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Searching for the constituents of the atom

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Abstract. This is a short account of the research that established the electron, proton and neutron as the basic constituents of atoms. It is written from the point of view of a physicist rather than a historian and tries to explain the scientific pathways to establishing these atomic constituents.

1. Introduction

In science the term *discovery* can sometimes be misleading. The emergence of a new idea or concept can be a messy process and assigning credit is not always straightforward. Ideas often float around in flawed embryonic forms for many years, relying on the clarity of thought and insight of particular individuals to cut through the confusion and draw the threads to a clear conclusion. It is also true that the history of science is littered with many more discarded hypotheses than accepted ideas; the terms *electron*, *proton*, *neutron* and related words all existed in the literature in various guises long before being used to describe components of atoms. Demonstration that they were the components of *all* atoms and not just of one specific atom or in a specific experiment is an important step.

The phrase *splitting the atom* is famous, but also misleading. It has been attributed to many different findings during the 20th century, including some of those discussed here. At face value it seems to imply dividing an atom in two, like cutting a cake. But atoms are not amorphous blobs of gloop. They are intricate quantum mechanical structures composed mainly of empty space in which light electrons orbit a very small and heavy nucleus made of protons and neutrons. It will be seen that a better phrase might be *knocking bits out of atoms*, but it is less poetic and makes for a worse newspaper headline.

It is interesting to delve into the late 19th and early 20th centuries, partly because the elements of excellent research in physics have not changed much. Clever people perform ingenious experiments. These experiments are enabled by technological advances that are used to develop cutting-edge equipment - and no one is an island; scientists collaborate and communicate, and usually build on the ideas of others.

Some readers may have studied some physics and some may not. In order to appreciate these historical developments, there are some basic physics results that are useful to summarise before continuing. Electric forces exist between charges; like charges repel and unlike charges attract. A positive charge moving in an electric field generated by a voltage between two electrodes will be attracted towards the negatively charged electrode, altering its direction of motion. This is analogous to the parabolic path of a ball thrown in the Earth's gravitational field which is acting on the mass of the ball. The electric force depends on the strength of the field and the size of the charge. Moreover, the more massive the particle is, the greater its inertia and the harder it is to alter its motion. Therefore, measuring the acceleration of the particle from the deflection of its path by a known field allows the charge-to-mass ratio q/m to be deduced. With q/m measured, if either mass m or charge q is known from another experiment, the other can be found.

The reader may be familiar with the fact that currents in magnetic fields are also subject to forces, for example, generating motion in an electric motor. Currents are composed of moving charges and so a charged particle moving in a magnetic field experiences a magnetic force. These magnetic forces are odd in that the direction of the force is perpendicular to the field and the particle's velocity, forcing it to travel in a circular path. As the size of the force depends on the charge, measuring the acceleration produced by a magnetic field is another way to obtain q/m.

In summary the motion of charged particles is affected by electromagnetic fields and measuring their deflection in a known field can determine the ratio of charge to mass for the particle concerned.

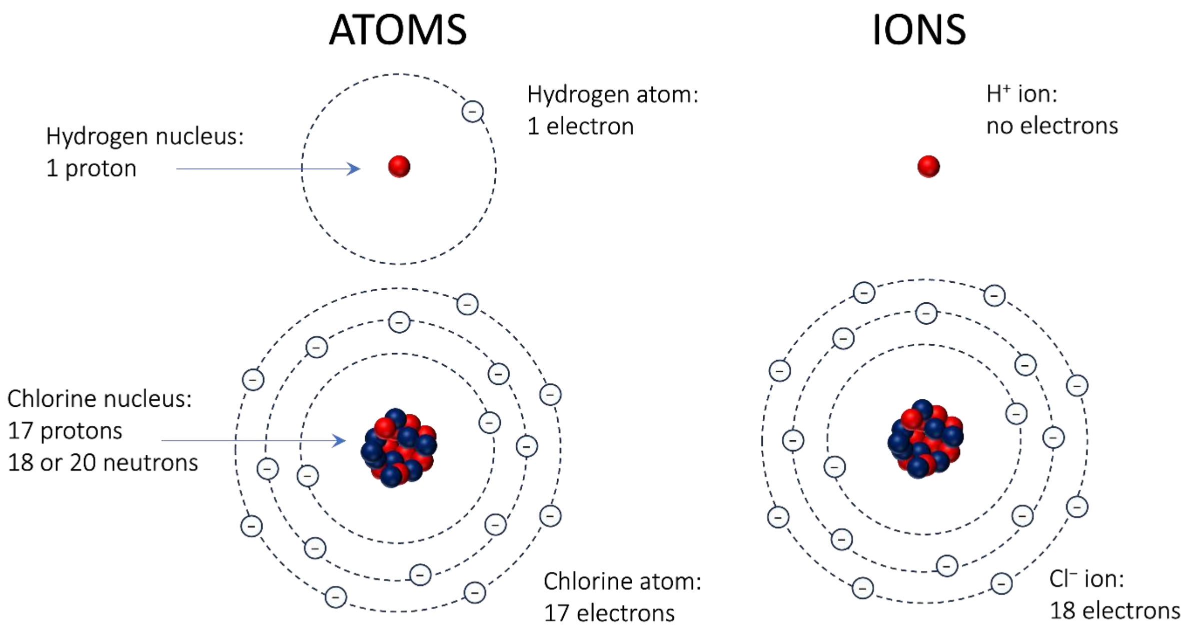

Figure 1. A cartoon of atomic and ionic structures. Do not be misled - the diagram is *not* to scale and the nucleus is a hundred thousand times smaller than the atom. Chlorine has two isotopes with 18 or 20 neutrons - see a later section for more detail on isotopes.

The story starts when atoms were a well-established concept in chemistry and physics but their innards had not yet been considered! When looking back on the historical development, hindsight is very useful to understand the steps that were taken. A cartoon of atomic structure is shown in figure 1. Today it is known that atoms consist of electrons orbiting an atomic nucleus, which itself is composed of protons and neutrons. In an electrically neutral atom the negative charge of the electrons is exactly balanced by the positive charge of the protons. The chemistry of an element concerns the bonds made by the atomic electrons with other atoms. So chemical properties are determined by the number of electrons in the neutral atom or equivalently the number of protons in the nucleus, the so-called atomic number of the element.

Atoms also exist as ions that carry a net electric charge. For example, a hydrogen atom might lose one of its electrons to form a singly-charged ion, H^+. Other atoms such as chlorine might acquire an additional electron to form a singly negative ion, Cl^-. Some atoms can acquire or lose more than one electron, forming multiply charged ions.

Knowing the secret of atomic structure and how atoms acquire charge will help in understanding how the discoveries were reached. When this paper has been read, sit back and wonder how difficult it

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might have been for the scientists involved who did not have our prior knowledge as they tried to solve the puzzle of what their experiments were telling them!

2. Electrons, electrolysis and cathode rays

The emergence of the electron as a fundamental particle rests on countless studies of electrical phenomena over the centuries from static electricity through to electrical currents. By the early 19th century conduction of electricity through materials was attracting interest. At the microscopic level in a metal electrical currents are due to moving electrons. In fluids and gases they correspond to the movement of charged ions.

Electrolysis, the passage of electricity through solutions of chemicals, helped to establish that individual ions could be associated with a fundamental amount of electric charge. With modern interpretation all singly-charged ions only carry a negative charge equal to that of an electron or the same positive amount. (Electrolysis can get complicated, but the complications have been relegated to footnotes.)

If a substance like HCl dissolves in water each molecule breaks up into a positive hydrogen ion[1] H^+ and a negative chlorine ion Cl^-. When a battery is connected to two electrodes dipped into the solution it is these ions that carry the electricity as they move through the liquid.

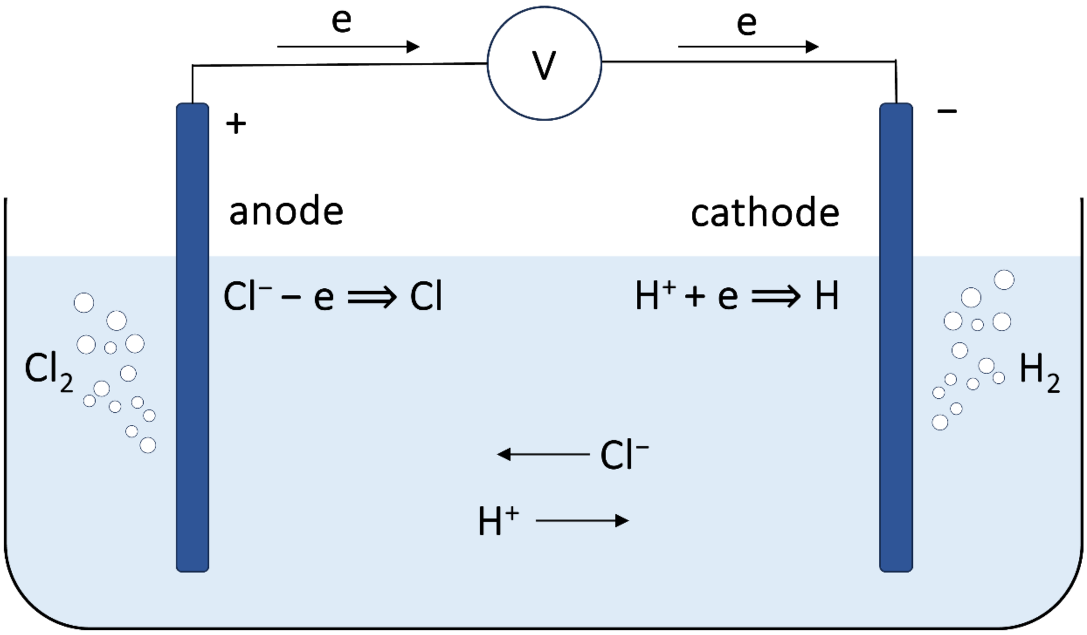

Figure 2. A schematic diagram of electrolysis. Charge flows in the external circuit as electrons moving in the wires and as ions in the solution. Positive ions move towards the negative cathode whereas negative ions are drawn to the positive anode. On reaching the cathode, the positive ions acquire electrons forming atoms. At the anode, the negative ions give up their electrons and also form atoms. In this manner charge flows around the whole circuit. Near the electrodes the liberated atoms combine to form molecules of the respective element, appearing in the form of gases in this example of HCl solution.

[1] When HCl dissolves there is actually a chemical reaction with a water molecule: $HCl + H_2O \rightarrow H_3O^+ + Cl^-$. Instead of a H^+ ion carrying charge it is really a H_3O^+ ion. At the cathode when an electron is added to this *hydronium* ion it produces a hydrogen atom and the water molecule again. As the overall outcome is the same, this complication will be hidden.

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The process is illustrated in figure 2. Let us concentrate for the moment on the negative electrode or cathode which draws positive ions towards it. For currents to flow around the whole circuit electrons must leave the cathode. An electron can do this by combining with an H^+ ion in the solution to form a H atom. Liberated H atoms combine to form H_2 and hydrogen gas will bubble from the cathode. To carry a certain amount of electricity, a certain number of electrons must leave the cathode, so a certain number of H atoms get liberated in this way. It is hard to count atoms, but easier to weigh the hydrogen produced. All hydrogen atoms have the same atomic mass[2], so the weight of the gas produced is proportional to the number of atoms.

A similar process happens at the positive electrode, the anode, which must receive electrons. The Cl^- ions, drawn towards the anode, give up their electron, forming Cl atoms. The atoms combine to form Cl_2 molecules and chlorine gas bubbles form at the anode.

For electrical conduction through the solution, the same number of electrons must leave the cathode and arrive at the anode. So the same number of H and Cl atoms must be produced. If the same amount of charge was passed through another solution that contained different singly-charged ions, then one ends up with the same number of those atoms as one did for H and Cl. The conclusion is Faraday's Law: if an amount of charge flows through a succession of solutions of singly-charged ions, the same number of atoms is deposited at each electrode[3].

This paper began by stating that an ion is an atom that has gained or lost electrons. But if those microscopic facts were not known beforehand, Faraday's Law suggested that a certain number of atoms was associated with a particular amount of electric charge[4]. It is then not a huge leap to suggest that each atom liberated in electrolysis as an ion carried the same amount of charge though the solution. With hindsight it is known that this is the charge carried by one electron but in the 1850s the concept of this fundamental particle was not yet established.

If the total charge passed through the solution and the mass of atoms deposited is measured, the ratio of these two quantities is the same as the q/m for an individual ion. Hydrogen was found to have the highest charge-to-mass ratio. It is now known that the hydrogen atom is one electron orbiting a single proton. The ion is a bare proton and q/m is higher than for other elements because they are heavier with more protons and neutrons in their nuclei. If the mass of an atom[5] was known, the size of the fundamental unit of charge carried by one ion from the q/m ratio could be obtained. In 1874 George Johnson Stoney, an Irish physicist at Queen's University Dublin, estimated this using results from the kinetic theory of gas molecules and extracted a fundamental quantity of electricity, which he called *the electron*. His number for the fundamental charge was five times smaller than modern values, but it was a pretty good estimate for the time. His electron was just a quantity of electricity, not yet a fundamental particle!

Cathode rays were discovered when scientists started looking at how electricity passed through gases at low pressure. These experiments became possible because of new pumps to reduce the pressure of a

[2] This is not strictly true due the presence of the naturally-occurring isotope, deuterium with roughly twice the mass; this can be taken into account but only 0.0156% of the atoms are deuterium. More on isotopes will be discussed later.

[3] Textbooks quote Faraday's Law in terms of something called *chemical equivalent weight* rather than numbers. This concept takes into account multiply-charged ions and also solutions that contain molecular ions like SO_4^{2-} in a sulphate. But things will be kept simple here and a physical chemistry book can be consulted for more information.

[4] For elements that formed doubly-charged ions the same amount of electricity produced half the number of atoms compared to a singly-charged ion as two electrons were needed to neutralise each ion. The more general conclusion is that a particular amount of electricity was associated with ions in integer units; singly, doubly, triply-charged ions being associated with multiples of one, two or three times this fundamental amount.

[5] It is easy to weigh a sample of an element. The weight is the number of atoms multiplied by the atomic mass. The issue boiled down to knowing Avogadro's Number, which related to how many atoms are in a particular mass of that material. For chemists it is the number of atoms in a mole.

gas in a vessel and new power supplies to place high voltages across electrodes in those vessels. Early versions of gas discharge lamps were produced in the 1850s and when high voltage was switched on the gases glowed, as shown in figure 3. It is now known that there are natural processes such as radioactivity that randomly ionise a few atoms in any gas into positive ions and electrons. When high voltage is placed across such gas at low pressure the electrons are accelerated towards the anode and away from the cathode. They look as if they came from the cathode, hence the name *cathode rays*. Conversely the positive ions are repelled from the anode and the paper will come back to these *anode rays* later. Some ions and electrons will crash into other gas atoms causing more ionisation, and the lower the gas pressure the further they travel before this happens. When an electron and an ion recombine a small amount of energy is released as light. With large numbers of recombinations, this light can be seen as the gas glowing inside the vessels. The glass wall itself also has a ghostly green glow when the accelerated electrons hit it.

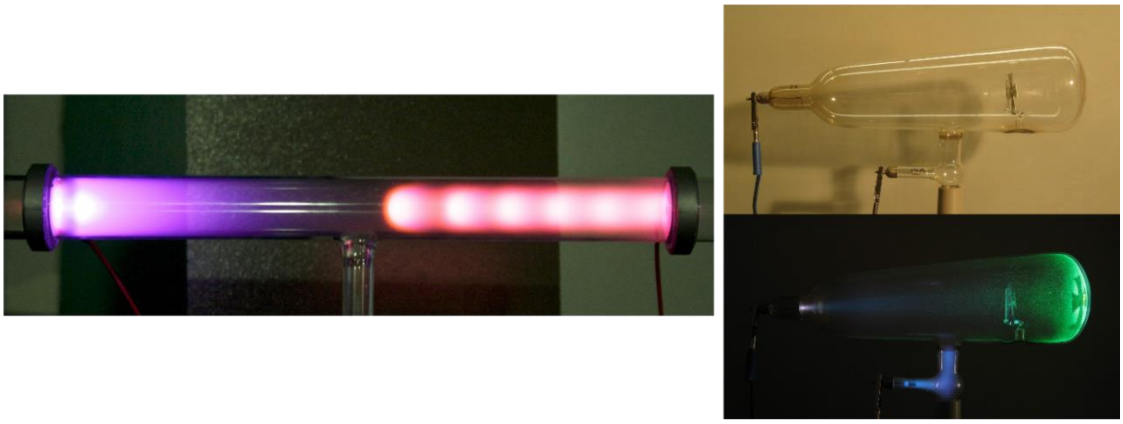

Figure 3. A photograph (left) of a gas discharge tube containing low pressure gas with several thousand volts applied to electrodes at each end. The cathode rays produce the purple glow and the anode rays give a pink/red glow on the other side. The alternating bright and dark bands are caused by instabilities in the ion clouds. *Photo credit: cropped version of Flickr $\#44441894404$ by J.A. Schnitzer, reproduced under CC BY-SA 2.0.* A photograph of a tube (right) at lower pressure. With fewer gas atoms in the vessel the cathode rays (here moving left to right) are less visible inside but a strong green glow is seen as they strike the glass. A shadow is also produced by a metal cross in the tube. *Photo credit: D-Kuru/Wikimedia Commons, reproduced under CC BY-SA 2.0.*

There were lots of arguments about the nature of the cathode rays. British scientists thought they were charged particles. But the German consensus was that they were some new form of electromagnetic radiation mainly because then the only other thing known to cause ghostly green glows was ultraviolet light, which causes certain substances to fluoresce. In 1869 Johann Hittorf found that objects cast shadows in the cathode rays (see figure 3), concluding that cathode rays travelled in straight lines like rays of light and also that the green glows arose as the rays hit the glass. Eugen Goldstein from Berlin in 1876 showed that cathode rays were emitted perpendicular to a flat cathode; this is difficult to explain if they were electromagnetic radiation, which radiates in all directions. Henrick Hertz showed that cathode rays could pass through thin foils just like electromagnetic waves. But particles smaller than atoms might also get through!

Arthur Schuster in 1890 at the University of Manchester showed that cathode rays could be bent by electric fields in a direction suggesting they were negatively charged. William Crookes showed they could also be deflected by a magnet. Electromagnetic radiation is unaffected by electric and magnetic fields in this way. In Paris in 1895 Jean-Baptiste Perrin collected cathode rays in a cup and showed directly that they had negative charge using an electroscope. There were many ideas floating around that

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needed to be drawn together. A viable hypothesis was finally postulated by J.J. Thomson at Cambridge, who argued that particles formed cathode rays. He called them corpuscles but they would later become known as electrons.

Thomson carefully repeated the deflection measurements [1], [2]. The force on a particle due to an electric field depends on its charge and the field strength. Similarly the force due to a magnetic field depends on charge and field strength, but also on the velocity of the charge. If known magnetic *and* electric fields are used, the dependency on charge can be cancelled and therefore the speed of the corpuscles can be inferred. Thomson found that they travelled astonishingly fast, around a thousand times the speed of hydrogen molecules in a gas. These corpuscles moved faster than any material object that had been measured before at a third of the speed of light. Then he used electric deflection alone to measure the charge-to-mass ratio. The q/m was huge, around seventeen hundred times bigger than H^+ ions in electrolysis. Either the electron charge was huge or its mass was tiny. Moreover, Thomson found corpuscles with exactly the same q/m from many different sources. They were emitted from hot metals when light hit certain metals and by radioactive substances. Therefore, these corpuscles seemed to be a universal component of matter. This was the discovery of the electron as a fundamental component of all atoms.

The charge on the electron was clearly an important thing to determine. There were several measurements made in Cambridge following the observation by Charles Wilson that ions act as centres for condensation of vapours into droplets. If the number of droplets is counted and the total mass of the vapour is measured, the average mass of one droplet is obtained. Their weight would make the droplet fall under gravity, but if an electric field was applied, that force could be counterbalanced with an electric force depending on field and the charge of the drop. If the field strength is known, the droplet's charge can be determined. Assuming one ion condenses one drop, the charge per ion is obtained, which should be a multiple of the fundamental unit of charge. These are really tricky experiments for many different reasons. A few years later Robert Millikan made the definitive measurement in Chicago on individual drops of oil. This gets one out of many problems, although Cambridge values were not too far off.

The size of the fundamental charge turned out to be the same as the positive charge on a H^+ ion. Given their much greater q/m electrons must be tiny, around seventeen hundred times less massive than H^+ ions. The fundamental unit of electricity had therefore become tied to Thomson's corpuscles, which is why they acquired the name *electrons*. We still have not directly seen *any* charges less that of an electron, which seems to be the smallest lump of charge that can occur. Later positively charged electrons, antimatter equivalents called positrons, were found in cosmic rays. The modern understanding of an electron as a point-like particle – so it has no size – but with mass, charge and spin, still feels mysterious.

3. Protons, the nuclear atom and nuclear reactions

The proton is the atomic nucleus of the hydrogen atom - at least that is now known! The proton was discovered soon after it had been established that the atom had a nucleus.

In 1815 William Prout, a physician and part-time chemist in London, noticed that early measurements of atomic masses were roughly integer multiples of the mass of the hydrogen atom. He suggested that all atoms were composed of H atoms or *protyles*. That might be interpreted as being the first suggestion that protons were a component of atoms but as more measurements were done the situation became confused; some atomic masses appeared not to be integer multiples of the H atom. This happened because measurements were made of the average mass of a sample of atoms, but some elements are mixtures of isotopes, atoms of the same element but with different atomic masses. It will be seen later that neutrons are needed to explain isotopes.

Goldstein's studies of cathode rays were briefly mentioned previously. In 1886 he was the first to observe anode rays, composed of moving positive ions in gas discharge tubes. If the gas in the tube was hydrogen then it is known now that the ions are protons. Some people attribute the discovery of protons to him, except that he had no idea that they were universal components of all atoms. And anode rays are only protons when hydrogen is used; usually they are ionised gas atoms.

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Different gases have ions with different q/m, due to their differing molecular masses and because some ions have multiple charges. In 1898 Wilhelm Wien showed that hydrogen had anode rays with the largest q/m, a similar finding to that for H^+ ions in electrolysis. Thomson used electrons to develop a crude model of the atom with negative corpuscles embedded in a blob of positive material like plums in a pudding. Positive gas ions were formed by plucking plums out of the pudding, explaining the formation of ions in anode rays.

In a new job at Manchester in the early 1900s Ernest Rutherford – my great-great-grand PhD supervisor in the genealogy of research supervision – was fresh from pioneering research on radioactive decay in Canada. Three different types of radioactivity, α, β and γ, had been characterised[6] but their true nature was only just being worked out. Just after coming to Manchester Rutherford proved that α particles were identical to ions of helium [3].

In 1906 Rutherford noticed that a beam of α particles from a radium source spread out slightly when passing through a metal foil. Radium, extracted from uranium ore, was one of the most expensive substances at the time. He assigned an undergraduate student, Ernest Marsden and Hans Geiger (of the eponymous counter fame) to investigate. They did experiments over the winter of 1909 that revealed a strange phenomenon. In addition to the slight spreading occasionally some α particles underwent huge deflections at large angles. These large deflections were not consistent with Thomson's plum pudding.

Rutherford pondered the results over the next winter and announced his conclusion at the Manchester Literary and Philosophical Society in March 1911: *The theory of JJ Thomson does not entertain a very large deflection of an α particle traversing a single atom, unless it is supposed that the diameter of the sphere of positive electricity is minute compared with the diameter of influence of the atom.* The atomic nucleus was born: a minute nucleus of concentrated positive charge generating electrical fields capable of reversing the trajectories of a small number of α particles making head-on collisions. It carries practically all the atomic mass with featherweight electrons orbiting around it. This finding is still used in marketing the city of Manchester today.

As a follow up Marsden investigated α particles travelling through hydrogen gas. He found that the collision of an α particle with a hydrogen atom could cause the atom to be knocked forward, a bit like playing nuclear billiards. These knocked-on *H particles* appeared to travel four times the range of α particles. He found knocked-on atoms when using other gases but he always saw longer-ranged H particles as well and their rate seemed to far exceed the amount of any stray hydrogen that might exist as a contaminant in these other gases. Given that they were a common feature of all his experiments he speculated incorrectly that they might be also emitted along with the α particles by the radioactive source. He then left for a job in New Zealand in 1915.

Rutherford was intrigued and continued experimenting when he could between war work on the detection of submarines. He used equipment similar to that shown in figure 4. The results were published in four classic papers in 1919 [4]-[7]. He found that the particles knocked on in hydrogen gas were indeed hydrogen nuclei by measuring their q/m and determined velocities, using similar methods to Thomson's corpuscle experiments. He showed that in very close collisions the characteristics were not consistent with electrostatic forces; this is the first evidence for the strong nuclear force at play. He measured carefully recoiling oxygen and nitrogen atoms produced by elastic collisions of α particles with those gases. Then he found something really surprising. If he was looking at the H particles produced by the interaction of α particles on hydrogenous substances in a vacuum, the number would increase dramatically when nitrogen gas was introduced. He very carefully and painstakingly eliminated all possibilities except the conclusion that the α particles were interacting with nitrogen nuclei to produce the H particles.

In the last paper in the series he noted with caution *...it is difficult to avoid the conclusion that the long-range atoms arising from the collision of α's with nitrogen are not nitrogen atoms but probably atoms of hydrogen. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom*

[6] Several more have been discovered since!

which is liberated formed a constituent part of the nitrogen nucleus [7]. Later experiments showed that what was true with nitrogen was true with other gases and metal foils. The H particles or protons could be liberated from all elements and were therefore a universal constituent of all atomic nuclei.

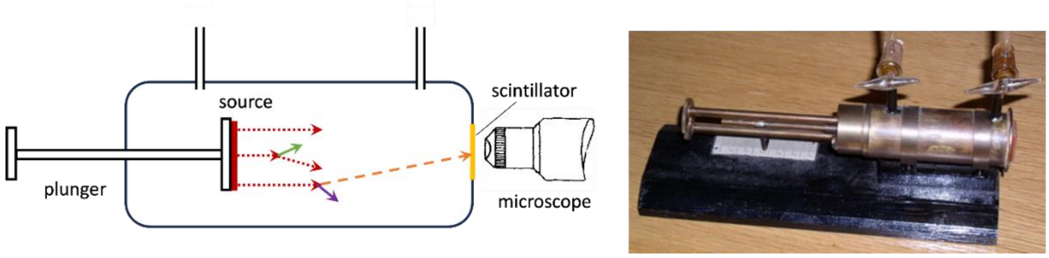

Figure 4. The schematic (left) shows an α source on a plunger which can be moved with respect to a scintillator screen. Particles hitting the screen produce flashes of light that can be observed with a microscope. Gas is introduced using the inlets at the top. Three types of events are illustrated. The most common is an α particle gradually slowing down in the gas (upper event). Occasionally (middle event) an α particle will elastically scatter from a gas atom; its path is deflected and the gas nucleus is knocked on (solid arrow). Very rarely (lower event) a reaction between an α particle and a gas atom produces a proton and oxygen nucleus. The oxygen nucleus stops quickly but the proton (dashed line) travels further. As drawn the plunger distance only allows protons from reaction events to cause flashes on the screen. The photograph by the author (right) shows the apparatus itself. This version was built in Cambridge in the 1920s [8].

Rutherford remained rather bothered; he could not relieve himself of the worry that the apparatus was not completely hydrogen-free. Indeed while the word *proton* first appears in the literature in 1920, after its adoption as the term for the hydrogen nucleus by a meeting of the British Association for the Advancement of Science it seems that Rutherford himself was a little reticent to use the new name until he had convinced himself [9]. In 1921 he did careful experiments with James Chadwick showing that protons knocked on from hydrogen gas had demonstrably less energy that those liberated from reactions on nitrogen nuclei. Later painstaking research was done by Patrick Blackett at Rutherford's suggestion in Cambridge. In 1924 he published a paper on cloud chamber observations spotting just six disintegrations of the type that Rutherford had discovered in four hundred thousand photographs of α particle tracks [10], [11]. Blackett revealed the details of the process: an α particle was swallowed by a nitrogen nucleus to form an excited fluorine nucleus, which ejects a proton leaving a residual nucleus of oxygen summarised by the reaction

$$\alpha + {}^{14}\mathrm{N} \rightarrow {}^{18}\mathrm{F} \rightarrow p + {}^{17}\mathrm{O}\,.$$

A coda is important for continuing this story. In the late 1920s it appeared that protons from the reaction formed groups with different energies, populating excited quantum states in the product nucleus that decayed by γ rays, high-energy packets of electromagnetic radiation.

4. Neutrons, electronic detectors and nuclear billiards

Neutron is a word that had appeared in the literature in different guises [12] but thoughts of a neutron as components of nuclei were provoked by the realisation that atomic masses were larger than the sum of the masses of the protons in the nucleus and the atomic electrons. There must be something else inside!

In 1900 β radioactivity had been shown to be the emission electrons by Henri Becquerel's measurement of their q/m. So it appeared that electrons existed inside the nucleus along with protons. Francis Aston had refined the use of electromagnetic fields on anode rays to develop devices that could very accurately measure atomic masses. He made the first observation of *isotopes* in 1912 when he saw

Journal of Physics: Conference Series **2877** (2024) 012092 doi:10.1088/1742-6596/2877/1/012092

two types of neon atoms with masses approximately twenty and twenty two times that of an H atom. Henry Moseley had shown in Manchester in 1913 that atomic number, the position in the periodic table of chemical elements, corresponded to the number of protons in the nucleus. Neon has atomic number 10, so the mass of protons is 10 times that of an H nucleus. But these only accounted for half the atomic mass. What else made up the rest? Perhaps neutral entities with a similar mass to the proton, which became known as neutrons. The nucleus of each element has to have a specific number of protons but the neutron number could vary giving rise to different isotopes.

A nice theoretical hypothesis, but could neutrons be detected and it be proved that they were components of a nucleus by experiment? A common proposition at the time was that neutrons were composed of nuclear electrons (as opposed to atomic electrons that orbit the nucleus) somehow bound together with a proton to give a neutral particle. This persuasively, albeit inaccurately, accounted for the origin of the electrons emitted in β decay. Many people speculated along these lines. Rutherford provoked some searches for them, but nothing was found.

Before the 1920s experiments were done by detecting the emitted charged particles from the flashes of light or scintillation produced when they hit zinc sulphide screens. These were counted by the human eye, which was difficult work that had to be carefully done. The human element made it tricky. Discrepancies between some British results and those from Vienna highlighted these issues and so an electrical method of detection, first developed by Geiger and Rutherford at Manchester in 1908, was resurrected by several laboratories. Ionisation chambers measure the electrical signals produced as a particle passes through a gas causing ionisation. Such signals could be processed and recorded using electrical equipment. Unlike humans ion chambers do not have to sit in the dark for their eyes to accommodate and they do not get tired! They can count at higher rates, but were also more reliable at very low rates when a human might get bored or distracted. Moreover, a particle's energy could be determined directly from the amplitude of the signal. Previously the energy was inferred less accurately from how far the particles travelled as they slowed down and stopped in a gas. But there was a downside as ionisation chambers are sensitive to γ rays as well as to charged particles.

Rutherford and Chadwick's work had showed that the α-induced reactions are accompanied by γ rays, as noted at the end of the previous section. But radium sources also produce γ rays. With an ion chamber one could not tell if a detected γ ray was from a reaction or from the source. For these counter experiments a source needed to be used which emitted only α particles. Polonium, an element discovered by Pierre and Marie Curie in 1898, produces α particles but with many fewer γ rays than radium. With a polonium source, if a γ ray was seen one could be more confident that they were from a reaction. However, polonium was difficult to obtain and only groups in Paris, Berlin and Cambridge had enough for experiments.

In Berlin in 1930 Walter Bothe surveyed reactions of α particles on various targets and found protons and γ rays were produced in many cases. On targets of lithium and beryllium he found only γ rays. For beryllium targets the reactions were particularly unusual. With α bombardment they produced a radiation, *Be radiation*, ten times more penetrating than any known γ rays. It was assumed that these were just γ rays of higher energy than observed before.The Paris laboratory had the biggest supply of polonium, a source ten times the strength of that in Berlin. Irène Curie, Marie's daughter and her husband, Frederick Joliot found that Be radiation was even more penetrating than in Bothe's results. Around that time Robert Millikan visited Paris and was hypothesising that cosmic rays produced protons and electrons in the atmosphere. Stimulated by this idea the Joliot-Curies decided to see if protons were produced by the action of Be radiation on various targets, as shown in figure 5. Generally they found nothing unless hydrogenous materials like paraffin or cellophane were used. A series of elaborate experiments showed that the Be radiation knocked protons out of these materials, but it was still thought that Be radiation was γ rays and this hypothesis led to curious conclusions. The measured proton energies indicated γ rays that would be five or six times the energy of the initial α particle, so where did this energy come from?

In Cambridge Hugh Webster, directed by James Chadwick, reproduced the Berlin findings but found the curious result that Be radiation was most intense along the direction of travel of the initial α particles.

It looked like something being knocked forward rather than the emission of γ rays, which should radiate in all directions. Be radiation might be particles rather than electromagnetic radiation? If it were composed of neutral particles with similar mass to the proton, energy-momentum conservation in the collision suggested that they would have a rather modest kinetic energy, removing the issue of how highly energetic γ rays were produced. He looked for tracks of these neutral particles in cloud chambers but found nothing; later that null result was explained because their sources were just too weak to see enough events.

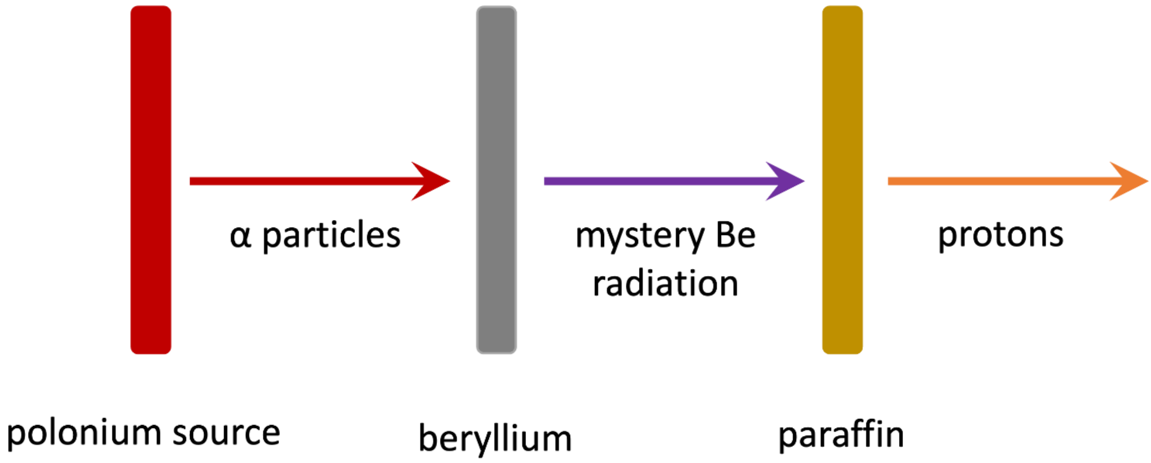

Figure 5. A schematic diagram showing the Joliot-Curies's experiments. A polonium source is used to bombard a beryllium foil with α particles. A mysterious penetrating radiation was produced that could knock out protons from the hydrogen atoms in a material like paraffin.

Chadwick started experiments with a small ionisation chamber with a value amplifier connected to an early chart recorder, but he needed more polonium. He had recently visited The John Hopkins University in Baltimore and seen radon (a decay product of radium) used for medical therapy. The radon quickly decays to polonium, reducing the therapeutic value of the radon cells. Chadwick was given these dead radon cells, which were useless for therapy but full of polonium. Harvesting them, he soon had as much as the Paris group. That meant that in just ten days he was able to measure the effects of Be radiation on a range of substances from hydrogen to argon. Be radiation on hydrogen gas produced elastically knocked-on protons, whilst in other cases Be radiation produced the corresponding recoiling nuclei. The measured energies of all these recoils only made sense in terms of energy and momentum conservation if Be radiation was neutral particles, neutrons with similar mass to the proton [13]. In hydrogen targets the collision between a neutron and proton would be like two snooker balls with the neutron stopping and the proton knocked forward. Heavier target nuclei would get less of a kick. He wrote a short note for the journal *Nature* just ten days later in February 1932 [14]; that was fast publishing even by modern standards. He suggested the existence of the neutron, adding that violation of momentum and energy conservation might be another explanation, albeit an unlikely one.

At that stage the neutron mass was not precisely known. If it were a bound state of a proton and an electron then it should be a bit lighter than the sum of the two[7]. In 1935 Chadwick and Maurice Goldhaber were able to extract accurate measurements of the neutron mass from reactions between γ rays and the heavy hydrogen isotope, deuterium. The neutron is heavier than a proton plus electron, so the neutron had to be a particle in its own right rather than a bound electron-proton system. Indeed the

[7] If there are two particles that are stuck together, energy needs to be supplied to rip them apart. Since Albert Einstein showed that energy and mass are equivalent via $E = mc^2$, that additional energy gives extra mass so that the mass of the separated particles will be higher than the composite system.

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mass difference means that free neutrons are radioactive; they β decay to a proton and electron with a half life of around ten minutes.

Shortly after the discovery Chadwick was recorded as saying neutrons would not be useful. However, because they are not charged they can sneak into nuclei without the electrostatic repulsion that a charged particle experiences as it approaches a positive nucleus. So neutrons do not need to be accelerated to high energy to cause nuclear reactions. They can be used to create new radioactive isotopes that can be used in medicine for imaging and therapy without much fuss. Similarly they are used to induce nuclear fission reactions, releasing useful energy.

5. Conclusions

By 1935 the basic constituents of atoms and nuclei had been established. An atom is mostly empty space in which electrons orbit. The nucleus had been discovered and was known to contain protons and neutrons held together by a curious new interaction, the strong nuclear force. At the time no one realised how difficult it would be to understand how the protons and neutrons move within the nucleus under the action of their mutual strong interactions. That is still a challenge today for modern nuclear physics. The reactions between nuclei power processes in stars, explaining how the Sun shines. Indeed since the Big Bang produced little else other than hydrogen, all the other chemical elements have been produced in nuclear reactions in stellar burning or more catastrophic cosmic events like supernovae or neutron star mergers. Neutrons were used extensively to initiate nuclear reactions leading to the discovery of the first man-made radioisotopes [15]. From Rutherford's initial studies of nuclear reactions induced by radioactive α particles, charged particle accelerators were developed to be able to initiate nuclear reactions at increasing energies, leading ultimately to machines like the CERN Large Hadron Collider that uncovered deeper structure within protons and neutrons themselves. Accelerators proved useful for other things too like cancer therapy. But back in the mid-1930s nuclear fission was about to be discovered using neutron-induced reactions. A war was about to start in which nuclear physics would lose its innocence with the development of nuclear weapons before later proving its worth to society in many more positive ways over the ensuing decades.

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