X-rays, Radiation, and the Physical Atom:

New discoveries around the turn of the 20th century

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History of Modern Physical Sciences

The End of Science

At the end of the 19th century, many people had the feeling that all of the major laws of the natural world had been discovered and that it was now just a matter of working out all of the details. This thinking was well summarized by A.A. Michelson (1852–1931), an American experimentalist.

Michelson, 1894

"It seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all phenomena which come under our notice."

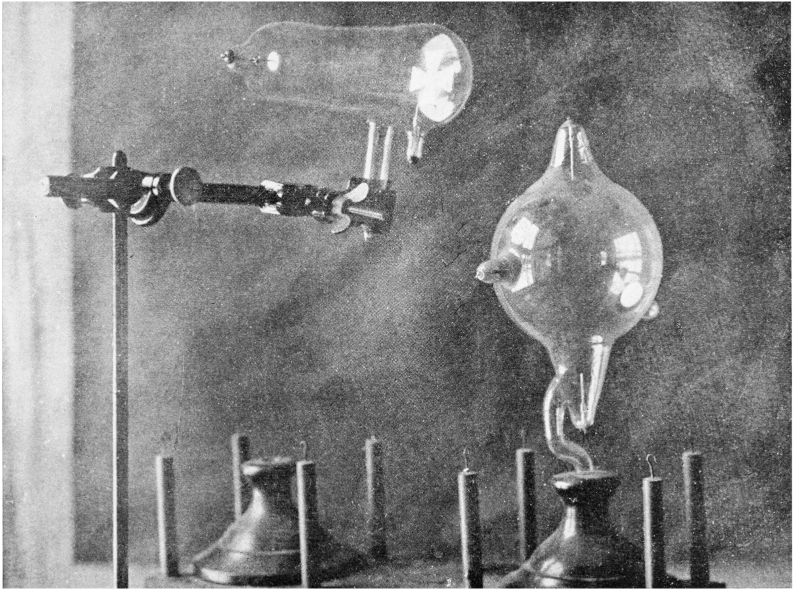
In the following decade, however, there were a number of new discoveries and new theories that would throw this thinking into turmoil.

Cathode Rays and Radiant Electricity

In England, research on cathode rays was pioneered by William Crooks (1832–1919), who had studied at the Royal College of Chemistry under August Wilhelm von Hoffman, one of Liebig's students. In 1879, he published the article "On Radiant Matter."

He was interested in the phenomena associated with vacuum tubes. When the gas was drawn out of a sealed glass chamber and an electrical current was joined through the tube, the tube would give a luminescence, the properties of which *depended on the quantity and type of gas remaining in the tube*. Crookes studied the nature of the electricity passing from the cathode to the anode.

Crooks developed a number of experiments to show that the electricity traveled between the electrodes by *rectilinear rays*. For example, a mica shield in the form of a Maltese cross would cast a shadow on the far wall, or a propeller could be driven by the rays.



An example of the sort of apparatus that Crookes used

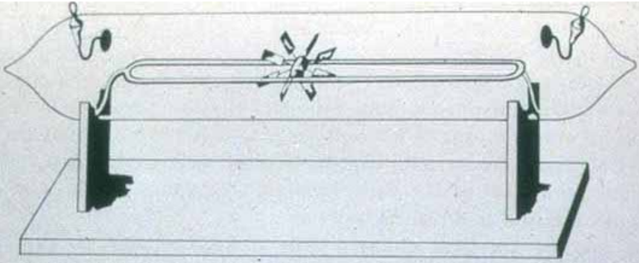
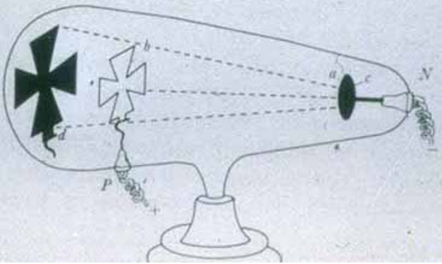


Fig. 1. From *Electrical Engineer* (*New York*), *21:* 237, March 4, 1896.



Textbook diagrams of “Crookes tubes,” 1896

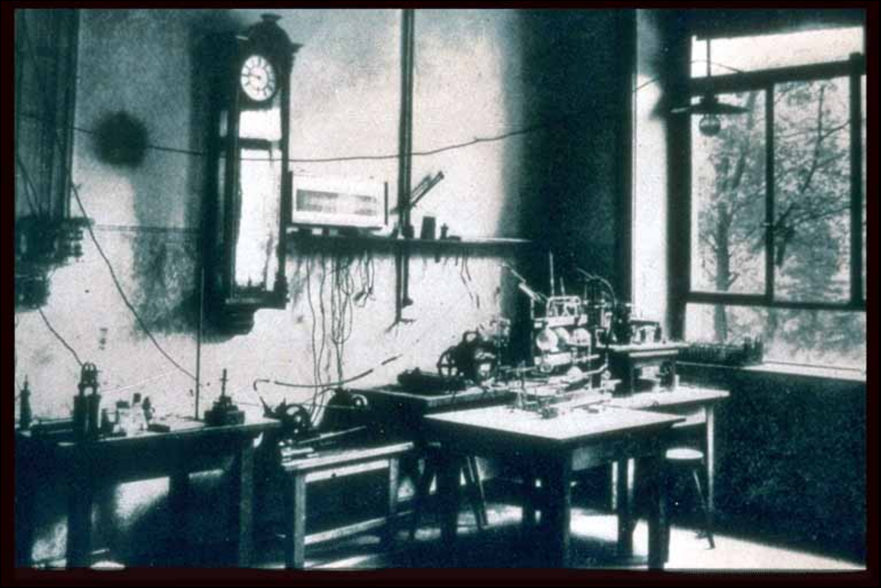
Wilhelm Röntgen (1845–1923)

- Röntgen was from a middle class mercantile family.
- He studied mechanical engineering at Zurich Polytechnic and took a PhD from Zurich University, under Clausius.
- He taught at a number of German universities, such as Würzburg and Munich.
- He worked on a broad range of problems in physics, mostly trivial, only spending two years on x-rays.
- He discovered x-rays in 1895, and was granted the first Nobel Prize in Physics for this discovery, 1901.

A Chance Discovery

In 1895, Röntgen was experimenting with cathode rays. Since he thought they might be ultraviolet light, he projected them onto a plate coated with a fluorescent material – potassium platino-cyanide. It glowed. He sealed his tube in black cardboard, and to check if the seal was good, he turned on the tube in the darkened room. He was mystified when a fluorescent plate on the far side of his work-bench started glowing.

He knew that the cathode rays could not penetrate the tube and cardboard. He put his hand in front of the plate and saw a blurry skeletal image of his hand and wedding ring projected onto the screen. He worked intensely for six weeks. Unlike electromagnetic waves, he could not find any reflection, refraction or diffusion patterns, or polarization. (We now know how to exhibit all of these phenomena.) He speculated that these rays must be a different kind of *ether wave*. He called this mysterious new radiation *x-rays* to highlight the mystery of their nature.

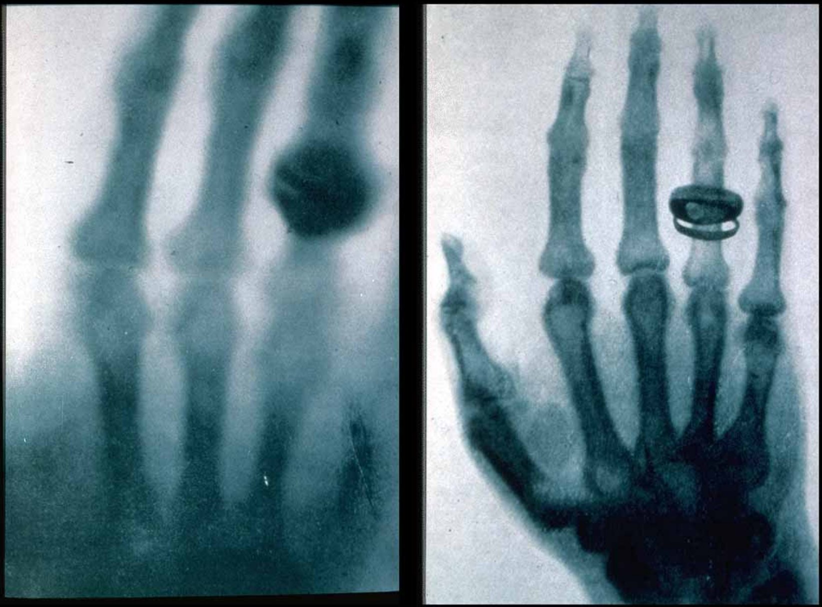


Röntgen’s laboratory at the University of Wurzburg

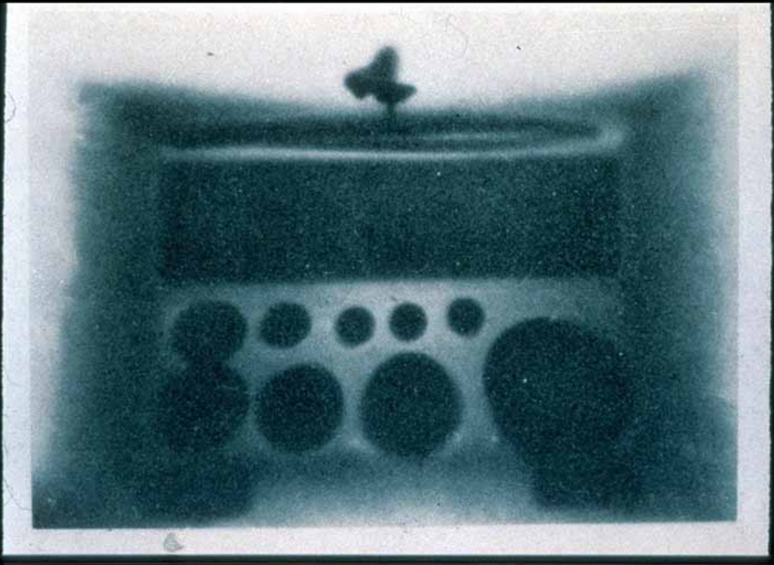
Professional Reception

Röntgen's paper – including photos – was published in a local journal with copies sent to a number of key physicists. It was quickly translated into English, French, Italian and Russian. In the next year, some 100 physics papers were published on the new rays.

Physicians saw the implications immediately and they started working with physicists to develop new medical technologies – taking photos of human fetuses, tumors, internal organs, the digestive system, and so on.

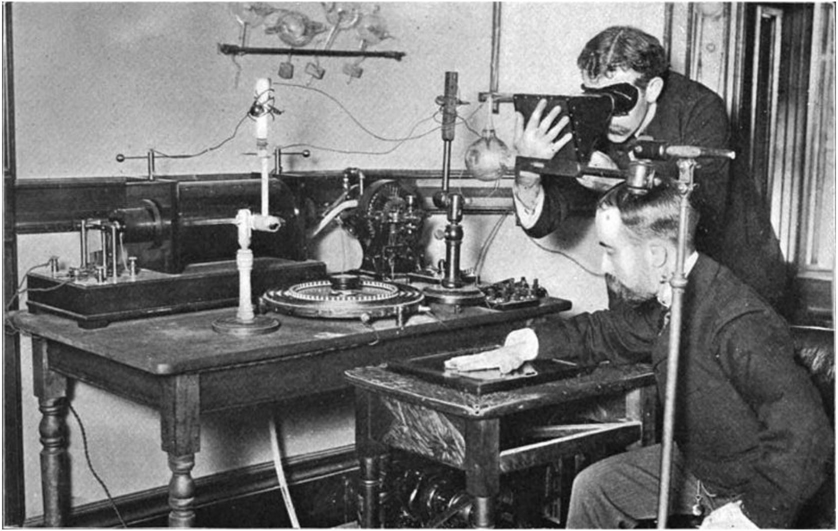


Some of Röntgen's photographs, human hand



A box of weights

The Medical Use of X-Rays



Physicians taking a photograph and making a live observation with x-rays

Edison’s Floroscope

Thomas Edison and an assistant examining his hand in real time with an x-ray device

Popular Reception

The discovery of x-rays was the most sensational scientific discovery of the time.

Newspaper interview with Röntgen

"Journalist: When you discovered this phenomena, what did you think?
Röntgen: I didn't think. I investigated.
Journalist: What is it?
Röntgen: I don't know."

The Victorian British were scandalized at the possibility of people seeing their internal organs. A London merchant advertised x-ray proof underwear – "No lady safe without it!". From a limerick of the time: "*I hear they'll gaze // Through cloak and gown – and even stays // These naughty, naughty Röntgen rays*." Severe cases of burns and hair loss were reported but the danger was not understood. A Parisian merchant used x-rays as a *depilatory therapy* for women to remove unwanted facial hair.

More Radiation

In the excitement over the discovery of x-rays, both scientists and amateurs began to search for new types of radiation. Between 1895 and 1912, as many as twelve new types of light and rays were announced. A number were found to be *irreproducible* – for example "black light" and "n-rays." Others were later reinterpreted. In 1896, however, a new, and fully reproducible, radiation was found by Henri Becquerel.

Since light was now generally understood to be a form of radiant electromagnetic energy, just as heat was understood to be radiant kinetic energy, Becquerel wanted to see if certain substances could retain light – as metal, for example, retains and radiates heat.

He exposed a number of salts to the sun and then later to a photographic plate.

- Among these were some uranium salts.

The uranium produced a silhouette of its crystalline structure on the plates.

Becquerel's Photographic Plate

Uranium Salts

Originally, Becquerel *falsely* believed that the uranium was a source of x-rays that had been *charged by the sun*. At one point, he set up his apparatus for charing the the uranium salts, but the city was overcast for days. He went ahead and developed the plates anyway and found the *same patterns as before*.

He then reproduced this effect in total darkness.

He tried to affect the process in a number of different ways – for example using heat, electricity, compression, chemical reactions, and so on, but this made no change in the effect of the radiation.

He concluded that these new rays seemed to emanate *spontaneously* from the matter.

Marie Sklodowska Curie (1867–1934)

Marie Sklodowska was from a middle-class background in Russian-controlled Warsaw, Poland. He father was a gymnasium teacher and political dissident. She was educated at the "Flying University" in Warsaw and studied in Paris under Becquerel.

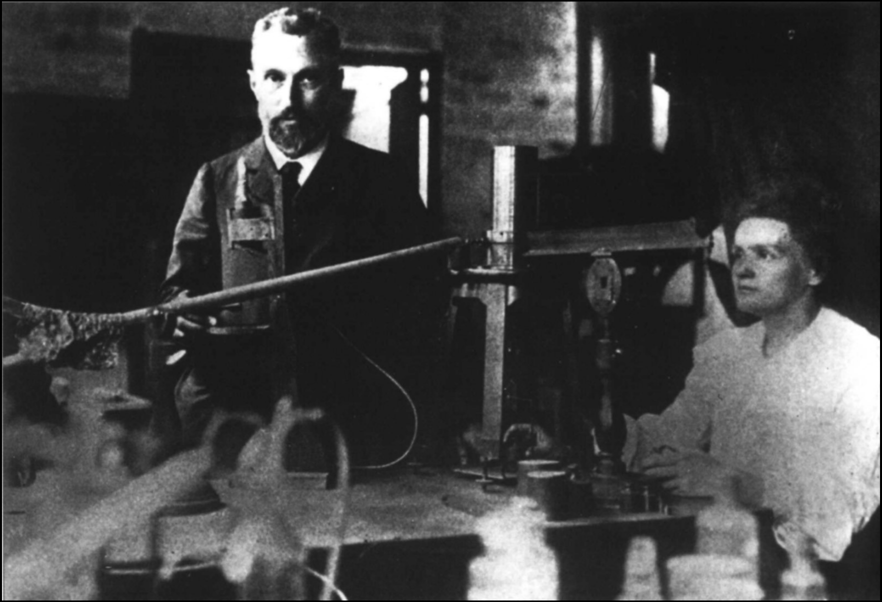
She married the physicist Pierre Curie, and they worked together and became scientific celebrities. They were granted a Nobel Prize, with Becquerel, in 1903. Pierre was killed in an accident in 1906, and Marie was offered his position at the Sorbonne – becoming the first female professor in France.

There was a scandalous love affair, between Marie and P. Langevin, who had been one of Pierre's students, and was married. A duel was fought. Around this time, she was granted a second Nobel Prize.

Curie developed radiology technologies and headed the French radiology logistics in the Great War. She became director of the Radiology Institute. She died of issues related to radiation exposure.

A Scientific Couple

The Curies get ready for a bicycle ride in front of their house



The Curies in their laboratory

Radioactivity

The Curies started studying the radioactive effects that could be produced by uranium between a pair of charged plates. The only thing that effected this phenomena was the amount of uranium involved; and, hence, the charged-plate apparatus could be used to detect radiation. A few other substances produced a similar effect. M. Curie called this phenomena *radioactivity*.

The Curies' apparatus allowed them to look for radioactive sources more quickly, and they found radioactive effects, for example, in *thorium* and *pitchblende*.

They realized that the pitchblende was more active than pure uranium, and so began the search for a new elemental source of radiation.

Working Conditions

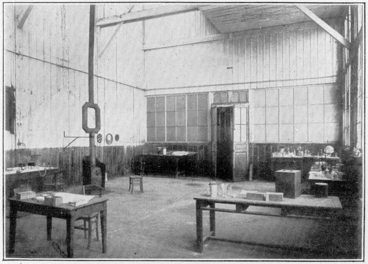
The laboratory where M. Curie started her work on radioactivity was famously rustic. She described it as follows in her memoirs:

M. Curie

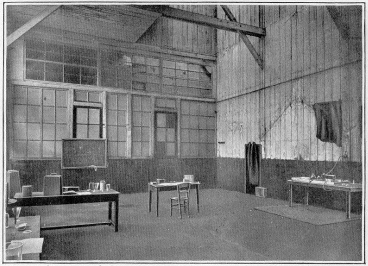
"For lack of anything better, the Director [of the school of physics and chemistry] permitted us to use an abandoned shed which had been in service as a dissecting room of the School of Medicine. Its glass roof did not afford complete shelter against the rain; the heat was suffocating in the summer, and the bitter cold of winter was only a little lessened by the iron stove, except in its immediate vicinity. There was no question of obtaining the needed proper apparatus in common use by chemists. We simply had some pine benches with furnaces and gas burners."

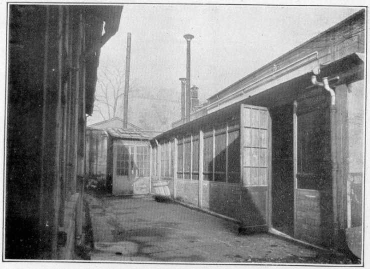
Pièce dans laquelle étaient effectués les traitements chimiques du minerai et la concentration du radium.

VUE I.

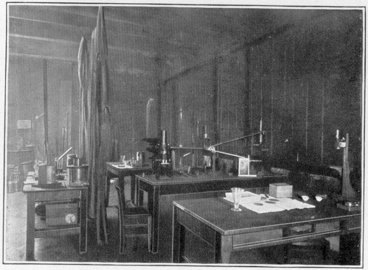


VUE II.





Vue extérieure des bâtiments où ont été faites les recherches relatives à la découverte du radium.
(École de Physique et de Chimie de la ville de Paris.)



Installation des mesures de radioactivité.

Pitchblende

Pitchblende is a radioactive, uranium-rich mineral and ore, containing about 30 different elements.

The Curies were able to determine that there were two new elements (*radium* and *polonium*) in the pitchblende, but they had not yet extracted enough to do any chemical analysis – that is, to determine the atomic weight, spectrum, chemical properties, and so on.

Once the announcement of the new elements were made, they were given some extra funds to hire assistants.

A piece of pitchblend

New Elements

M. Curie sifted through around a 1000 kilos of pitchblende to isolate a tenth of a gram of radium – that is, 1:10,000,000. It was around 1,000,000 times more radioactive than uranium. Moreover, both radium and polonium fit into open spots in the periodic table of the elements.

M. Curie wrote up the results for her PhD dissertation. It was defended in June, 1903. There was a celebration at Paul Langevin's house afterward, attended by Ernest Rutherford.

Rutherford

"After a lively evening, we retired about 11 o'clock to the garden, where Professor Curie brought out a tube coated in part with zinc sulphide and containing a large quantity of radium in solution. The luminosity was brilliant in the darkness and it was a splendid final to an unforgettable day."

The Physical Atom

For 19th-century natural philosophers, the atom was purely a theoretical idea that served various roles, depending on the theory they were developing.

For most it was a hard "massy" sphere. For theorists such as W. Thomson it was a mathematical vortex, a "singularity." For Boltzmann and Maxwell it was the assumed substrate of a statistical theory of heat.

In the early 1890s it was still possible for serious physicists to deny the actual existence of atoms.

Around the turn of the century, however, this began to change and the atom became an object of laboratory practice.

The Cavendish

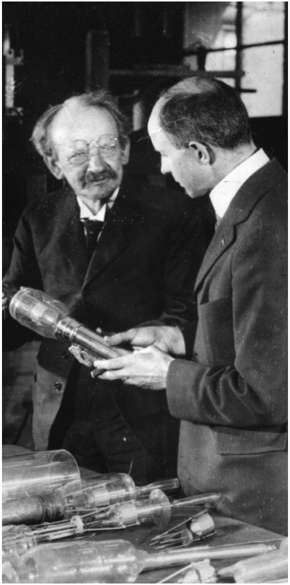
The old Cavendish

The Cavendish Laboratory was established at Cambridge with money from the House of Devonshire. It was meant to train researchers in physics.

The directors of the lab were chosen from the most important British physicists – J.C. Maxwell, Lord Rayleigh (John Strutt), J.J. Thomson, and so on.

The goal was to integrate training in research with a university education, in order to move away from the dominating influence of the mathematical tripos.

J.J. Thomson (1856–1940)



From a middle-class Manchester family, and educated at Cambridge (2nd Wrangler, Smith's Prize). Appointed director of the Cavendish at 28yo. He turned the attention of the Cavendish to the new phenomena of x-rays and radioactivity, and directed the work of 7 future Nobel laureates and 27 FRSs.

Awarded the Nobel Prize, 1906, for the discovery of the electron. Passed the Cavendish to Rutherford, in 1919, and became Master of Trinity College. *Recent Researches in Electricity and Magnetism*, 1882. *Conduction of Electricity Through Gases*, 1892.

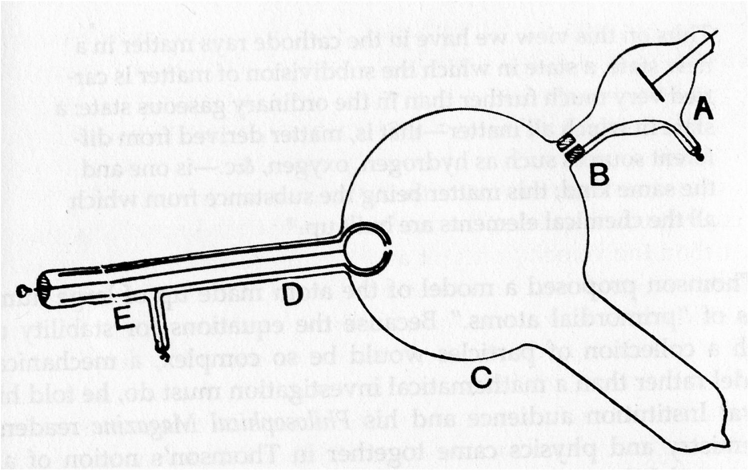
Cathode Rays in Electromagnetic Fields

J.J. Thomson made superior cathode tubes that allowed him to get much more of the air out – at the time, they did not believed that a complete vacuum would work. This allowed him to deflect the cathode rays with magnets – they veered towards the positive pole. He created an electromagnetic field using charged plates and electromagnets to study the velocity and the *charge-to-mass ratio* of the rays.

Between charged plates, the deflection of the rays will depend on charge, e, while the momentum, $p = mv$, will depend on mass, m, and velocity, v. So the total deflection can be expressed in terms of the ratio e/m – the charge-to-mass ratio.

Under an electromagnet, the induced electric effect of a moving charge is a result of its velocity and charge.

By varying the fields, J.J. Thomson and his team could get experimental values for both the *velocity* and the *charge-to-mass* ratio.



J.J. Thomson's cathode ray apparatus. *A* is the cathode, *B* the anode, and *DE* the detection device. Rays are only detected when they pass through the slit at the end of *DE*.

Just a Ratio

The charge-to-mass ratio indicated that, under the assumption that there were electrical "corpuscles," they were either a 1,000 times smaller than a hydrogen atom or the charge was 1,000 times greater than a hydrogen ion, H^+. (This was latter found to be closer to 2,000 times.) J.J. Thomson took it as obvious that the particles must be smaller.

J.J. Thomson, Lecture at the Royal Institution, 1897

"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's Three Hypotheses on the Physical Atom

1. Cathode rays are composed of tiny "corpuscles," the size and charge of which do not depend on the gas in the tube.

2. These particles are the physical constituents of the atom. So, it should be possible to construct models of the atom which were based on more *fundamental building blocks*.

3. The negative particles were the only physical constituents of the atom. (This hypothesis was later abandoned.)

J.J. Thomson, 1936

"At first there were very few who believed in the existence of these bodies smaller than atoms. I was even told by a distinguished physicist at my 1897 lecture at the Royal Institution that he thought I had been 'pulling their legs'."

J.J. Thomson's Plum Pudding Model

Over the next decade, Thomson put forward a number different physical models of the atom.

In his 1903 lectures at Yale University, Thomson proposed that the simplest model of the atom was a sphere of uniformly distributed positive charge filled with tiny electrons arranged like the currents "in a plum pudding." At this point, the only particles that they were certain were in the atom were electrons – so there needed to be 2,000 of them in the hydrogen atom.

Other theorists, however, disagreed with this model, and the experimental work of Thomson's student E. Rutherford, would soon point toward two more subatomic particles.

Nagaoka's Saturnian Model of the Atom

In 1904, Hantarō Nagaoka (長岡 半太郎, 1865–1950) published a critique of both of the atomic models of William Thomson (Lord Kelvin) and J.J. Thomson, because they proposed that positive and negative charges were interpenetrating.

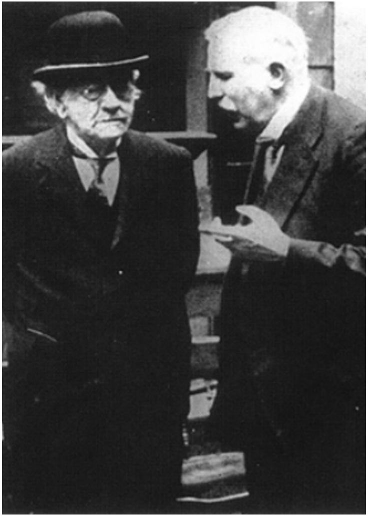
Nagaoka took a materialistic, particle-based approach and proposed a model in which small negatively charged electrons would be arranged around a positively charged center of much larger mass. He set the electrons orbiting uniformly in a ring, which gave rise to the image of the rings of Saturn.

The model was made on an *analogy* with Saturn, but in the atom everything was held together by electrostatic forces, whereas in Saturn everything is held together by gravity. (Rutherford referred to Nagaoka's work in his 1911 paper giving an experimental argument for a solid massive center in the atom.)

Ernest Rutherford (1871–1937)

Rutherford grew up in rural New Zealand in a large working-class family, studied at the Cavendish with Thomson, worked at McGill and Manchester, before returning to head the Cavendish. He received the Nobel Prize in chemistry, 1908.

He used the special properties of radioactivity to turn the objects themselves into experimental tools. He directed some of the most important experimental work of the time; discovered the *proton*, predicted the *neutron* and oversaw the Cavendish when it was discovered. *Radioactivity* (1904); *The Newer Alchemy* (1937).



Rutherford's Early Work

Following the results of the Curies, Rutherford started to experiment with uranium. He discovered that at least two types of rays were involved. He called them α- and β-rays. He showed that α-rays are blocked by aluminum foil while β-rays are not. He and Becquerel used the same methods as J.J. Thomson to show that β-rays are identical to cathode rays – that is, streams of electrons.

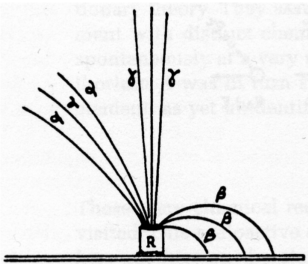
For his first academic position, Rutherford moved to McGill, Montreal. Here started collaborating with Fredrik Soddy (1877–1956), a chemistry instructor. In the next 10 years they published over 70 papers. They discovered that there are three emissions: α- and β-particles and γ-rays. They developed chemical means for separating the various parts of radioactive materials – original elements, transformation elements, and end products. The transformation elements could be chemically separated out, and then they would spontaneously generate more "radioactivity."

Soddy

"Rutherford and his radioactive emanations got to me before many weeks had elapsed and I abandoned all to follow him. For more than two years, scientific life became hectic to a degree rare in the lifetime of an individual, rare perhaps in the lifetime of an institution."

Rutherford and Soddy used electromagnetic fields to explore the three types of emissions. They showed that γ-rays are high energy, short-wavelength *electromagnetic waves*, and confirmed that β-particles are electrons.

They then demonstrated that α-particles must be positively charged and much larger than electrons – we consider them to Helium ions, He^{++}, the nuclei of helium atoms.



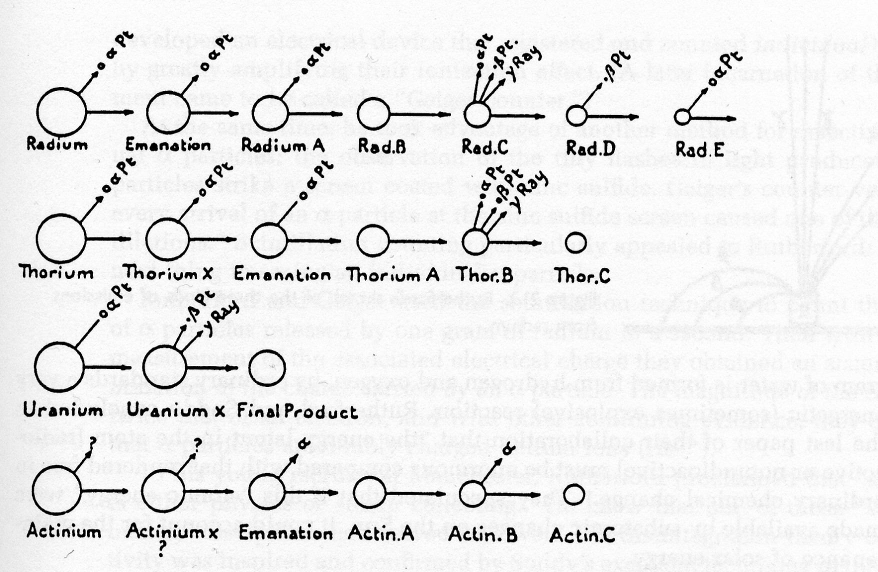
Spontaneous Disintegration

They studied the transformations of ratioactive elements and showed that each transmutation was accompanied by radioactive emissions. They determined that the process was purely random; that it did not depend on the atom's age and could not be predicted – leading to the concept of *half-life*. Initially, they could not collect enough of the various transformation substances to carry out chemical analysis, so they proposed provisional names based purely on their position in the process of decay.

Once they had traced these processes they could start to study the quantity of the energy released in the process. 1gm of radium *spontaneously released* 2,000 times the energy produced when 1gm of H_2O is formed.

Rutherford and Soddy

"The energy latent in the atom must be enormous compared with that rendered free in ordinary chemical exchange."



Radioactive decay, presented by Rutherford in a lecture at the Royal Institution

Rutherford's Work at Manchester

At Manchester University, Rutherford started to work on the α-particles.

Hans Geiger, a postdoc from Germany, invented a device that would produce a bright point of light on a screen when a single α-particle hit it. (This was later modified to the create the Geiger Counter.) This allowed them to count individual α-particles by "scintillations."

By passing them through induced electromagnetic fields, they were able to measure the charge on the α-particle, and found it to be a positive charge, twice that of the electron's negative charge.

Rutherford and Geiger used radium to bombard air and metal foils with α-particles. The room was kept dark for counting the scintillations. The scintillations were mostly directly in front of the source, but there was also some scatter. Rutherford conjectured that these scatters could be used to explore the internal structure of the atom.

Rutherford's "Strong Right Arm"

Marsden, an undergraduate, was given the task of looking for scattering at greater than 90°.

Rutherford

"I agreed with Geiger that young Marsden, who he had been training in radioactive methods, ought to begin a research. Why not let him see if any α-particles can be scattered through a large angle? I did not believe they would."

Marsden fired the α-particles at gold foil which was .0004mm thick, with the stopping power of 1.6mm of air. About 1 in 20,000 α-particles were deflected at 90° or greater.

Rutherford

"This was quite the most incredible event that ever happened to me in my life. It 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 in the face."

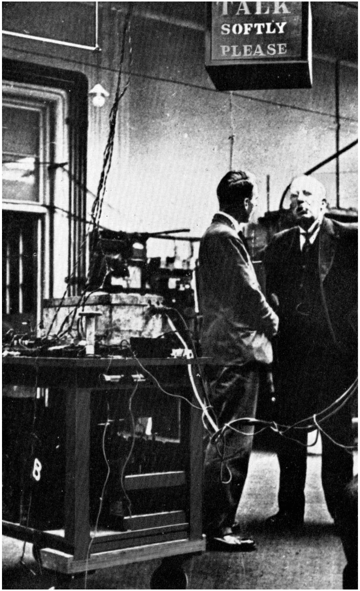
Rutherford's Atomic Model

In order to be turned back, the α-particles had to come close to something that was both very small and very highly charged. He called this charged center the *nucleus*. He estimated that the nucleus was 100,000 times smaller than the atom itself – later revised to 23,000 times for Uranium, and 145,000 times for Hydrogen.

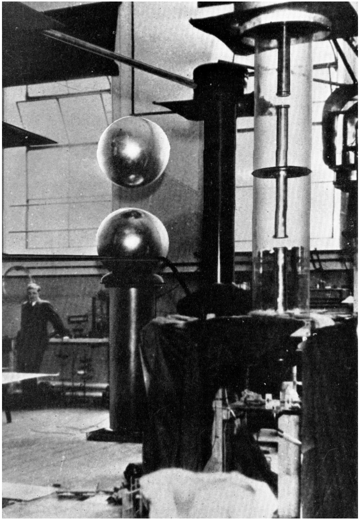
Rutherford had been taught that atoms were "nice hard little fellows," now he argued that they were almost entirely empty space.

Rutherford's model was mostly ignored until two other researchers used it as a core component of their research programs.

- Niels Bohr (1885–1962), who was doing a postdoctoral fellowship at Manchester, used it, with modifications, as the basis of his new quantum theory of the atom.
- Harry Moseley (1887–1915), one of Rutherford's Manchester group, used it to give a physical account of a number of mysterious features of the periodic table, having to do with what we call isotopes.



J. Ratcliffe, E. Rutherford



Inside the Cavendish, 1930s

Chemical and Physical Atoms

Moseley argued that the most important feature of *chemical* elements was not the weight but the number of protons, and the positive charge that these involved – that is, their *atomic number*.

This would explain why many substances that should come in the same place in the table of elements had slightly different atomic weights.

Weights were determined by the sum of all three particles – *electrons* ($-$), *protons* ($+$) and *neutrons* (0) – while chemical properties were purely a result of electrical charge.

He called versions of the same element that had different weights *isotopes* – for example iodine-127 and iodine-131, or uranium-238, uranium-235 and uranium-234.

Overview

Around the turn of the 20th century, there were a number of discoveries of completely unexpected effects: x-rays, other forms of radiation, radioactivity.

These new x-rays cast doubt on the theories of light and electromagnetism. Radioactivity cast doubt on the way in which matter had been understood as inert – it had no conceivable explanation within classical physics. How would the worldview of the 19th century have to change to accommodate these new findings?

At the same time that the atom entered laboratory practice, it was found to have *internal structure*. The physical atom and the chemical atom were now understood to be the same, but whereas the atom cannot be split by chemical processes it can by physical processes. In order to study the internal structure of the atom, we need to use sub-atomic particles and processes.