When Energy is Released from Atoms

When Energy is Released from Atoms:

The Story of the Manhattan Project

By

Falin Chen

Cambridge Scholars Publishing

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PREFACE

When energy was released from atoms the world as we know it was forever changed. This brought to an end the Second World War that had robbed 55 million of their lives, while the U.S. and Soviet camps were soon to enter a nuclear Cold War hinging on their mutually assured destruction. This war of words without actions continually played out on the international stage, allowing modern nuclear bombs to become hundreds and even thousands of times more powerful than the one dropped on Hiroshima. Nuclear nations' bomb reserves now number between the hundreds and the thousands and possess a combined force capable of decimating the human race many times over. Just as the writing of this book was nearing its completion, North Korea was brazenly declaring its intention to test a hydrogen bomb in the Pacific and threatening the U.S. with a missile strike on the island of Guam. If these North Korean missiles were to be fitted with nuclear bombs, we would bear witness to a nuclear war. The first to suffer at the hands of this calamitous conflict would likely be North Korea itself, with Japan and South Korea potentially enduring serious casualties in its aftermath.

With the Manhattan Project as its protagonist, this terrifying drama has been acted out from the year 1939 to this very day and is still in the ascendancy. This scientific national security project recognized as possessing the largest scale, costing the most money and having the most profound influence on the world introduced humanity to the horror of our mutually assured destruction. Its developmental course is one truly worthy of our deepest contemplation and is the one we ought not to forget to reflect upon. When deciding to explore this topic with all its explosive details we were able to find an abundance of pertinent information. If you were to search for nuclear-bomb-related content on my school National Taiwan University's library website, hundreds of books and reports would spring onto your screen. What stands out is that most of these works are focused on the same few topics, such as the project's evolution, the bombing of Japan, nuclear conflict and critique of Oppenheimer. The outline of this book was structured in accordance with this information, around which we scoured all over for further knowledge and finally arranged key incidents and interesting stories into a timeline. For this, I must give thanks to the three outstanding assistants who aided me in this research: Hsin-Wei Chuang, Ya-Ting Chen and Sheng-You Yu.

Put simply, one can divide this book into four main sections. The first is contained in Chapter One. It begins with the discoveries of radioactive rays and the nucleus and continues up to the successful induction of a nuclear fission chain reaction. It is an account of the inception of nuclear physics. The second section spans Chapters Two to Five and is the very subject of this book. These four chapters chronicle the three primary project facilities from their beginnings to their ends. The third section includes Chapters Six and Seven which recount the explosive stories from around the world that followed the development of the nuclear bomb. The fourth section contains the last two chapters and discusses the political feuds that directly followed the war, as well as comments on the Manhattan Project's historical orientation. If you are not particularly interested in physics, you could skip the first chapter – this omission will not have much of an impact on your understanding of the project. If you are only interested in the project itself, you could read only the second section. If you are more curious about the postwar development of the nuclear bomb, you could read the two chapters of the third section. Those interested in politics could read Chapter Eight and gain a deeper understanding of how the U.S. employs its intelligence system to attack dissidents. Chapter Nine is an evaluation of the project aimed at inciting deeper insights from those who read it. Interested readers can have a go at writing their own versions of this appraisal.

If there is anything that makes this book unique, it ought to be that it is a collection of a large variety of stories. Readers can pick up key information and interesting tidbits from the further reading we have provided as well as other materials available to the public. By collating this information in accordance with your own personal viewpoint and understanding, you can arrange these events into a narrative of your own. Aside from focusing on the close relationship between the logical flow of this work and its timeline, readers can attempt to form their own opinions from the content we have provided. Although the stories in this work are all popular anecdotes, the perspectives we have put together and commentary provided are, to a certain degree, unique. We hope to aid readers with an interest in the Manhattan Project in better getting to know its central characters, technical standards, administrative muscle and historical legacy.

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PROLOGUE: 1895-1945

The fifty-year span between 1895 and 1945 saw a series of upheavals and incidents that would alter the course of human civilization. During the first 45 years of this period, the study of physics leaped from the cloud of mystery surrounding radioactive rays to bold inquiries into the very essence of matter. This concluded in the establishment of a framework for nuclear physics and exploration into new fields such as quantum, particle and high-energy physics, gradually allowing us to make headway into questions about the birth of the universe as well as its eventual end.

Just as this emerging field of nuclear physics was beginning to bear fruit, the most deadly conflict in human history erupted – WWII. In the West, Nazi Germany invaded Poland before rapidly swallowing up much of continental Europe. In the East, Japanese military powers already had a foothold in Korea and northeast China where they laid waste to local communities and enslaved their people before annihilating the American Pacific fleet in the distant waters of Pearl Harbor, Hawaii. All over the world, nations were dragged into the war by invaders from both the East and West, with only a small minority able to escape this dire fate.

At this time, a group of European Jewish scientists who had immigrated to the U.S. to escape German tyranny became greatly concerned about a nuclear fission chain reaction produced in a Berlin laboratory. They believed this breakthrough could move Hitler a step ahead in the race to create a nuclear bomb, and thus did their utmost to lobby the Roosevelt administration to engage in their own nuclear bomb research as soon as possible. The U.S. responded by stumbling through preparations for the nuclear bomb project for nearly three years, eventually leading to the full-scale launch of the Manhattan Project – the scientific endeavor with the most massive scale, highest cost and most profound influence on the world – in 1942.

Within the project's three-year duration, its leader Major General Leslie Groves mobilized a nearly 500 000-strong group of researchers and workers from almost nothing. Around 25 billion dollars adjusted to today's value were put to use in building the nuclear weapons industry able to keep pace with a U.S. automobile industry that had already been in business for half a century. Just for the enrichment of uranium-235 alone, the U.S. military put together a gigantic industrial boomtown in Tennessee that consumed one-tenth of the country's electricity supply and was home to 75 000 workers and their families. In order to assemble their one thousand cyclotrons, the project went as far as borrowing 15 000 tons of silver from the U.S. Treasury to replace the brass coils – a material in desperately short supply – needed to build motors for these contraptions.

On 16 July 1945, as dawn broke in the New Mexico desert canyon named "Jornada del Muerto" or "Journey of Death," a mushroom cloud carrying deadly radiation and temperatures thousands of degrees high shot up from the ground. A light brighter than the rays of thousands of suns illuminated the dim morning earth, reflecting peculiar transparency. Sand and stone were transformed into a green-gold glass-like material, almost all flora and fauna were decimated and nearby structures were all razed to the ground. This was the world's first-ever nuclear detonation; the fruits of the Manhattan Project's labor jointly facilitated by a group of physicists who began immigrating to the U.S. in 1933 in an escape from tyranny in Europe. These elite immigrants (many of whom were Jewish) brought new science to the U.S.: nuclear physics. This took Einstein's mass-energy equivalence formula $E=mc^2$ and adapted it for the creation of nuclear power, developing a technique that uses the destruction of matter for the generation of energy. In the end, this allowed them to produce nuclear weapons with immense destructive power: one uranium and four plutonium bombs.

Looking at the goal behind the establishment of the Manhattan Project, one would deem it a success. This is due to its transformation of scientific theories that were still in the experimental phase of their development into tangible nuclear bombs; two of which were dropped on Japan, ending WWII in the process. But looking at the Manhattan Project in terms of its impact on the world, it would be deemed a failure. This is because it failed to bring peace to the human race and drew the world into the nuclear Cold War. The mutual destruction assured between national powers in this conflict propped up the mere appearance of developing human civilization and a peaceful planet. Some historians would even go as far as claiming the Manhattan Project sounded the death knell for all humanity, as from the moment our civilization stepped on to this road to ruin up there have been no signs of turning back.

Regardless of its place in our history, the Manhattan project's three superlatives – having the largest scale, highest cost and most profound impact – to this day mean it is universally regarded as an unparalleled feat of scientific development. But throughout its implementation the prospect of failure often surfaced, and if any of its potential issues were not dealt with, the entire project might have come to a premature end. The fact that it was miraculously completed in just 28 months, despite this journey being akin to a stumble over a rocky road, could only be down to a group of cool-headed, clear thinking and iron-willed leaders on multiple steps of the hierarchical ladder. These project heads put forward wise policy decisions at every critical moment, persevered in their unyielding management of every undertaking and contemplated every possible way to surpass the obstacles in their path. It was this level of commitment that allowed them to accomplish such a large and complex project within the time allocated to them.

How did these astute policies, administrative endeavors and great leaps over stumbling blocks come about? This is precisely what is discussed in this book. To tell this story in its entirety, we need to start in the year 1895.

Chapter One

The Development of Nuclear Physics: 1895-1945

In all of Chinese history 1895, the year the Qing Dynasty was defeated by western colonial powers, was perhaps the most torrid year for this nation. After the Qing gates had been broken down by steel ships and cannons from the U.S. and Europe, the Japanese – who in this year had emerged as a major eastern power – thrashed the Beiyang Fleet in the First Sino-Japanese War. This earned them reparations and land ceded from China, including Taiwan which became the first colony of the Empire of Japan. From then on Japan ran riot over the southeast Asian countries surrounding China, brazenly expanding its territory. This year thus became known as the dawn of Japanese imperialism, as it gave rise to the crushing of the preeminent Qing Empire by Japanese bandits wielding both katanas and bayonets. On top of this, this eastern power was not only able to send the Tsarist forces packing back to Siberia from the Liaodong Peninsula during the Russo-Japanese War, in the expanse of the Pacific Ocean they were even able to obliterate the United States Pacific Fleet in under four hours. The Japanese ran the only empire that could attack three of the most powerful contemporary powers in the world within the same half-century *and* secure victory. However, 1895, the very same year that gave rise to their empire, was the point in time that set its destruction in motion. This was due to a succession of scientific laws gradually being uncovered in 1895, facilitating the creation of the nuclear bombs that would be dropped on Japan.

The pioneer at the center of these revelations was Wilhelm Röntgen (1845-1923) – director of the University of Würzburg at the time. He discovered the previously unheard of “X-rays” by using the two electrodes at the poles of a cathode ray tube to excite the electrons within. The next year saw the French physicist Henri Becquerel (1852-1908) discover another ray through his experiments with uranyl sulfate that, just like the X-ray, was highly penetrative. This ray, however, was produced by a natural radiation process and did not require excitation. Following this, Becquerel’s students – Marie and Pierre Curie (1867-1934 & 1859-1906) who married in 1895 – continued his research into this natural radiation. Using several tons of uranium ore the couple extracted trace amounts of two highly radioactive new elements: polonium (Po) and radium (Ra). They went on to define the scientific concepts of radioactivity and radioelements (which were later referred to as radioisotopes), launching this brand new field of nuclear physics. Also in 1895, the New Zealand physicist Ernest Rutherford (1871-1937) entered the Cavendish Laboratory at Cambridge University to begin exploring the structure of the atom, work which would raise the curtain on research into nuclear fission chain reactions. As a result of Röntgen’s discovery and the serendipitous convergence of these significant breakthroughs, 1895 is often referred to by the scientific world as the beginning of modern physics.

The Discovery of the Electron

Just as research into radioactivity was taking off in continental Europe, in the U.K. Cambridge University was making quick inroads into the study of atomic structure. The first fruits of their labor belonged to the Cavendish Laboratory's J.J. Thomson (1856-1940), who in 1897 discovered the electron, setting off the vitally important wave of scientific study aimed at exploring the fundamental structure of matter. During Thomson's time electricity was widely accepted to be a moving energy form with a current that could be produced by chemical means (like a battery, as Volta {1745-1827} had discovered) or by physical means (like a magnetic field, as Faraday {1791-1867} had discovered). This electric current could be drawn onto metal wires, but its underlying nature was still unknown. In an attempt to explore this mystery, Thomson used the cathode ray tube – an instrument extensively used at the time – to conduct electric current experiments. After charging the tube between the anode and cathode, the electric current (which moves in the opposite direction to the electron current) in Thomson's experiment could pass from the positive to negative pole without a metal wire.

Thomson noticed that the residual gases in the tube emitted light when struck by electric currents. This light's path would be deflected when in contact with a magnetic field, bringing Thomson to deduce that this current had a negative charge. At the same time, he made note of the change in temperature that occurred when the current hit the tube's plate along with the degree of deflection produced when it passed through the magnetic field. Thomson could then assert that this electric current was composed of negatively charged particles and calculate their charge-to-mass ratio (electric charge over mass). He called these particles “corpuscles,” a term later replaced by electrons. Thomson discovered that electrons are not only present in the air; traces of them can also be found in metal wires, leading him to infer that electrons exist in all types of matter. He later put forward the first atomic model: atoms are spheres composed of evenly distributed positively charged particles (which became known as “protons” after 1920) with negatively charged electrons evenly dispersed within. In his model, each atom has a size of approximately 10^{-10} meters.

The study of electrons then fell static for some years before it took a significant step forward with the University of Chicago’s Robert A. Millikan (1868-1953) in 1910. Millikan made improvements to the oil drop experiment apparatus used for John Townsend’s (1868-1957) work in the Cavendish Laboratory, suspending electrically charged oil droplets of different sizes between two horizontal plates. As he knew the strength of the electric field and net weight of the oil prior to the experiment, Millikan could measure the amount of electricity that caused the oil to be suspended, and then use mechanical equilibrium to calculate the electrical charge of the oil drops. Via several experiments, Millikan discovered that each electrical value he calculated was a multiple of a specific base value calculated as 1.592×10^{-19}, a number he deduced to be the charge of an electron. It was later proven that his proposed number was extremely close to the real charge an electron carries of 1.602×10^{-19} coulombs. After achieving this value, he used Thomson’s mass-to-charge ratio to calculate the electron’s mass to approximately 1/1800th of a hydrogen atom (or 1/1836th of a proton to be exact).

The Discovery of Three Different Rays

The next to take up the mantle of nuclear physics and make a vital contribution to the field was Ernest Rutherford. A long-time friend of the Curies, he had been using Marie's discovery radium since 1898 to study the fundamental properties of radiation. In a series of experiments Rutherford discovered that radium would transmute into thorium, thus deducing that radioactivity is brought about by an unstable atom transmuting into a more stable one; and not as a result of changes occurring in a group of regular atoms or molecules (otherwise known as a chemical reaction). The appearance of radiation is one of how transmutation is exhibited. Rutherford also found that these radioactive rays were comprised of a chain of fast-moving particles that are a combination of other particles released from radon gas and electrons captured from the air. After these particles have lost their electric charge, they become neutral helium atoms.

In order to gain a deeper understanding of the physical properties and radioactive behavior of these rays, Rutherford designed an experiment using radium as a radiation source. This new experiment aimed to observe the reaction that occurs when a radioactive ray strikes a thin metal foil. After gaining sufficient data through a lengthy period of experimentation, Rutherford divided radioactive rays into three categories. The first would be blocked by a metal foil, bouncing back or deflecting away. It was comprised of a type of positively charged particle and weighed about as much as a helium atom (it later became known as the alpha $\{\alpha\}$ ray). The second type would penetrate through thinner metal foils, was comprised of a type of negatively charged particle and weighed about as much as an electron (it later became known as the beta {β} ray). The third type of ray – the electromagnetic radiation that was the most penetrative of the three – could pierce through any metal foil (this later became known as the gamma {γ} ray).

Following on from this experiment, Rutherford discovered that radioactive elements could transmute by emitting alpha or beta rays. Their level of radioactivity would decline by half after a certain amount of time; a time period that later became known as the half-life. The uranium-226 isotope, for example, has a half-life of 1599 years and decays at a rate of 3.7 x 10^{10} (37 billion) transmutations a second (this vexing number was later simplified as 1 *Ci*, or one curie). Plutonium-239, on the other hand, has a half-life of 24,100 years and decays at a rate of 62 *Ci* a second. Radioactive elements also emit energy during their transmutation. One gram of radium, for instance, produces between and 10^9 and 10^{10} *cal* of energy during its transmutation.[1]

Despite his discovery of these three types of radiation, along with the fact that when elements go through radioactive transmutation new elements are formed, Rutherford was still quite bothered by questions that arose from his

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[1] 1*cal* = 4.187 *joules*; 1 *watt* = 1 *joule/second*; 1 *eV* (electron volt) = 1.602 x 10^{-19} *joules*. This represents the kinetic energy produced by one electron pushed by one volt. The following are three numerical examples. (1) An electron pushed by a 1.5 *V* battery possesses 1.5 *eV* of kinetic energy, (2) When gunpowder ignites, each particle possesses 9 *eV* of kinetic energy, (3) The kinetic energy released from a nuclear reaction is counted in *MeV*s (mega electron volts) – over 100 000 times higher than that of a gunpowder explosion. The nuclear bombs dropped on Hiroshima and Nagasaki released 200 *MeV* of kinetic energy in a single fission reaction.

breakthroughs. He wanted to know what kind of changes take place inside the atom when a radioactive element goes through transmutation, especially as this was potentially connected to the study of alchemy (heating one element to create a new one) that was so popular at the time. Rutherford had always wanted to explain how his research had nothing to do with this witchcraft, and so was far from the patient in his pursuits. However, Rutherford's scientific accomplishments kept him well away from the entanglements of alchemical witchcraft, as his discovery of radioactive transmutation creating new elements had at this time already become a commonly discussed topic in the physics community. This allowed Rutherford, after returning to the U.K. in 1907 to take up a teaching post at the University of Manchester, to promptly recreate the equipment he had used at the Cavendish Laboratory. This was used to continue his experimentation observing the internal changes that take place in atoms when the alpha particles released from radon gas strike gold foil (which was only a few thousand atoms thick). But to his great disappointment, no visible deflection was observed in his experiment, as the vast majority of alpha particles upon hitting the foil sailed right through it. This may have meant that the inside of the atom was nothing but a meaningless void, a notion Rutherford was not convinced by.

Constructing an Atomic Model

In order to satisfy this curiosity, Rutherford, cautious by nature, believed there was a need to look more carefully for alpha particles with sizable deflections. To do so, he invited Hans Geiger (1882-1945) to redesign his experiment to measure alpha particles that might deflect in different directions. Geiger subsequently invited Rutherford's student Ernest Marsden (1889-1970) to join him in this endeavor. They decided to coat the interior of the existing vacuum tube with fluorescent materials, meaning that once alpha particles struck the inner wall of the tube, a glimmering fluorescent light would appear. Without any precise instruments with which to observe their results, these scientists recorded the number of fluorescent flashes along with their distribution by eye. By the end of their experiment, they found that within every 8000 alpha particles only one would bounce back, while many generated large-angle deflections. Rutherford was quite thrilled with these findings. Following a period of consultation and consideration, in 1909 he put forward an atomic structure differing from Thomson's. In this model, all of the atom's positive charge and the vast majority of its mass resides in its center, known as the nucleus, while the negatively charged electrons – which are smaller and lighter than the nucleus – revolve around this center. A year later, he used this experiment's findings to take his theory a step further, pointing out that the nucleus is approximately 10^{-15} meters in size while the atom as a whole is 10^{-10} meters (the same size as Thomson's estimation). Given today's understanding of physics, Rutherford's atomic model can be described as follows: the atom can be viewed as a sports field encircled by a 400-meter running track, with the nucleus being a small grain of rice placed at its center and the innermost electron moving around the track, orbiting this minuscule grain.

However, Rutherford's innovative atomic structure in fitting with the outcome of his experiment became quite unstable under an inspection using the laws of electrodynamics. According to James C. Maxwell's (1831-1879) electromagnetic theory, Rutherford's circumference-circling electrons would release energy via electromagnetic radiation, gradually moving off their orbit and falling towards the central nucleus. This idea, however, ran counter to the information revealed in the experiment. This contradiction was resolved by the Danish scientist Niels Bohr (1885-1962) in 1913, when he proposed his own atomic model, devising the atomic structure we all know today.

Bohr was a Jewish Danish physicist who, after receiving his doctorate, conducted electron research in Thomson's Cambridge laboratory. But, as Thomson did not take to his ideas, not long after his arrival, he transferred to the University of Manchester to join Rutherford in studying the atomic model. Early in this spell, Bohr submitted an outline of his research to Rutherford importing Max Planck's (1858-1947) quantum theory into Rutherford's atomic model. Bohr deduced that an atom's electrons ought to exist in a set of discrete states, revolving around the nucleus on orbits of different energy levels, and introduced the concepts of energy levels and frequency to Rutherford's model. According to Bohr's theory, electrons can only exist in a stable state on a set of discrete energy levels. If an electron is to move to another energy level, it needs to jump between one and the other. When an electron changes its orbit and energy level, the atom will either emit or absorb a specific photon frequency. In other words, in Bohr's quantum atomic model, electrons follow their energy level's orbit in a stable motion but do not release or absorb any energy. Only when an electron changes its orbit does electromagnetic radiation use light to release or absorb energy. While this finding could not put Rutherford's question of what happens inside an atom when radioactive elements transmute to rest, it did construct a genuine atomic model with an enormous impact on nuclear physics.

The Discovery of the Proton and Neutron

In 1919, six years after Bohr had brought forward his electron orbit model, Rutherford's team managed to prove that positively charged protons exist in hydrogen nuclei by bombarding nitrogen atoms with alpha particles. The proton's mass was concentrated in the central atomic nucleus, while the atomic weight was estimated using the quantitative results from the bombardment experiment. From his masses of data, Rutherford found that the atomic weight was proportional to the number of protons, usually at a rate of two to one. He thus came to suspect that another unknown particle with a neutral charge existed in the atomic nucleus. This hypothesis would have to wait until 1932 to be proven by Rutherford's student James Chadwick (1891-1974).

When Chadwick discovered the neutron he had already received his doctoral degree from Rutherford and been appointed as the Cavendish Laboratory assistant director of research. At the time he was still engaged in the alpha particle bombardment experiments Rutherford's laboratory was so adept in, albeit with the target of their bombardment having been changed from gold foil to beryllium powder. Chadwick found that when beryllium was bombarded a powerfully penetrative radioactive ray (later named beryllium radiation) composed of a chain of neutrally charged particles moving at high speed would be produced. As they had no electric charge, these particles would penetrate much further into their targets than protons would. In May 1932, Chadwick published a paper entitled "The Existence of a Neutron." From then on this particle became known as the neutron and its radioactive ray as neutron radiation.

Up to now, the atomic model, as far as we can understand it, has been constructed: the atom is comprised of positively charged protons and neutrally charged neutrons concentrated in its nucleus as well as negatively charged electrons moving on different energy level orbits. But the undying curiosity of the scientific world did not stop here, as there were still many questions left unanswered, including the reasons for radioactive decay that remained shrouded in a haze of mystery. In order to clear the fog of this enigma scientists continued to employ bombardment experiments to explore the unknown world lying deep within the atom. Sure enough, their bombardments eventually allowed a theory for nuclear fission reactions to breakthrough.

Delving into Nuclear Fission Reactions

When discussing nuclear fission, it is best to start from Enrico Fermi's (1901-1954) experiment. This Italian physicist married to a Jewish wife is known as a researcher endowed with many skills. Not only did his theoretical work bring him to the height of academic accomplishment, but he was also even more apt to build experimental apparatus with which to explore the implementation of scientific theory. In 1933 Fermi explained beta decay using quantum theory, entering the field of nuclear physics in the process. The next year he commenced on a series of experiments using neutrons to bombard a variety of targets, examining whether it was possible to produce radioactive rays artificially. He chose neutrons as the bombarding particles for two possible reasons: (1) Chadwick's previous proton bombardment experimentation was very inefficient (it took one million α particles to excite just 30 neutrons), (2) As neutrons carry no charge, they would not be repelled by the electrically charged protons, and would therefore be able to penetrate the atomic nucleus further.

With an increase in efficacy in mind, Fermi chose radium that decayed into radon, which in turn quickly decayed into polonium and emitted alpha particles, as a neutron source. This would then be used to bombard beryllium and excite neutrons. Fermi estimated that this neutron source would be able to produce 100 000 neutrons every second, with every neutron carrying 10 MeV of energy. For his targets, Fermi selected 63 different elements, including 37 that could produce human-made radioactive rays. But these elements all possessed notably short half-lives and so could not produce the desired results in his experiment. By June 1934, Fermi had augmented his neutron source, increasing its efficiency tenfold (it was now able to produce one million neutrons per second) and selected uranium-238 – the isotope with the highest known atomic weight at the time – as his target. The results of this experiment were breathtaking: Fermi discovered a new element with an atomic weight of 239. This was named a transuranium element but was later shown to be plutonium-239.

In response to Fermi's proclamation that he had discovered a transuranium element, the German scientist Ida Noddack (1896-1978) put forward a contrasting interpretation. This chemical scientist, known for her discovery of the element rhenium, believed that when heavy metal elements are bombarded by neutrons, they will often split into other elements or isotopes with lower atomic weights; not into heavier new elements as Fermi had proclaimed. This argument later became the foundation for the theory of nuclear fission. However, many years later, it was proven that Fermi's experiment could have produced both nuclear fission and a new element. This was because fast neutrons (moving at speeds of 20 000 *km* per second, with 10 *MeV* in kinetic energy) will cause uranium-238 to fissure and slow neutrons (also known as thermal neutrons and moving at speeds of 2 km per second with 0.025 *MeV* in kinetic energy) will be absorbed by uranium-238, which will then become the transuranium element with an atomic weight of 239. In his experiment, Fermi also found that while fast neutrons bring on radiation decay more rapidly, the rate at which slow neutrons initiate decay is higher. From his derivations of Schrödinger's wave mechanics equation Fermi learned that the rate at which neutrons bombard their way into the atomic nucleus is inversely proportional to their velocity; just like when a golf ball moves at a slower speed, there is a higher chance of it making its way into the hole.

Why did Fermi assume that he had discovered a transuranium element but could not detect the fragments left behind by nuclear fission? Later generations explained this by pointing to the specific properties of the elements he used: radon and beryllium. (1) Radon emits both alpha and gamma rays, the latter of which interferes with detection and is precisely why no fission fragments were found. (2) The new element created via the bombardment of uranium-238 has a half-life of 13 minutes, very close to the 14.6-minute half-life of the barium isotope produced with nuclear fission. These two fission products were therefore easily confused.

Aside from garnering Noddack's suspicion, Fermi's discovery of a transuranium element gave rise to several waves of experimental research and theoretical discussion from European scientists. The most vital breakthrough arising from this came in October 1938 with the German chemistry professors Otto Hahn (1879-1968) and Fritz Strassmann's (1902-1980) uranium bombardment experiments in the Kaiser Wilhelm Institute for Chemistry in Berlin-Dahlem. By bombarding one piece of uranium, they broke it into two pieces of barium isotopes roughly equal in weight. Most importantly, they discovered that a decrease in the total mass of the uranium had occurred, with the lost weight being converted into particles of either kinetic or thermal energy.

Two months later, news of this experiment's findings made its way to Lise Meitner (1878-1968) – a German Jewish physicist who had fled to Sweden. As soon as she had received a report on the experiment Meitner and her nephew Otto Frisch (1904-1968) set to work using the uranium fission equation to prove that Hahn and Strassman had succeeded in setting off a nuclear fission chain reaction. They then inferred that aside from the large amount of energy released, a large volume of neutrons would also be produced, sustaining the collisions required for a chain reaction. The two of them also calculated the amount of energy released by this chain reaction to be 200 *MeV* (the actual amount is 170 *MeV*), and that it was a consequence of losing mass (about 0.2 protons in mass). They concluded that Einstein's $E = mc^2$ equation was the theoretical basis for the energy release that occurs during nuclear fission. In a nutshell, this energy is used to speed up neutrons, further enhance the effectiveness of bombardment and increase the amount of energy released. This cycle repeats over and over again, allowing chain reactions to continue indefinitely.

In January 1939 Meitner sent her results to Bohr who at the time was still in Denmark but later verified the accuracy of her calculations while on a boat to the U.S. Shortly after arriving in New York, Bohr, in conjunction with Fermi, revealed the astonishing discovery of this uranium-235 chain reaction to the Conference on Theoretical Physics in Washington, D.C. Within a few months of this, Bohr had proposed his liquid drop theory explaining the changes that take place during nuclear fission. The French Jewish physicist Hans von Halban (1908-1964) went on to find from this experiment that one fission of a uranium nucleus would generate 3.5±0.7 neutrons, not far off from the actual amount of 2.4. While at Princeton Bohr and John Wheeler (1911-2008) developed a more complete theoretical model for nuclear fission, putting forward the most critical concept of a fission barrier:[2] (1) When the amount of energy residing in an atomic nucleus exceeds a specific limit, a natural fission reaction will occur (this usually occurs in elements with atomic weights above 96). (2) If this amount is below the limit (as in uranium and its isotopes; its largest limit being 55 *MeV*), additional energy to bring the nucleus to an excited state will be needed to surpass this barrier (as in the uranium-238 neutron bombardment experiment). This new energy comes from additional proton kinetic energy and energy released from atomic nucleus fission. (3) The limit also

[2] The minimum energy required to trigger the protons in a nuclear fission chain reaction: Elements situated in the center of the periodic table often have a barrier as high as 55 *MeV* (one million volts). The barriers of heavier elements like uranium and plutonium can drop to as low as 5 to 6 *MeV*.

determines whether or not there are sufficient slow neutrons to induce fission.

This limit thus became the barrier for nuclear fission; it would have to be surpassed for fission to occur. The principle of slow neutron bombardment producing uranium-235 nuclear fission reactions was proven by Columbia University's John Dunning (1907-1975) in March 1940. Bohr and Wheeler published the above-mentioned findings in the 15 February 1939 edition of the U.S. journal *Physical Review*, while in March of the same year a paper jointly written by scientists from Austria, the Soviet Union, France and Italy entitled "Liberation of Neutrons in the Nuclear Explosion of Uranium" appeared in the U.K.'s *Nature*. Upon giving an open lecture on nuclear fission research in Washington, D.C., Fermi was allocated 1500 dollars by the U.S. Navy to conduct experiments at Columbia, setting in motion American research into this field. By this time, the nuclear fission reaction was an openly discussed topic within physics circles, with American and European nuclear physicists champing at the bit to get involved in its study.

Nuclear Physics: Bombarding its Way to a Nuclear Explosion

Up until this point in the history of nuclear physics, most had a basic understanding of the atom – the substance that constitutes the most fundamental structure of all matter. While studying this structure, it was found that neutron bombardment could cause these atoms to split, allowing even more neutrons to continue to collide with the atomic nucleus. This would bring on a nuclear fission chain reaction, releasing a considerable amount of energy. The emergence of this massive bundle of energy inspired