The Discovery of the Proton
Three Seminal Experiments in Early Atomic Physics

K. Ullmann

May 25, 2017

1 Introduction

The 20th century saw a monumental change in our understanding of matter. New, exotic particles were discovered with dizzying frequency - the positron in 1932, the muon in 1937, the pion, kaon, and lambda in 1947, the neutrino in 1956, the first quarks in 1969, the vector bosons in 1983 - finally culminating with the discovery of the Higg's boson, confirmed in 2013, another remarkable success of the Standard Model. All of this is even more astounding when we remember that at the turn of that very same century, we had yet to discover the humble proton.

The proton is somewhat unique in the history of particle discoveries because, unlike the many particles mentioned above, there does not exist a unique moment or experiment that we can point to and say definitively, here we have our discovery. The proton's origin story stretches back through time, to the first atomists of ancient Greece, and perhaps beyond. The history of the proton is inextricably bound to the whole history of atomic physics. Even so, three experiments in particular were vital to our final, clear picture of the proton. The first was the famous gold foil experiment, which lead to the discovery of the nucleus. The second was a seminal experiment by Rutherford in which he bombarded light atoms with α particles and found that hydrogen atoms were ejected. Finally, Aston's experiments measuring atomic weights gave us the theory of isotopes, and put the proton in its proper place as a constituent of all elements. With the results of these three experiments, we can say with confidence that the proton had been found.

2 The History of the Proton

Before diving into the three most important experiments in the discovery of the proton, it will be helpful to take a quick tour through its history. The first ideas about the proton can be traced back to our very first attempts at a theory of elementary matter. However, our modern conception of the proton begins much later, with the English chemist William Prout (1785 - 1850). Prout, noticing that the atomic weights of the known elements were all integer multiples of the atomic weight of hydrogen, hypothesized in 1815 that hydrogen was perhaps the most fundamental object, and that all other elements were simply derivatives of hydrogen. He named this object the protyle. Prout's hypothesis, however, was soon discarded, when in 1828 Jons Jakob Berzclius and later, in 1832, Edward Turner appeared to have disproved the idea by carefully weighing various elements and finding fractional weights.

Atomic physics took another important step forward in 1869, when Mendeleev published the earliest version of our modern periodic table of the elements. His main innovation was in ordering elements by their chemical properties as opposed to the conventional classification by atomic weight.

His table marked the beginning of our understanding of atomic number, and hence was an early hint at the existence of the proton.

After another thirty-odd years, J.J. Thompson famously discovered the electron in 1897. Here we find the very first elementary particle that was not itself an atom, a huge leap forward for our understanding of matter. In 1899, Rutherford discovered and named α and β rays. The discovery of radiation led to a rush of activity, as scientists raced to uncover the properties of these mysterious emanations. In 1903, Rutherford added γ radiation to the family. It was also during this year that α rays were found to be positively charged. By 1909 it had been definitely demonstrated that α rays were in fact He ions.

After Thompson discovered the electron, he posited the "plum pudding" model of the atom to explain its neutral charge. He suggested that positive and negative charges were distributed uniformly throughout the atom, much like the plums in a pudding. This theory was quickly abandoned when Rutherford laid out his nucleus theory in 1911. The new nucleus theory was sharpened in 1913 by Bohr, who postulated not only that the nucleus existed as a core of centralized and localized charge in the atom, but that moved in orbits around it, much like the planets orbiting the sun. It was also in 1913 that Moseley laid out his law concerning atomic x-ray spectra. Moseley's law was our first understanding of atomic number as a physically meaningful measure, and not a mere accounting trick.

This swift accumulation of knowledge came to a head in 1919, when Rutherford published a landmark series of papers entitled "Collision of α particles with light atoms I, II, III, and IV". (Refs [6], [7], [8], [9]. After bombarding gases with α particles, Rutherford found that hydrogen ions were ejected. If any one single experiment should be given the title of the "discovery of the proton" this would surely be it, and we will investigate this experiment in detail in section 4. These experiments lead Rutherford in 1920 to coin the word "proton", in a nod to Prout. [1]

Although it had been named, our understanding of the proton was still lacking. In the same year that Rutherford published his α particle research, Aston created the first modern mass spectrometer. Thanks to Aston's careful measurements, the theory of isotopy was born, and the integer weights of the elements were rediscovered. Aston's work, and Chadwick's discovery of the neutron in 1932, finally put the proton in its proper place as one of the two constituents of the atomic nucleus, and vindicated Prout, a century later. Our theory of the atom, with its three elementary subatomic particles, Thomson's electron, Rutherford's proton, and Chadwick's neutron, was complete. [2]

3 The Gold Foil Experiment

Having concluded our whirlwind tour of the proton's history, we now turn to the three experiments most significant to it's discovery. The gold foil experiment is perhaps one of the most famous individual experiments in science, often taught to high school students or recreated in undergraduate physics labs. Its fame is well deserved. This experiment, really a series of investigations, revealed the atomic nucleus. Although the experiments are often known by Rutherford's name, the most significant study was actually performed by Hans Geiger and Ernest Marsden in 1913, and explained in their landmark paper entitled "The laws of deflexion of α particles through large angles" [3]

Earlier studies had shown that the observed deflections of α and β radiation through various materials were inconsistent with the plum pudding model, and lead Rutherford to postulate his

[1] See Rutherford's footnote in Ref [1]. Gerlach [2] and others also credit Rutherford for the name.

[2] Until, of course, it was upturned once again by the discovery of the composite nature of the proton and neutron. But how nice and tidy things were for a time!

nucleus theory,[3] which he laid out in detail in 1911. [5] Motivated by these recent experimental and theoretical successes, Geiger and Marsden designed their definitive 1913 experiment.

Figure 1 shows their original schematic drawing. The experiment consists of a lead box B, mounted on a rotatable platform A, sitting in an airtight tube C. The box contained a thin film of gold foil F, and a radium source R, which stayed fixed while the box was rotated. A diaphragm D ensured the particles were directed in a thin beam. The microscope M and scintillating screen S affixed to its end rotated with the box, so that measurements from the scintillator could be taken at different angles (from 5° to 150°) with respect to the beam direction. The measurements they took were simple counts, by eye, of the flashes of light that would occur on the zinc-sulphide screen each time it was struck with an α particle. The goal was to discover the charge distribution within the atoms constituting the foil. A uniform distribution in deflection angles would suggest a uniform charge distribution in the material. [3]

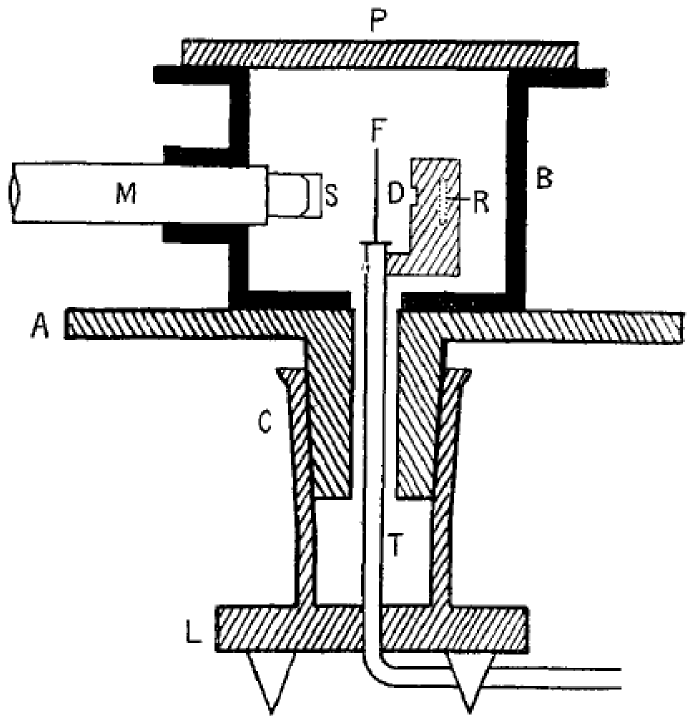

Figure 1: Geiger-Marsden experimental set up (Source: Ref [3])

Their results included four key findings. First and foremost was the dependence of the number of scintillations N on the scattering angle ϕ. A linear relationship $N \propto \csc^4 \frac{\phi}{2}$ was established, exactly as predicted by Rutherford [5]. Next, different thicknesses of foil were used to determine the relationship between N and the thickness T. Unsurprisingly, with a thicker foil target, fewer α particles made it to the screen. Third, by swapping out the gold for other materials, Geiger and Marsden observed a direct relationship of N with the square of the atomic weight of the element used for the foil. Finally, they investigated the relationship of N to the velocity v of the α particles, using mica sheets to slow them down, and discovered that N varied inversely with v^4. Each one of these results matched Rutherford's predictions, and the nucleus theory was firmly established. [3]

[3] Rutherford was already quite famous at the time, having discovered and named α, β, and γ radiation, and was awarded the Nobel Prize in Chemistry in 1908 "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances" [4]

4 α Bombardment

Next on our list is another set of α particle collision experiments, this time performed by Rutherford himself. With these historic investigations Rutherford became the first person in history to split the atom.

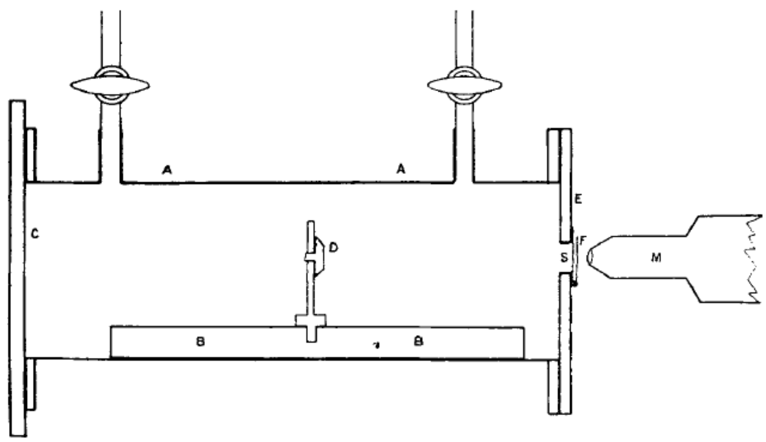

Figure 2: Rutherford bombardment set up (Source: Ref [6])

As with the gold foil experiment, the general idea behind the bombardment experiment was to shoot α particles at a substance, except this time Rutherford choose various gases as the target. The experimental design is shown in figure 2. The distance between the radium source D and the scintillator screen S was variable, by sliding the mount B. As in the gold foil experiment, measurements were taken by observing the scintillations by eye, quite a tedious process. In an illuminating passage, Rutherford describes the painstaking care with which he and his assistant, William Kay, made observations:

> In these experiments, two workers are required, one to remove the source of radiation and to make experimental adjustments, and the other to do the counting. Before beginning to count, the observer rests his eyes for half an hour in a dark room and should not expose his eyes to any but a weak light during the whole time of counting. The experiments were made in a large darkened room with a small dark chamber attached to which the observer retired when it was necessary to turn on the light for experimental adjustments. It was found convenient in practice to count for 1 minute and then rest for an equal interval, the times and data being recorded by the assistant. As a rule, the eye becomes fatigued after an hour's counting and the results become erratic and unreliable. It is not desirable to count for more than 1 hour per day, and preferably only a few times per week. [6]

Rutherfords investigations proceeded as follows: Upon introducing O_2 or CO_2 to the chamber, the number of scintillations was observed to decrease. This result was expected, as the gas acts as a barrier, slowing the particles to a stop before they can reach the screen. Next, air from the laboratory was introduced to the chamber, and now, the number of scintillations was observed to *increase.* Hydrogen particles were seemingly produced from thin air. After carefully ruling out potential sources of hydrogen contamination from H_2O or dust, Rutherford hypothesized that the nitrogen present in the air was carrying these H particles. When he introduced pure nitrogen into the chamber, the number of scintillations rose even further, confirming his suspicions. Rutherford took many additional measurements and made many small variations to his experiment, for example by changing the pressure of the gas in the chamber, and testing the particle's deflections in a magnetic field.

Although Rutherford didn't know it at the time, the process taking place in the chamber was the reaction $^{14}N + \alpha \rightarrow {}^{17}O + p$. He had achieved nuclear transmutation. Despite missing this astounding fact, the significance of his findings were by no means lost on him. Rutherford correctly concluded that bare hydrogen nuclei were being knocked out of the nucleus of nitrogen, and in the following year he dubbed these particles "protons."

5 Mass Spectrometry

Although at this point it is tempting to declare the proton found and be done with the matter, our picture of the proton was still incomplete. In the same year that Rutherford was making his observations with α particles, Francis Aston was conducting crucial research into atomic weight. Without his careful measurements, the proton could not have been properly understood as primary constituent of all atomic nuclei, and so our "discovery" is not complete without a discussion of his ingenius invention, the mass spectrometer.

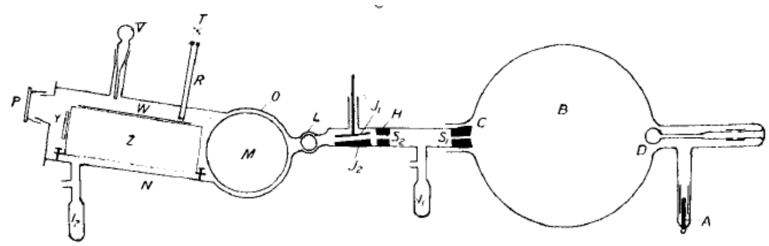

Figure 3: Aston mass spectrometer (Source: Ref [10])

Aston's schematic is shown in figure 3. The most salient details include the discharge tube B, where particles were ionized using X-rays, and then accelerated to the left. The particles pass through an electric field between J1 and J2, and a subsequent magnetic field in the region M. Aston's insight was to arrange these fields in such a manner as to direct all particles having the same charge-mass ratio to the same point on the detector plate W. By studying one material at a time, the particles could be guaranteed to have the same electric charge, and so relative measures of the mass were obtained. A photograph of Aston's measurements is shown in figure 4; the mass is noted in units relative to the atomic weight of oxygen which was taken to be exactly 16.[4] Aston's experiments lead him to discover the isotopes. He found that each chemical element was in fact made up of isotopes that had integer multiples of the weight of hydrogen. With this result, the nucleus theory, and the understanding of the proton from Rutherford's experiments, Prout was finally vindicated. Hydrogen ions were indeed a fundamental building block of all of the elements; the proton had been discovered.

[4]Gerlach discusses this choice of units, and Aston's results, in some depth in his book "Matter, Electricity, Energy: The Principles of Modern Atomistics and Experimental Results of Atomic Investigation." [2] His text gives a fantastic snapshot of atomic physics at the turn of the century, before the neutron had been discovered.

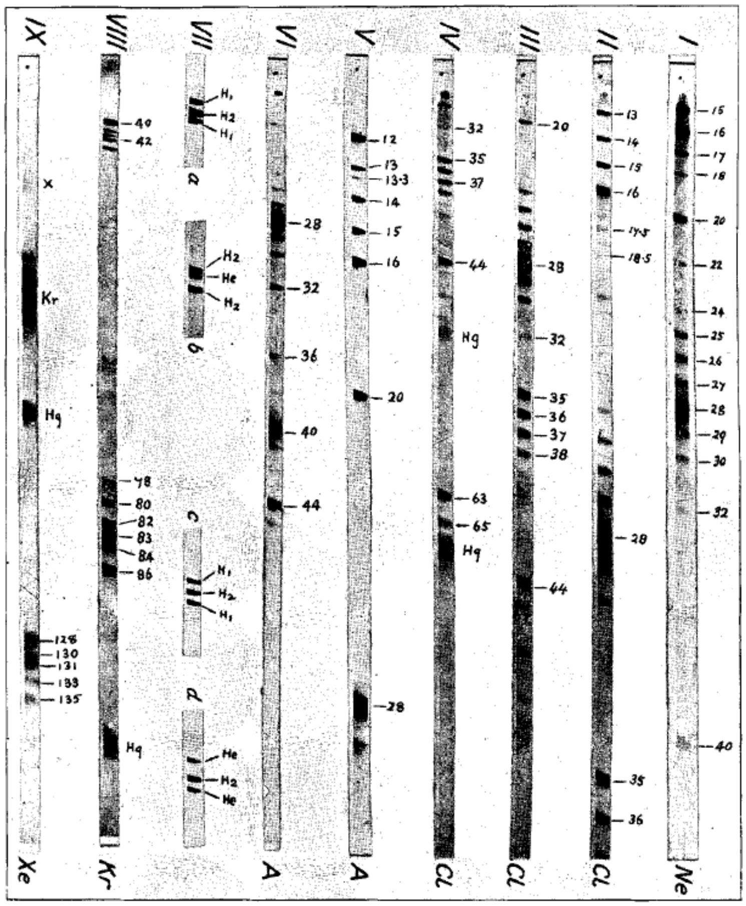

Figure 4: Mass spectra for various elements (Source: Ref [10])

6 Final Remarks

It is astounding to look back and realize that merely a century ago, even after Einstein had completed the theory of general relativity, we were only just beginning to scratch the surface of atomic physics. The discovery of the proton is central to that history. Unlike many later particle discoveries, the proton was not found by any single experiment, and it was found despite the fact that no one was looking for it. The three experiments described in this article are perhaps the most important with respect the proton's discovery, but there was a great deal of essential complementary research. Many experiments, and many scientists, including Thomson, Rutherford, Chadwick, Geiger, Marsden, Darwin, Aston, Curie, and others, were integral to the discovery and understanding of this basic building block of matter. Rutherford was especially prolific, pioneering an entirely new field of experimental physics. Today our understanding of the proton has evolved, but its history and the techniques used to investigate it will never lose their significance.

References

[1] Professor Orme Masson F.R.S. Xxiv. the constitution of atoms. *Philosophical Magazine Series 6*, 41(242):281–285, 1921.

[2] W. Gerlach and F.J. Fuchs. *Matter, Electricity, Energy: The Principles of Modern Atomistics and Experimental Results of Atomic Investigation.* D. Van Nostrand Company, Inc., 1928.

[3] Dr. H. Geiger and E. Marsden. Lxi. the laws of deflexion of a particles through large angles. *Philosophical Magazine Series 6*, 25(148):604–623, 1913.

[4] Nobel Media AB 2014. The nobel prize in chemistry 1908, May 2017.

[5] Professor E. Rutherford F.R.S. Lxxix. the scattering of α and β particles by matter and the structure of the atom. *Philosophical Magazine Series 6*, 21(125):669–688, 1911.

[6] Professor Sir E. Ruthefrod F.R.S. Li. collision of α particles with light atoms i. hydrogen. *Philosophical Magazine Series 6*, 37(222):537–561, 1919.

[7] Professor Sir E. Rutherford F.R.S. Lii. collision of α particles with light atoms ii. velocity of the hydrogen atom. *Philosophical Magazine Series 6*, 37(222):562–571, 1919.

[8] Professor Sir E. Rutherford F.R.S. Liii. collision of α particles with light atoms iii. nitrogen and oxygen atoms. *Philosophical Magazine Series 6*, 37(222):571–580, 1919.

[9] Professor Sir E. Rutherford F.R.S. Liv. collision of α particles with light atoms. iv. an anomalous effect in nitrogen. *Philosophical Magazine Series 6*, 37(222):581–587, 1919.

[10] F.W. Aston M.A. D.Sc. Lix. the mass-spectra of chemical elements. *Philosophical Magazine Series 6*, 39(233):611–625, 1920.