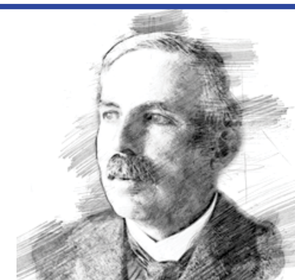
# Building Ideas

## Developing a Model of the Atom



Ernest Rutherford

While Greek philosophers like Democritus had reasoned that matter was made of tiny, indivisible particles as early as the $5^{th}$ Century B.C.E., the modern notion of the atom was not proposed until the beginning of the $19^{th}$ Century. Even after English mathematics tutor John Dalton showed how treating substances as though they were made of atoms could enable one to determine the relative proportions of different elements in a compound, not all scientists were convinced that these particles were real entities. That changed in 1905 when Albert Einstein published a paper that explained a phenomenon called Brownian motion (the erratic movement of microscopic particles when they are suspended in a fluid). His work furthered supported the conclusion that matter must be made of discrete entities. In 1908, when the French physicist Jean-Baptiste Perrin empirically verified Einstein's explanation, the reality of atoms was hard to question.

Yet, even before the reality of atoms was firmly established, evidence emerged that was interpreted to mean that atoms were made up of still smaller entities. To understand this landscape requires going back to the early 1800's and the work of William Prout. Building on the work of John Dalton, Prout had noticed that all of the elements known at that time appeared to have atomic weights that were multiples of hydrogen's atomic weight. He proposed that hydrogen could serve as a building block for all other atoms, and he named this fundamental particle the "protyle". In the late 1800s, a British scientist named William Crookes hoped that spectroscopy (the study of light emitted from vaporized elements) might provide evidence for the existence of the protyle. Although Crookes failed in this search, he later set aside his spectroscopic investigations to experiment with a new instrument called the cathode ray tube.

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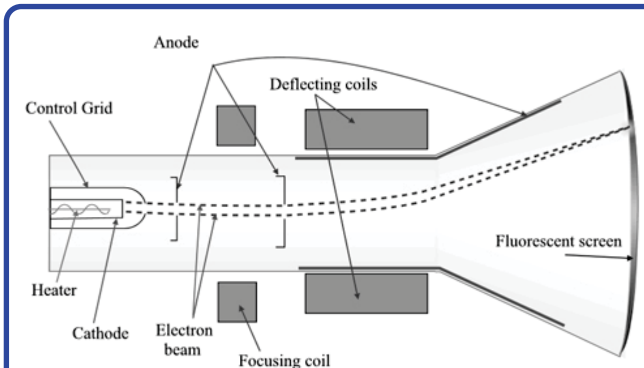
**Crookes and others in this story are conducting basic research. Such research is done to extend our understanding of the natural world with little if any thought regarding its utility for society. While basic research often draws the ire of those concerned about potentially wasteful spending, its impacts can be far-reaching. Basic research creates a broad base of knowledge upon which other scientists can make connections they otherwise could never make, and often results in the creation of technology that could not have been foreseen.**

A cathode ray tube consists of an evacuated glass cylinder with metal plates at either end. When an electric potential difference is applied to the two ends of the tube, a glowing greenish beam emanates from the negative electrode (or cathode). Scientists were uncertain precisely what these "cathode rays" were. Some, like Crookes, thought they were charged particles being ejected from the cathode, while others believed they were a form of electromagnetic wave. The study of these mysterious rays and the device that produced them became a subject of concerted research across Europe during the final decade of the $19^{th}$ century. In 1895, Perrin (who thirteen years later would provide empirical evidence in support of Einstein's theory for Brownian motion) demonstrated that cathode rays could be deflected using a magnetic field. Based on their trajectory, he concluded that the rays behaved like matter that had a negative electrical charge.




*Diagramming of a cathode ray tube.*

J.J. Thomson, the head of the prestigious Cavendish Laboratory at Cambridge University, took up and expanded on Perrin's work. First, Thomson provided evidence that the rays carried electric charge by using a magnet to bend the rays around a corner to an electrometer. As Thomson explained "this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays..." He next took a straight cathode ray tube and drilled a hole through its anode. He then focused the cathode ray beam to travel beyond the anode, striking the glass on the other side. In the space between

*Cathode ray tube*, adapted from https://en.wikipedia.org/wiki/Cathode-ray_tube#/media/File:Cathode_ray_Tube.PNG the anode and the glass, he set up a pair of metal plates capable of generating an electric field perpendicular to the beam. When Thomson activated the field, he was able to change the direction of the beam. Thomson now had two means of altering the direction of his rays: electric fields and magnetic fields.

In a third investigation, Thomson added a pair of coils capable of generating a magnetic field outside the tube. The electric and magnetic fields were arranged so that each would push the cathode rays in opposite directions, moving the spot on the glass wall up or down. By balancing the electric and magnetic fields against one another, Thomson was able to use their strengths and the geometry of the tube to calculate the ratio between each particle's mass and electric charge. He repeated the process several times with a variety of gases and cathode materials, in each case obtaining the same ratio. When compared to the mass to charge ratio of the smallest previously known particle, a hydrogen ion ($H^+$), he determined that the cathode ray particles were nearly 2,000 times lighter. Thomson reported these findings in an 1897 article in which he concluded:

> Thus on this view we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter—that is, matter derived from different sources such as hydrogen, oxygen, &c.—is one and the same kind; this matter being the substance from which all the chemical elements are built up.

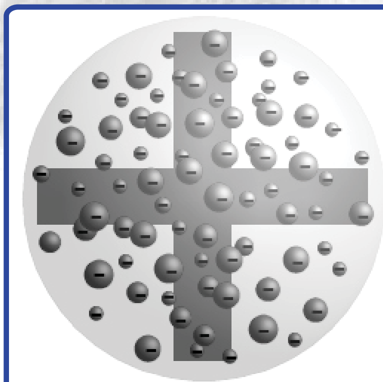
Thomson interpreted this as evidence for the existence of subatomic particles, shattering the most important characteristic of the atom from Democritus to Dalton - its indivisibility. In his paper, he referred to it as a "carrier of electricity." but it soon became known as an "electron."

**1. Science is often portrayed as a set of self-evident ideas and explanations about nature. (a) How does the work of Thomson illustrate that science is better characterized as a puzzle-solving activity? (b) In what ways might "puzzle solving" misrepresent how science works?**

The electron's existence raised new questions about the structure of the previously indivisible atom, particularly in light of Einstein's investigations of Brownian motion and Perrin's subsequent empirical work further substantiated the actual existence of atoms. For example, electrons are negatively charged, but atoms are electrically neutral. So, if atoms are, in part, made up of electrons, is some positive material present to offset the electrons' negative charge? In addition, electrons have very little mass. Unless thousands of them are present in each atom, their total mass would be negligible compared to that of the atom as a whole. How could scientists account for the remaining mass?

**2. Oftentimes, new evidence and understanding raise fresh questions about nature that would have previously made little or no sense. Science is better viewed as a creative process of idea development and refinement rather than a linear march toward certainty. A great strength of science is that even its most well accepted ideas are open to revision in light of new evidence or reinterpretation of prior evidence. (a) Using examples from this story, what factors, other than new observations, affect how and why science ideas change? (b) How is the possibility of changing even well-established ideas a strength of science?**

Thomson struggled to devise a model of the atom that would effectively account for his evidence that atoms are at least partially made up of electrons. Initially, he proposed a model incorporating thousands of electrons to account for the atom's weight, but abandoned this after new data only supported the number of electrons being roughly equal to half of an atom's atomic weight. By 1907, he had devised a new model where electrons were uniformly dispersed through a positively charged medium. Thomson's idea was later named the "plum pudding model," since the electrons were scattered throughout the positively charged atomic mass like raisins in the traditional English Christmas dessert.



*Plum pudding model*

*Plum Pudding Model*, adapted from https://upload.wikimedia.org/wikipedia/commons/0/04/PlumPuddingModel_ManyCorpuscles.png

Note that the year is 1907 and Jean Perrin has yet to provide the empirical evidence in support of Einstein's explanation for Brownian motion that would convince most all scientists that atoms were real entities. Yet, Thomson and others are attempting to piece together a model of the atom, already convinced that atoms are real. This kind of situation is not uncommon in science. For example, at the time that Watson, Crick, and others were attempting to determine the structure of DNA, some scientists were not yet convinced it was the genetic material. What this illustrates is that evidence does not tell people what to think. It must be interpreted. Only after knowledge becomes well-established does an idea appear to have been unambiguously determined by data.

Speculation regarding the structure of the atom extended well beyond Thomson's Cambridge laboratory. Across the world, an international community of physicists was at work evaluating the "plum pudding model" and proposing alternative ideas. Perrin, whose earlier work on cathode rays had inspired Thomson's experiments, proposed an atom that consisted of "one or several masses very strongly charged with positive electricity...and, on the other hand, by a multitude of corpuscles, in the manner of small negative planets." At nearly the same time, the Japanese physicist Hantaro Nagaoka proposed a similar "Saturnian" model, where electrons moved in central rings around a central positively-charged sphere. Meanwhile, in Germany, Johannes Stark envisioned the atom as a surface consisting of spherical zones of positive energy with small point-like electrons nestled between them. Determining the validity of these proposed models, or perhaps a better but yet to be developed model, was a daunting task that, as with much scientific research, required creative insight and new investigative techniques.

The major challenge confronting scientists interested in understanding atomic structure was that atoms were simply too small to be observed directly. This difficulty in studying something that cannot be directly observed is common with many natural phenomena that scientists seek to understand. While many creative approaches were considered and attempted, the insight that subatomic particles themselves might be used as probes showed promise. By firing subatomic particles at atoms and recording what occurred, information might be gained that would assist in creating an atomic model. Consider, for instance, that if many marbles were directed towards a large but unseen object, the direction in which marbles appeared to bounce off the object could be used to reconstruct a shape of the object. The hope was that this same kind of approach might yield data that would assist in understanding the structure of atoms. At first, scientists' subatomic toolkit appeared to be limited to the electron, until a young researcher working under Thomson at the Cavendish thought of another way to probe the atom. His name was Ernest Rutherford.

Rutherford was born in New Zealand and had earned a research scholarship at the Cavendish in 1895. His initial research centered upon the ionization of gases after subjection to X-Rays, but in 1897 he shifted his focus to a phenomenon that had recently been observed in France. Henri Becquerel and colleagues, Marie and Pierre Curie, had come across a new, and not fully understood, type of radiation from elements such as uranium. Rutherford eventually concluded that uranium actually emitted two different kinds of radiation. The first, which he called alpha radiation, was easily absorbed and had a positive electric charge. The second type, called beta radiation, was 100 times more penetrating and had a negative charge.

Rutherford continued to investigate these two types of radiation even after he left the Cavendish for a research position in Montreal, Canada. Working with chemist Frederick Soddy, he determined that alpha rays consisted of dipositive helium ions with a double positive charge, and beta radiation consisted of particles whose characteristics were identical to Thomson's electron. By the time he returned to Britain in 1907 to become chair of the physics department at the University of Manchester, he realized that the stream of particles emitted by radioactive materials could be directed at atoms to see how they responded. This, in turn, might provide useful evidence for determining the structure of an atom. Rutherford recruited a pair of talented students, Hans Geiger and Ernest Marsden to assist in an investigation that he hoped would shed light on the distribution of electric charge within an atom. Over the next three years, they devised a series of experiments to investigate how different types of matter scattered alpha and beta particles.

Geiger and Marsden designed a means of focusing the alpha particles into a fine beam that could be directed at a thin (only a few atoms thick) metal foil mounted in front of a zinc sulfide screen. When alpha particles struck the screen, they produced small flashes of light (or scintillations) that allowed observers to calculate how much their trajectories changed after passing through the foil. Rutherford thought that tracking these scintillations would allow him to better understand the structure of the atoms in the foil (Figure 1, *Page 4*).

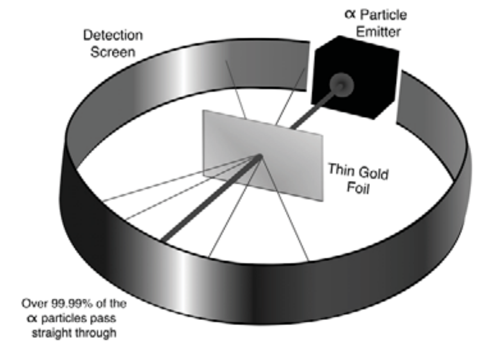


*Figure 1. Rutherford's gold foil experimental set up*

Rutherford assigned the task of observing the scintillations to Geiger and Marsden. The two sat in a dark room using a movable, low-powered microscope to count the number and location of scintillations. If the plum pudding model were correct, the trajectories of the alpha particles would be deflected only slightly after passing through the foil because charge and mass were uniformly distributed throughout the atom. Initial observations appeared to support Thomson's model, but one day in 1909, Rutherford passed by Geiger and Marsden's lab and suggested that they check if the foil was reflecting any of the particles. "I do not think he expected any such result," Marsden recalled later, "but it was one of those 'hunches' that perhaps some effect might be observed." A few weeks later, Marsden and Geiger reported that while almost all scintillations appeared to indicate the alpha particles passed straight through the gold foil, some sparkles of light occurred at places on the zinc sulfide screen that indicated they had been deflected at various angles – some as large as 90 degrees. As Rutherford noted, "[i]t was about as credible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

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**While Rutherford is often given credit for the "gold foil experiment," Marsden and Geiger clearly had an important role to play. Oftentimes, the stories that are told about science focus on one person, but more often than not, science is the result of many people working together to understand the natural world.**

**3. Rarely is scientific investigation characterized as including "hunches." Yet, scientists oftentimes make decisions about how to move forward with little evidence to inform their decisions. Using examples from this story, explain how intuition and fortunate accidents are also at work within the story of science.**

After mathematically analyzing the angles of deflection, Rutherford drew the following conclusions from what Geiger and Marsden had observed. First, most of the alpha particles passed through without any deflection. Noting that nothing appeared to have hindered their movement, Rutherford proposed that atoms must consist of mostly empty space. Second, some alpha particles were deflected. Because alpha particles are dipositive, he reasoned they must have encountered another region of positive charge, since similarly charged objects repel each other. He referred to this region as the nucleus. Third, because few alpha particles are deflected, the space occupied by the nucleus must be quite small.

In 1911, Rutherford published a paper titled "The Scattering of Alpha and Beta Particles by Matter and the Structure of the Atom" in which he presented his experimental results and proposed a new atomic model that would account for them. Citing the earlier proposals of Perrin and Nagaoka, Rutherford argued that rather than the homogeneous plum pudding set forth by Thomson, the atom consisted of a positively charged core (or *nucleus*) that contained the majority of the atom's mass, and this nucleus was surrounded by a cloud of negative electrons. The large deflections observed by Geiger and Marsden occurred when a positively charged alpha particle collided with the nucleus of an atom. Since these collisions were relatively rare, the nucleus of the atom had to be considerably smaller than the complete atom. Rutherford's ideas were in many respects counterintuitive. This new model required one to accept that the majority of the atom's volume consisted of empty space and that the positive charges in the nucleus did not repel one another. Though explanations of these phenomena were unclear, such concerns did not stop scientists from acknowledging the explanatory value of Rutherford's model.

The growing acceptance of Rutherford's ideas did not, however, mean that his atomic model was considered complete. In a 1920 lecture before the Royal Society, he outlined many of the model's shortcomings. Critics had noted that unlike planets revolving around the sun, the electrons Rutherford described would steadily lose energy and spiral into the nucleus. Rutherford's student, Niels Bohr, had proposed a new model using quantum mechanics that might resolve the problem, but Rutherford remained skeptical. Another flaw of his model was its inability to explain the mass of the nucleus. At the time, the only known subatomic particles were the negatively charged electrons and the positively charged components of the nucleus, which Rutherford named *protons*. To take a commonly cited example, the helium nucleus was four times as massive as a proton, but had only twice the electrical charge. Rutherford suggested the existence of a third fundamental particle, a sort of proton-electron composite, whose mass was equal to the proton but with no electrical charge. He referred to this hypothetical particle as a *neutron*.

*Gold foil experiment*, adapted from https://www.pngfly.com/png-z0epz7/

**4. Not only do scientists have to be creative and speculate in developing investigations and analyzing data, they also must create ideas that account for the data. Many people wrongly think that data tells scientists what to think, that science is not creative, and that creativity may lead to biased results. Use examples from this story to counter these mistaken ideas about how science and scientists work.**

At this point in his career, Rutherford had replaced his former teacher J.J. Thomson as head of the Cavendish Laboratory, and his administrative responsibilities left him with few opportunities for independent research. By 1932, however, one of his researchers, James Chadwick, confirmed that a particle matching the description Rutherford had put forward in 1920 was emitted when the element beryllium was bombarded with alpha particles. The evidence for the neutron resolved earlier discrepancies concerning atomic mass and provided an explanation for the existence of isotopes, substances that share the same physical and chemical properties but possess different atomic masses.

Investigations into atomic structure and the nature of matter continued beyond these three fundamental particles. Well into the 20th century, a growing number of researchers would draw upon new tools (like particle accelerators) and theoretical approaches (like quantum mechanics) to explain the behavior of atoms and their component particles. Their experiences would share many characteristics with the story presented here. While conceptions of the atom have evolved over time, the desire to comprehend matter at its most basic level has remained a constant motivation. This search has driven scientists to collaborate across international boundaries to establish a common vocabulary and standards of evidence. It spurred the creation of new research centers and inspired investigators to develop innovative solutions to difficult scientific problems. Above all, the quest to understand the atom unified the previously disparate fields of physics and chemistry and provided a common analytical framework.

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**The road to our current understanding of the atom includes many players, many ideas, and spans centuries. Science research is always influenced by prior ways of thinking as well as the thinking of others. Yet, many people envision scientific breakthroughs as "eureka" moments. While many of the scientists in this story may have felt "eureka" moments of exciting realizations, the overall story demonstrates how human understanding of the natural world is a community effort and moves forward in unpredictable ways.**

**Building Ideas: Developing a Model of the Atom**
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