Part 2
Inside the Nucleus

Isotopes (1913)

While Rutherford and his crew studied the nature of the nucleus, his former colleague from McGill, Fredrick Soddy, investigated the products of radioactive decay. He found forty substances leading, step by step, from uranium to lead. Some of these substances had different radioactive properties but identical chemical ones and thus occupied the same place in the periodic table. He noted "…their atoms have identical outsides, but different insides," but he did not know what was inside. Soddy called those elements isotopes[1].

In some isotopes, he and Rutherford recognized that the radiation level changed over the short time of their experiments; some lost activity and some gained. He measured the time it took for radioactivity to diminish by half and called it the isotope's half-life period, or half-life[2]. One of the reasons that it took Marie Curie ten years to isolate polonium is that its half-life is only 138 days[3]. Before she could complete her isolation, half of the polonium had changed to another element.

[1] In Greek, isotope means "in the same place."
[2] Half-life is the time it takes from one half of a radioactive element to change into another. It is measured by a decrease in radioactivity of the first element and an increase in the second.
[3] This is a troublesomely-short half-life, that of U^{235} is 700 million years, while U^{238}'s is 4.5 billion.

Transmutation (1918)

In the first quarter of the twentieth century, firing alpha particles at various elements was all the rage. In 1913, Rutherford had Ernest Marsden shooting them at different gases, but Marsden accepted a positon in New Zealand and put the experiment on hold. When James Chadwick returned from a German prisoner of war camp, (he had the misfortune of being a Brit in Berlin at the start of the First World War) he and Rutherford continued Marsden's experiments. When they bombarded nitrogen, they produced a highly-energetic, positively-charged particle with the mass of a hydrogen atom. Rutherford named it the proton and thought that the alpha particle had knocked it lose from the nitrogen nucleus. The remaining element, having lost one proton, should have been the lighter element carbon, but rather they found the heavier oxygen.[4] For the first time, man had made one element from another. Of the discovery, Rutherford expostulated in his booming voice, "For Christ's sake…don't call it transmutation. They'll have our heads off as alchemists."

Rutherford and Chadwick had proven that the atom consisted of a nucleus of positive protons surrounded by negative electrons, but there was a problem. Hydrogen has one proton and helium has two, but it takes four atoms of hydrogen to weigh as much as one atom of helium. In 1920, Rutherford deduced that there must be some other particle in the nucleus to make up this missing mass, and it could not have a charge. He speculated that it consisted of a proton with a closely associated electron. A year later he called this combination a neutron, but no one had ever seen evidence of one, nor would they for a decade.

[4] Rather than knocking a proton loose from nitrogen and producing carbon as Rutherford thought, the alpha particle, which contains two protons, added one into the nitrogen nucleus producing oxygen with one proton left over.

Lawrence, Berkeley and the Cyclotron (1930)

Alpha particles frustrated Rutherford. Their source was rare and costly, and they had barely enough energy to enter the nucleus; he wanted a copious supply of particles with much higher energies. To satisfy his request two of his graduate students, James Cockcroft and Ernest Walton, developed a complicated, high-voltage linear device that accelerated alpha particles to a much higher speed, but the Cockcroft-Walton generator had its drawbacks. In Germany, however, others were experimenting with lower voltage particle accelerators.

One day in 1929, an up-and-coming associate professor of physics, Ernest Lawrence, was browsing scientific publications in the University of California, Berkeley library, when he came across an article in German by a Norwegian student, Rolf Wideröe. Although he could not read the article, the schematic of a particle accelerator, caught his eye. The contrivance used oscillating magnetic fields of modest voltage to accelerate protons. Only the frequency of oscillation and the length of the glass tube down which they sped limited the particles' energy.

To get energies in the range of the millions of electron volts[5] (Mev) needed for further experiments, the tube needed to be longer than could fit in Lawrence's laboratory. How could he get the same acceleration in a smaller space? What about a circular track, like a horse race track? Around and around a charged particle flew, accelerated by alternating magnetic fields. With each rotation, its speed was boosted, like a man pushing kids on a merry-go-round, faster and faster. In the stacks of the library in Berkeley, the cyclotron was born.

Lawrence's first model would have made Rutherford's frugal heart sing; four inches in diameter and made of brass, wire and wax, it cost twenty-five dollars. With each successive iteration, its size increased: eleven inches, then twenty-seven inches, then thirty-seven, then sixty culminating in a one-hundred-eighty-four-inch machine that produced proton particle energies of 400 Mev. Lawrence received a patent for the cyclotron in 1934 and the Nobel Prize in 1939.

In 1932 Igor Vasilyevich Kurchatov created a baby cyclotron in the Radium Institute in Leningrad, but it did not work well. Construction of a larger instrument began in 1939, but Germany invaded the Soviet Union before it could be completed.

[5] One million electron volts is the kinetic energy (speed) imparted to one electron by the application of one million volts. It is a very small amount of energy, except when imparted to a sub-atomic particle.

Cockcroft and Walton, Splitting the Atom (1932)

When Cockcroft and Walton hit a lithium nucleus with a high-energy proton from their linear accelerator, it shattered into two helium nuclei with the release of a great deal of energy. There was excitement, calling the splitting of the atom an incredible source of power and a great boon to mankind, but Rutherford quickly poured cold water on the idea. "…anyone who looked for a source of power in the transformation of atoms was talking merest moonshine."

Chadwick and The Neutron (1932)

In the early 1920s, Chadwick began a series of experiments looking specifically for the neutron that Rutherford knew must exist and, a decade later, he found it. When he bombarded beryllium with alpha particles, it produced high-energy radiation that could penetrate eight inches of lead (an energized proton or an alpha particle will be stopped by less than one sixteenth of an inch). As it had no charge Chadwick at first assumed the energy was gamma rays but when he repeated the experiment, putting a layer of wax in the way, protons were expelled. Whatever was coming from beryllium knocked protons from the hydrogen atoms in the wax. He measured this unknown energy and that of the expelled protons and calculated that both had approximately the same mass. In June 1932, Chadwick published "The Existence of a Neutron" in *Proceedings of the Royal Society*.

A chargeless particle with the same mass as the proton now inhabited the center of the atom and it could be liberated at a great speed. Being neutral, it could enter the positively-charged nucleus without being repelled. Scientists immediately began bombarding all kinds of elements with neutrons to see what would happen.

Neutrons and Isotopes

Chadwick had solved Rutherford's dilemma that helium weighs four times as much as hydrogen. Hydrogen has one proton and helium has two protons and two neutrons. As a neutron has no charge, an atom can have more or fewer without effecting its chemical properties; its radioactive properties however, differ with the number of neutrons. In 1913, Soddy did not know that different isotopes of an element have different numbers of neutrons, twenty years later it was common scientific knowledge.[6]

[6] I am using the designation $_1H^1$ and $_2He^4$ for hydrogen and helium. The subscript represents the number of protons, the atomic number, and the superscript the number of protons and neutrons, the atomic weight. Each element has the same atomic number, but may have a different atomic weight. A hydrogen atom can take on a neutron and become the isotope, deuterium ($_1H^2$) or two and be tritium ($_1H^3$). I have usually omitted the subscript; so, deuterium is show as H^2 and tritium as H^3. Two of uranium's several isotopes, U^{235} and U^{238} are of special interest.

Leo Szilard's Obsession (1933)

One rainy London day, after attending a Rutherford lecture in which he used the term "moonshine", Hungarian physicist, Leo Szilard was waiting for a green light to cross Southampton Row near the British Museum when he had a thought. If Cockcroft and Walton's high-speed proton could shatter a nucleus and release the energy stored within, a high-energy neutron might do the same; and if the shattering released two additional neutrons, then it could start a chain reaction that would grow exponentially, producing energy at every step. His new idea overcame his irritation with his cold, wet feet and with Rutherford's dismissive comment and he began to plan. The next year Szilard patented a device using x-rays to create a neutron beam which bombarded some undetermined element that was somehow altered, releasing energy and more neutrons. The device used heat from the reaction to make steam. Szilard experimented with various elements, first beryllium, then indium. For five years, he was obsessed with the idea of a chain reaction and the enormous power it would release; in 1933 he had already seen a clear glimpse of the future, but none of his experiments produced extra neutrons.

Fermi's Fountain: Slow and Fast Neutrons (1934)

Just as alpha particles had been shot at various nuclei in the 1920s and accelerated protons in the early 1930s, so it was with neutrons after their discovery. In his Rome laboratory, Enrico Fermi bombarded all the known elements and measured their degree of radioactivity using the newly-invented geiger counter[7]. He noticed that when he did his experiments on a marble table, the radioactivity was much less than when he used a wooden one. He carefully repeated his experiments and finally surmised that atoms in the wood slowed the neutrons and that, in some cases, slower neutrons reacted more readily than fast. When someone suggested that the hydrogen in water might also slow neutrons, Fermi and his colleagues immersed their experimental apparatus in a nearby goldfish pond with results like those on the wood table. Fermi's Fountain is now an historic site of the European Physical Society.

Fermi's bombardment of uranium with slow neutrons produced many radioactive substances; among them were elements heavier than uranium – transuranic elements – or so he thought. Creating or discovering a new element was a big deal and the Italian scientists were beside themselves with joy. Unfortunately, rather than producing transuranic elements, it seems certain that Fermi had split the uranium atom but did not know it. He named two new elements, ausonium and hesperium, and received the Nobel Prize in 1938, but his new elements did not exist; no one asked for the return of the prize or the money.

[7] Hans Geiger and Walther Müller invented the device in 1928 to detect ionizing radiation. It effectively measures alpha and beta particles, neutrons, gamma and x-ray radiation.