CHAPTER 1

Discovering the Secrets of the Uranium Nucleus

Nuclear Physics in the Year 1932

During the first three decades of the 20th century, physics underwent a development as dramatic as the scientific revolution in the 17th century. This development was represented by Albert Einstein whose Theory of Relativity, developed in the years 1905–15, wrapped up classical physics in the most satisfying way, as well as by Max Planck, Marie Curie, Ernest Rutherford, Niels Bohr, Werner Heisenberg and many others. Through their combined efforts, science achieved a deep understanding of the structure of atoms and the natural laws that govern atomic and nuclear processes.

In 1932, the physicists thus knew that all atoms consist of a very small, positively charged nucleus around which orbit a number of negatively charged electrons. In a neutral atom, the total negative charge of the electrons perfectly balances the positive charge on the protons in the nucleus. The lightest atom is the hydrogen atom, which only has one positive proton in its nucleus, and one negatively charged electron rotating around it. The physicists also knew that almost the entire mass of the atom is concentrated in the nucleus. Finally, they knew that all other nuclei than the hydrogen nucleus must contain something in addition to protons; otherwise, the masses would not add up. The second-lightest atomic nucleus is found in the element helium. Even though it only contains two protons, it has a mass that is approximately four times larger than the mass of the proton. The answer to this scientific riddle came in 1932, when English physicist James Chadwick demonstrated the existence of a hitherto unknown neutral particle whose mass was almost the same as that of the proton. He named this particle a neutron, and this new discovery made it possible to understand the composition of the different elements.

Each element is characterized by the number of protons in its nucleus, called its atomic number. A neutral atom of a given element contains exactly the same number of electrons as protons, because each proton carries one positive elementary charge and each electron carries one negative elementary charge. Further, any given element, in addition to the characteristic number of positively charged protons in its nucleus, may contain a number of neutrons, which carry no electrical charge. The total number of protons and neutrons is called the element's mass number.

In the Earth we find elements with atomic numbers between 1 and 92. The element with one proton in its nucleus is, as mentioned, hydrogen, which is designated by the symbol H. The element with two protons in its nucleus is helium (He). The element with eight protons in its nucleus is oxygen (O), and the element with 92 protons in its nucleus is uranium (U). Elements with more than 92 protons in their nucleus can only be produced artificially – they do not exist naturally on our planet, or at least only in extremely small quantities.

Elements appear in several varieties, called isotopes. Take, for instance, uranium. All uranium nuclei contain exactly 92 protons, but the number of neutrons can vary. The most important isotopes of uranium are U-235 and U-238, 235 and 238 being the mass number – i.e., the total number of protons and neutrons in the two isotopes. Of these isotopes, U-238 is by far the most common. 99.3 percent of the uranium found in the ground is U-238, while only 0.7 percent is U-235.

Some isotopes are stable, while others are unstable and decay spontaneously into a different element by releasing different types of radiation, usually alpha particles (identical to helium nuclei) or beta particles (identical to electrons). Unstable isotopes are also called radioactive isotopes. Element transformation thus takes place spontaneously in nature, but it is also possible to do it artificially, for example by bombarding an element with protons that are sped up through a specially designed machine called an accelerator. This was done successfully for the first time in 1932 in Rutherford's lab in Cambridge, when the physicists John Cockcroft and Ernest Walton bombarded the element lithium, which has three protons in its nucleus, with accelerated protons and found that this produced two helium nuclei, each of which contains two protons.

The Crafty Neutron

The discovery of the neutron made it clear that nature must harbor immense, hitherto unknown forces that held the atomic nucleus together. Think, for example, of a helium nucleus that consists of two protons and two neutrons. Based on ordinary understanding about electricity, it makes no sense that such a nucleus can exist. After all, the two positively charged protons are very close to each other and should repel each other with large electrical force. In order for the nucleus to remain as a unit, there must therefore also be some force of attraction between the protons and neutrons. And what is more, these forces must be much stronger than the electrical force of repulsion between the protons; otherwise, it would be easy to split atomic nuclei apart. And normally, it is not at all easy.

By accelerating positively charged protons through an accelerator and pointing them at, for example, helium, oxygen or uranium, physicists can calculate how much energy is required to split an atomic nucleus. Experiments like this were done in many places during the 1930s, finding that the energy with which a nucleus particle is bound in the nucleus is usually millions of times stronger than the energy with which an electron is bound in an atom.

The energy released by burning wood or in an internal combustion engine is called chemical energy and is only related to the rearrangement of atoms. Nothing happens to the atomic nucleus itself in chemical processes. Many scientists therefore asked themselves whether the much more potent energy stored in the atomic nucleus could be exploited in practice. Some prominent nuclear physicists believed so, having realized as early as in the 1930s that it must be such energy-releasing nuclear processes that take place in the center of the sun and other stars. But could similar processes be realized on our planet? This was a contested question. Most physicists, however, agreed with the famous experimental physicist Ernest Rutherford, Niels Bohr's mentor, when in 1933 he stated that all talk of exploiting the energy in the atomic nucleus was pure "moonshine".[10]

Even though scientists were not yet able to exploit nuclear power in practice, they could still study nuclear processes in their labs. Here, the neutron turned out to be the ideal projectile. While a positively charged proton has to be accelerated to a very high speed to overcome the electrical repulsion from another positively charged nucleus, a neutron – which is not electrically repelled – can sort of sneak its way into a nucleus and cause various nuclear reactions. These were relatively inexpensive experiments that did not require large accelerators, and they were carried out in many labs around Europe, but especially in Rome under the direction of physicist Enrico Fermi. He systematically bombarded one element after another with neutrons, in that way triggering unknown nuclear reactions and producing a number of new isotopes. At some point, he came to the element with the highest number of protons in its nucleus – i.e., uranium. Here, he observed some peculiar phenomena which he interpreted as the creation of transuranic nuclei, i.e. nuclei containing more than 92 protons. Observing electrons coming out, he imagined that a transuranic nucleus would be created when a uranium nucleus absorbed the incoming neutron, thereby becoming unstable and decaying by emitting a negatively charged electron.

The charge of the remaining nucleus had thus increased by one, meaning it would have 93 protons, instead of the 92 found in the original uranium nucleus. Or, if two electrons were emitted, the result would even be a transuranic nucleus with 94 protons. Fermi published his findings in 1934. Given his status as a prominent physicist, his conclusions were widely accepted by most of his colleagues. However, one German chemist, Ida Noddack, offered a different explanation. She suggested that instead of creating transuranic nuclei, Fermi's experiment might have actually broken the uranium nucleus into two or more fragments.[11] Unfortunately for Noddack, her hypothesis, being proposed by a relatively unknown female chemist, was largely dismissed at the time. While this was harmful to her career, the unjust dismissal may well have been fortunate for the world – for reasons that will become clear shortly!

In 1938, Fermi received the Nobel Prize in physics for his research into element transformation by means of neutrons. It was a great honor, and naturally he was invited to Stockholm for the prize ceremony on the day of Alfred Nobel's death, December 10. However, instead of returning home after the ceremony, he seized the opportunity to travel to the USA, where he had a standing invitation to become guest professor at Columbia University in New York. He was accompanied by his wife, Laura Fermi, who was Jewish. No doubt, Fermi anticipated the problems his family would soon face in fascist Italy, where the regime was introducing racial laws directed at Jews, just as had happened five years earlier in Hitler's Germany. Many, including Fermi, were aware that a new war was brewing, with Germany and Italy as allies. Germany had in the spring of 1938 annexed Austria without reprisals. In September of the same year, Hitler had obtained the approval of France and the United Kingdom – via the Munich Agreement – to seize control of the border region between Germany and Czechoslovakia. Without its border fortresses, Czechoslovakia could only wait for the inevitable German occupation. This took place in spring 1939. Shortly afterwards, Hitler started making demands for border revisions with Poland. However, this was when France and the United Kingdom put their foot down. Both countries pledged that they would declare war on Germany if the country went through with its threats against Poland.

The Christmas Holiday That Shook the World

The troubled years between 1932 and 1938 saw many attempts to exploit the 1932 discovery of the neutron to create element transformation. As mentioned above, Fermi had performed this kind of experiment for some years in Rome, but in the summer and fall of 1938, the well-known chemist Otto Hahn and his assistant Fritz Strassmann, both employed at the Kaiser Wilhelm Institute in Berlin, were also engrossed in studying the outcomes of bombarding uranium with neutrons. Like Fermi in Rome and the scientist couple Irène and Frédéric Joliot-Curie in Paris, they found that several new atomic nuclei were created. For many years, Hahn and Strassmann had collaborated closely with the talented Austrian physicist Lise Meitner. She had also contributed to the planning of the ongoing series of experiments, but in 1938 her Jewish ancestry forced her to flee from intensified Nazi persecution. Via the Netherlands and Denmark, Meitner arrived unharmed in Stockholm, where she was staying when, on December 21, she received a letter from Hahn in Berlin. In the letter, he wrote about the most recent attempts to identify the new particles created from neutron bombardment of uranium. And then came the great revelation: if Hahn had not been told over and over by his fellow physicists that an atomic nucleus under bombardment would only split off small parts such as protons, neutrons or helium nuclei, he as a chemist would have sworn that some of the new particles were nuclei of the well-known element barium, which has 56 protons in its nucleus – i.e., far fewer than the 92 protons in uranium. "Perhaps you can suggest some fantastic explanation," he added.[12]

On December 23, Meitner left Stockholm to spend the holiday visiting friends in Kungälv near Gothenburg. She arrived in the evening, and so did her nephew, physicist Otto Frisch, who worked at Niels Bohr's Institute in Copenhagen. After breakfast the next day, they ventured out into the beautiful winter landscape, eagerly discussing the contents of Hahn's letter. At first, Frisch flatly dismissed Hahn's claim, maintaining that the experiment must have been flawed.

© National Archives and Records Administration

Lise Meitner and Otto Hahn in their laboratory at the Kaiser Wilhelm Institute in Berlin, 1913.

Niels Bohr (second from the left) is pictured in Copenhagen in 1934, with four other nuclear physicists. Two of them, Edward Teller (fourth from the left) and Otto Frisch (fifth from the left), also made significant contributions to the development of nuclear weapons.

However, during their walk, the two came to think of the model of an atomic nucleus suggested by Niels Bohr a few years earlier. The model was called the liquid drop model because it compared an atomic nucleus to a drop of liquid, which is held together by chemical forces between its atoms, which give rise to surface tension. In an atomic nucleus, the electrical forces, which are repulsive, become stronger the more protons there are in the nucleus. The reason that uranium is the heaviest naturally occurring element must be that the long-range repulsive forces between the protons are only just kept in balance by the surface tension due to the strong short-range forces between the nuclear particles.