range of velocities such that the number of scattered particles varied as 1 : 10.
5. Quantitative experiments show that the fraction of particles of Ra C, which is scattered through an angle of 45° by a gold foil of 1 mm. air equivalent (2.1×10^{-5}cm), is 3.7×10^{-7} when the scattered particles are counted on a screen of 1 sq. mm. area placed at a distance of 1 cm. from the scattering foil. From this figure and the foregoing results, it can be calculated that the number of elementary charges composing the centre of the atom is equal to half the atomic weight.

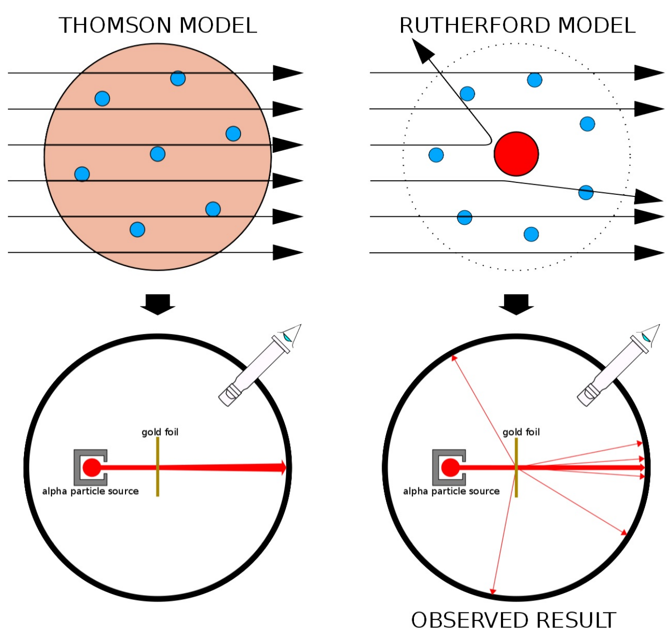


Figure 25: Predictions of Thomson and Rutherford models of the atom for α-particle scattering through thin metal foils. Image credit: By Kurzon - Own work, CC BY-SA 3.0, `https://commons.wikimedia.org/w/index.php?curid=32215297`

Rutherford's atomic model

Later in life, Rutherford expressed his surprise at Geiger and Marsden's initial results showing large angle deflections of α particles as follows:

> "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you"

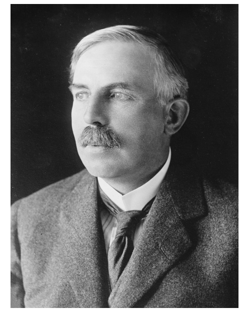


Figure 26: Ernest Rutherford. [Public domain]

Based on their results, Rutherford develop a model of the atom which he published in 1911.[10] In the introduction to the paper he describes his model as follows:

> Consider an atom which contains a charge $\pm Ne$ at its centre surrounded by a sphere of electrification containing a charge $\mp Ne$ supposed uniformly distributed throughout a sphere of radius R. e is the fundamental unit of charge... We shall suppose that for distances less than 10^{-12}cm. the central charge and also the charge on the α particle may be supposed to be concentrated at a point. It will be shown that the main deductions from the theory are independent of whether the central charge is supposed to be positive or negative. For convenience, the sign will be assumed to be positive. The question of the stability of the atom proposed need not be considered at this stage, for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts.

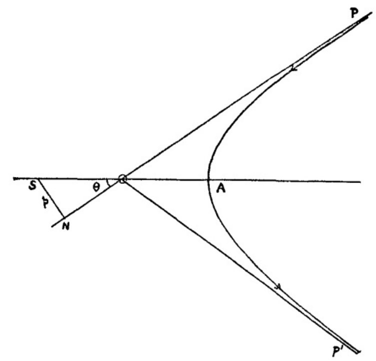


Figure 27: Scattering of an α particle in a hyperbolic trajectory in Rutherford's 1911 paper.

[10] References for this section: Rutherford's 1911 paper: `http://www.ymambrini.com/My_World/MMJC4Nov13_files/rutherford_PhilMag_21_669_1911.pdf`, Rutherford's 1914 paper: `https://www.chemteam.info/Chem-History/Rutherford-1914.html`, "Quantum Generations" by Helge Kragh, pg. 51, and "Inward Bound" by Abraham Pais, pg. 189

While Rutherford does not propose his own model for the distribution of outer changes (i.e. the electrons), in the conclusion to his paper, Rutherford makes a brief reference to an earlier proposed "planetary" model of the atom by the Japanese physicist Nagaoka:

> It is of interest to note that Nagaoka has mathematically considered the properties of a " Saturnian" atom which he supposed to consist of a central attracting mass surrounded by rings of rotating electrons. He showed that such a system was stable if the attractive force was large. From the point of view considered in this paper, the chance of large deflexion would practically be unaltered, whether the atom is considered to be a disk or a sphere.

By 1914, Rutherford had additional evidence from the more detailed experiments of Geiger and Marsden to allow him to refine his theory further. In his 1914 paper he describes his model as follows:

> In my previous paper I pointed out the importance of the study of the passage of the high speed α and β particles through matter as a means of throwing light on the internal structure of the atom. Attention was drawn to the remarkable fact, first observed by Geiger and Marsden, that a small fraction of the swift α particles from radioactive substances were able to be deflected through an angle of more than 90° as the results of an encounter with a single atom. It was shown that the type of atom devised by Lord Kelvin and worked out in great detail by Sir J. J.

> Thomson was unable to produce such large deflexions unless the diameter of the positive sphere was exceedingly small. In order to account for this large angle scattering of α particles, **I supposed that the atom consisted of a positively charged nucleus of small dimensions in which practically all the mass of the atom was concentrated. The nucleus was supposed to be surrounded by a distribution of electrons to make the atom electrically neutral, and extending to distances from the nucleus comparable with the ordinary accepted radius of the atom**. Some of the swift α particles passes through the atoms in their path and entered the intense electric field in the neighbourhood of the nucleus and were deflected from their rectilinear path.

Finally, Rutherford acknowledges the issues with the stability of a 'nuclear' atomic model, and the solution that Bohr proposed in 1913:

> Bohr has drawn attention to the difficulties of constructing atoms on the "nucleus" theory, and has shown that the stable positions of the external electrons cannot be deducted from the classical mechanics. By the introduction of a conception connected with Planck's quantum, he has shown that on a certain assumptions it is possible to construct simple atoms and molecules out of positive and negative nuclei, e. g. the hydrogen atom and molecule and the helium atom, which behave in many respects like the actual atoms or molecules. While there may be much difference of opinion as to the validity and of the underlying physical meaning of the assumptions made by Bohr, there can be no doubt that the theories of Bohr are of great interest and importance to all physicists as the first definite attempt to construct simple atoms and molecules and to explain their spectra.

Modelling Thomson and Rutherford's atoms

According to the syllabus:

> **A model is:** A representation that describes, simplifies, clarifies or provides an explanation of the workings, structure or relationships within an object, system or idea.

We will do two types of modelling exercises in this section.

The first is a physical model of the behaviour of the Thomson and Rutherford atomic models in the Geiger-Marsden experiment. We will ask ourselves:

- how does the behaviour we observe in our physical model *correctly* reproduce the predicted behaviour of the Rutherford and Thomson atoms in the Geiger Marsden experiment
- what behaviours are *not correctly* reproduced by this model
- assess the value of the *physical* model in the sense described in the syllabus - how effective is our physical model in describing, simplifying or clarifying the behaviour of the two competing models of the atom in the Geiger-Marsden experiment.

Our physical model:

We will use two large hoops, one covered in tissue paper, and one empty with a billiard ball suspended in the center.

The class will take turns to throw ping pong balls (representing α particles) at the two atoms.

Online simulation 1:

Open the following url: `https://www.compadre.org/PQP/quantum-need/section4_6.cfm` and explore the simulations in section 4.6 on Thomson's model, and 4.7 on Rutherford's model.

Online simulation 2:

Open the following page in a browser that supports flash (eg internet explorer), if you have one: `http://kcvs.ca/concrete/visualizations/modern-physics#Thomson_eoverm` and scroll to the bottom to select "Rutherford scattering experiment".

We will answer the same questions as for the physical model...

Chadwick's discovery of the neutron

As early as in his 1914 paper discussed in the previous section, Rutherford conceived of the idea that the nucleus may contain electrons in addition to positive particles (which at the time he termed 'positive electrons'):

> An important question arises whether the atomic nuclei, which all carry a positive charge, contain negative electrons. This question has been discussed by Bohr*, who concluded from the radioactive evidence that the high speed β particles have their origin in the nucleus. The general radioactive evidence certainly supports such a conclusion. It is well known that the radioactive transformations which are accompanied by the expulsion of high speed β particles are, like the α ray changes, unaffected by wide ranges of temperature or by physical and chemical conditions. On the nucleus theory, there can be no doubt that the α particle has its origin in the nucleus and gains a great part, if not all, or its energy of motion in escaping from the atom. It seems reasonable, therefore, to suppose that a β ray transformation also originates from the expulsion of a negative electron from the nucleus.

The belief that electrons are bound in the nucleus continued until 1932, with Chadwick's discovery of the neutron.

In 1930 Walther Bothe and Herbert Becker in Berlin found that if Beryllium was bombarded with α particles, an energetic radiation was emitted, which they believed to be gamma rays.[11]

In 1932 Irène Curie and her husband Frèdèric Joliot began to study the phenomenon, and found that the radiation could expel protons from paraffin wax. They interpreted this as a kind of 'Compton effect' (Compton discovered that electromagnetic radiation could scatter electrons in a "collision" that conserved momentum)

Chadwick and Rutherford, however, believed that the 'unknown radiation' the Joliot-Curies' had observed was in fact the particle they had been searching for (although they still conceived of this as a bound proton-pair), so Chadwick immediately set up his own experiment which he reported in his 1932 paper.

[11] References for this section: "Quantum Generations" by Helge Kragh, Chadwick's 1932 paper: `https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1932.0112`

Figure 28: James Chadwick. Image credit: Photo from the Nobel Foundation archive

Chadwick used a Polonium source to produce a particles which impacted a sample of ^{9}Be. The radiation emitted from the beryllium impacted on an ionisation chamber (see figure 6.0.1, right). The sudden production of ions in the chamber by the entry of an ionising particle is detected by means of an oscillograph connected in the output circuit of the amplifier. In one set of experiments the recoil velocity of nitrogen atoms in the ionisation chamber was measured (by measuring the length of the ionisation trails that they left when hit by a neutron). In another set of experiments a sheet of paraffin wax 2mm thick was placed between the Be source and the ionisation chamber, causing protons to be ejected from the paraffin. The velocity of the ejected protons was then determined from range measurements.

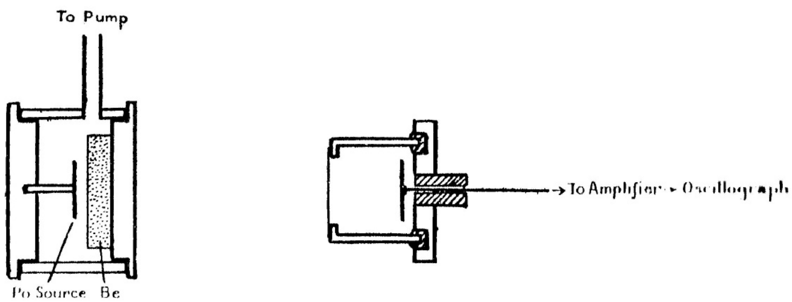


Figure 29: Figure showing experimental apparatus from Chadwick's 1932 paper, showing (left) the polonium source of α particles which impinge upon a ^{9}Be sample, and (right) the ionisation chamber.

Chadwick was able to show that the energy and momentum imparted to the nitrogen and hydrogen atoms meant that the unknown radiation could not be electromagnetic radiation (gamma rays) if energy and momentum were conserved in the collision. Instead Chadwick used **kinetic energy and momentum conservation** to show that the unknown radiation had to be neutral particles with a mass slightly greater than that of a proton.

Conservation of kinetic energy and momentum for the case where one particle (the neutron) has an initial velocity of V and final velocity V_f and the other particle with mass m (the hydrogen or nitrogen atom) has zero initial velocity and final velocity v gives us

$$MV = MV_f + mv$$

and

$$\frac{1}{2}MV^2 = \frac{1}{2}MV_f^2 + \frac{1}{2}mv_f^2$$

respectively.

The first equation can be rearranged to make V_f the subject, to eliminate it from the equation for conservation of KE. The equation for conservation of KE if then rearranged to make the final velocity of the hydrogen or nitrogen atom the subject.

$$MV^2 = M\left(V - \frac{m}{M}v\right)^2 + mv^2$$

$$MV^2 = MV^2 - 2Vvm + \frac{m^2}{M}v^2 + mv^2$$

$$2V = \left(\frac{m}{M} + 1\right)v$$

so

$$v = \frac{2M}{m+M}V$$

Using this equation, Chadwick could write

$$v_{proton} = \frac{2M}{1+M}V$$

$$3.3 \times 10^9 \text{cms}^{-1} = \frac{2M}{1+M}V$$

where the mass of the proton is taken to be 1 and M is the mass of the neutron (as a fraction of the mass of the proton) and V is the initial velocity of the neutron.

$$v_{nitrogen} = \frac{2M}{14+M}V$$

$$4.7 \times 10^8 \text{cms}^{-1} = \frac{2M}{14+M}V$$

. The ratio of these two equations can be taken to eliminate the initial velocity of the neutron, V, so that

$$\frac{3.3 \times 10^9}{4.7 \times 10^8} = \frac{M+14}{M+1}$$

to give a value for M, the mass of the neutron, as a fraction of the mass of a proton from these measurements as $M = 1.15$.

Chadwick also performed other measurements using neutrons emitted from boron, and calculated the mass of the neutron using a calculation of the mass defect in the reaction Mass of ^{11}B + mass of ^4He + K.E. of ^4He = mass of ^{14}N + mass of ^1n + K.E. of ^{14}N + K.E. of ^1n. The mass for the neutron obtained via this measurement was between 1.005 and 1.008 of the mass of a proton.

After obtaining this value, Chadwick speculates (we now know erroneously) about the nature of the particle he has discovered:

> Such a value for the mass of the neutron is to be expected if the neutron consists of a proton and an electron, and it lends strong support to this view.

and towards the conclusion of his paper he continues

It has so far been assumed that the neutron is a complex particle consisting of a proton and an electron. This is the simplest assumption and it is supported by the evidence that the mass of the neutron is about 1.006, just a little less than the sum of the masses of a proton and an electron... ...It is of course possible to suppose that the neutron may be an elementary particle. This view has little to recommend it at present, except the possibility of explaining the statistics of such nuclei as ^14N

References