Part 4
Tickling the Tail of the Elephant:
The World After Fission

The Word Gets Out (January, 1939)

After Christmas, Otto Frisch returned to Copenhagen and told Neils Bohr that Hahn and Strassman had split an atom of uranium with a neutron. Shortly thereafter, Bohr boarded an ocean liner for America; he requested a chalk board be set up in his cabin. At the Fifth Washington Conference on Theoretical Physics in January, 1939, he publicly announced the splitting of the atom, but many of the physicists attending the conference were skeptical. A reporter heard the news, wrote the story and it appeared in newspapers across the country the next day.

The Monday morning after the Washington conference, physicist Louis Alvarez was reading the *San Francisco Chronicle* while having his hair cut when he came across an article buried in the second section saying that two German scientists had split the atom. He bolted from the chair mid-snip and sprinted to the physics building on the U. C. Berkeley campus, spreading the word from lab to lab. Professor Robert Oppenheimer soon grasped the meaning of Hahn and Strassman's experiment and Meitner and Frisch's calculations. Within a week there appeared on his blackboard, a crude, but workable drawing for an atomic bomb. In March, Germany occupied the Czech uranium mines and halted exports.

Albert Einstein, Rudolph Peierls (pronounced piles), Otto Frisch, Emilio Segré, Franz Simon, Enrico Fermi, Lise Meitner, Leo Szilard, Ernest Wigner, Neils Bohr, and Klaus Fuchs were all refugee scientists fleeing totalitarian rule. Some were Jewish or married to Jews; some had relatives in occupied countries or in concentration camps. Despite their natural aversion to the consequences, they were motivated to build an atomic bomb by the fear that if Hitler got such a weapon, the war would be over in a few weeks and the evil of Nazism would rule the world.

Once Frisch and Meitner published their paper in *Nature*, everyone wanted to replicate Hahn and Strassman's work. Perhaps in Leningrad, I. V. Kurchatov did a little dance when he read the *Nature* article and his team started their own experiments.

Einstein's Letter and the Uranium Committee (August, 1939)

In the July, Long Island heat, two men walked down the main street of Patchogue, looking for the home of a Dr. Moore[1], but no one could help them. Back in their car they sat panting and soaked with sweat. "Perhaps I misunderstood the name of the town," the driver said and he began searching the map for a town with a similar name. "Could it be Cutchogue?" "Yes, now I remember, that was it." The driver started the engine and off they went to Cutchogue. Still ignorant of the address, they asked a boy with a fishing pole walking down a dirt road, "Do you know where Dr. Einstein lives?" "He lives two streets over in the house with the green door" the boy replied. It seemed that everyone on Long Island knew where the famous man could be found, except those who were looking for him. The two Hungarian physicists, Eugene Wigner and Leo Szilard, were meeting Einstein for a specific purpose.

It seemed more and more likely that a bomb could be built with the extraordinary power calculated by Meitner and Frisch, and in 1939, the Germans seemed likely to build it first with catastrophic consequences. After all, they had brilliant minds, including the scientists who discovered fission, vast reserves of uranium, and great motivation. If they were the first to develop the atomic bomb, they could, without doubt, rule the world. Wigner and Szilard were in Cutchogue to enlist Einstein's help in sending a letter to convince President Roosevelt that the United States needed to develop a nuclear bomb before Germany.

Einstein signed the letter in early August, but Roosevelt did not read it until October when he immediately grasped the idea that the Nazi's might "blow us up" and acted quickly. The United States Uranium Advisory Committee first met on October 21, 1939; its urgency heightened by the war now raging in Europe.

[1] Einstein was staying at Dr. Moore's cabin in Peconic, next door to Cutchogue, Long Island.

Frisch-Peierls, and Critical Mass[2] (March, 1940)

In late 1939, Otto Frisch, now working at the University of Birmingham with Mark Oliphant, did not believe a bomb possible. The isotope U^{235}, in which slow-neutron fission occurs, makes up such a small proportion of natural uranium that the exponentially-growing chain reaction necessary for an explosion is impossible, but Frisch wondered, what if fast neutrons encountered U^{235}? He expected they too would cause fission[3], but the much more abundant isotope, U^{238}, absorbs most fast neutrons. If there were no U^{238}, Frisch reasoned, all the neutrons could cause fission in the then concentrated U^{235}.

In June, his colleague, Rudolf Peierls, had calculated the critical mass of natural uranium and the result was several tons; when he redid the calculations at Frisch's request using pure U^{235}, it was about a kilogram[4]. This put an atomic bomb deliverable by an airplane within the realm of possibility, but any method of obtaining pure U^{235} would be a huge project. In March, 1940 they reported the results of their cogitations and calculations to Oliphant in a secret document known as the Frisch-Peierls Memorandum, which galvanized both Britain and the United States and set them on the path that led to Hiroshima.

The Frisch-Peierls Memorandum is an amazing document, which reads, in some parts, like science fiction. First is the description of the creation of an explosive chain reaction using pure U^{235}:

> *"…a moderate amount of U^{235} would indeed constitute an extremely efficient explosive."*
>
> *"…almost every collision produces fission…"*
>
> *"…one might think about 1 kg as a suitable size for a bomb."*

It goes on to discuss the nuts and bolts of building a weapon:

> *"…two hemispheres, which are pulled together by springs…"*
>
> *"It is necessary that such a sphere should be made in two (or more) parts which are brought together first when the explosion is wanted."*
>
> *"…the assembling of the parts should be done as rapidly as possible…"*

and a method of separating U^{235}:

> *"Effective methods for the separation of isotopes have been developed recently…to permit separation on a fairly large scale[5]."*

and a detailed description of the destructive power of the device, both from the explosion:

> *"As a weapon, the super-bomb would be practically irresistible. There is no material or structure that could be expected to resist the force of the explosion."*
>
> *"Effective protection is hardly possible…Deep cellars or tunnels may be comparatively safe from the effects of radiation, provided air can be supplied from an uncontaminated area…"*

"temperatures on the order of 10 billion degrees and pressure of about 10 trillion atmospheres are produced."

and from the accompanying radiation:

"…radiations would be fatal to living beings even a long time after the explosion."

"This cloud of radioactive material will kill everybody within a strip…several miles long."

"… bomb could probably not be used without killing large numbers of civilians…"

The memo concludes with the only option to defend against an atomic bomb:

"The most effective reply would be a counter-threat with a similar bomb."

Mark Oliphant passed the document on to Henry Tizard, chairman of the Committee for the Scientific Survey of Air Warfare, and it became the foundation of the MAUD[6] committee, which conducted experiments to explore the memo's conclusions. The MAUD Committee Report, presented to Churchill in July, 1941, led to the establishment of the Tube Alloys project to build a British atomic bomb, but from the start most people realized that the UK did not have the money or the security[7] to complete the project.

At the same time Churchill received the MAUD report, the U. S. Uranium Advisory Committee was informed of its findings. Oliphant traveled to America in the summer of 1941, and pushed for the U. S. to build a bomb before Hitler did, but he was distressed when he learned that the committee chairman, Lyman Briggs, had not shared the report's contents with the committee. There would not be a fire lit for the bomb in America until December.

[2] Critical mass is the minimum amount of uranium needed to produce one effective neutron for each atom split. This will sustain a chain reaction at constant power and heat. It depends on such things as the shape, concentration, purity and density of the mass, and neutron reflectors that surround it.
[3] U^{235} will split when impacted by a neutron with a wide range of energies, and is said to be fissile, while U^{238} is fissionable because only neutrons with a narrow, range of high energies will cause fission.
[4] Peierls had recently hired another German émigré physicist, Klaus Fuchs, to assist with the calculations.
[5] The report refers to thermal diffusion, a method developed in Germany that never became sufficient to create the quantity of U^{235} needed for a bomb.
[6] When Otto Frisch received a telegram from Neils Bohr, who was trapped in Nazi-occupied Denmark, it said to give his regards to Cockcroft and Maud Ray Kent. Assuming "Maud" cryptically referred to

some atomic phenomenon, they named the committee MAUD. After the war Bohr revealed that Maud Ray Kent was his children's governess and he was just sending greetings.
[7] Birmingham University had been bombed starting as early as October, 1940.

New Elements and a New Bomb (1941)

Transuranic elements[8] were the holy grail of 1930s nuclear physics. Fermi announced he had created ausonium and hesperium in 1934. Both Irene Joliot-Curie[9] and Otto Hahn thought they had found elements past uranium as well, but all three labs had unknowingly split the uranium atom. The first identified and isolated transuranic elements would be products of Lawrence's Berkeley cyclotrons.

Shortly after Louis Alvarez ran into the Radiation Lab in Berkeley, his hair in shambles, the lab started to replicate Hahn and Strassman's experiment using the sixty-inch cyclotron to produce high energy neutrons. Among the products produced were the elements barium and krypton, now expected from the fission process. They also found substances with curious half-lives, one of only twenty-three minutes and one of 2.3 days. At first, the three scientists working on the project, Edwin McMillan, Philip Abelson and Emilio Segré, thought these two substances were the same old radioactive products of fission and published a paper announcing their unsuccessful search for transuranic elements when in fact they had produced elements 93 and 94.

Rather than from the fission of U^{235}, the new elements resulted from the capture of a neutron by U^{238} resulting in the isotope, U^{239}, half of which decayed in 23 minutes to element number 93. After two days, half of this also decayed into element 94. McMillan and Abelson determined the chemical properties of one of these two new elements and named it Neptunium after Neptune, which is the next planet in the solar system after Uranus, namesake of uranium.

In 1940, after McMillan moved to MIT to work on radar, Glenn Seaborg took over his research at Berkeley and started exploring the other new element, number 94, which he named plutonium after the planet Pluto. He liked the sound of the name Ploooo-tonium rather than the non-euphonic, plutium; the symbol Pu was a boyish joke related to stinkniess; he was amused that Pu had been included in the periodic table.

By 1941, Seaborg was able to isolate plutonium and described its chemistry to such an extent that it could be readily separated from the other fission products. With the help of Segré, the team determined plutonium could indeed be used to create a chain reaction and was, in fact, almost twice as prone to fission as uranium.

Now there were two pathways to the bomb. One fueled by U^{235} and one by plutonium. $Uranium^{235}$ could potentially be separated from natural uranium, and plutonium could be created in a nuclear reactor, but in 1941, neither of these methods existed.

[8] Before 1940, the periodic table stopped at uranium, element number 92. Today there are at least twenty-five elements past uranium.
[9] Irene was the daughter Marie and Pierre Curie. She married Jean Frédéric Joliot and they both changed their last names to Joliot-Curie.

Fermi's Pile: Self-sustaining Chain Reaction (December, 1942)

Enrico Fermi learned of the splitting of the uranium atom in early January, 1939. He had just been honored with a Nobel Prize[10] for discovering the first transuranic elements, but he had actually observed the products of fission and not elements beyond uranium. Perhaps he was embarrassed, but his chagrin did not last and he immediately started replicating Hahn and Strassman's experiment in his lab at Columbia University. Before the end of the month, Fermi had split the first atom in America and was intent on investigating the details of fission. At the time, no one knew how many neutrons would be produced in a nuclear fission and thus, the probability of a chain reaction was still unknown.

Leo Szilard and Enrico Fermi, the two scientists best situated to make progress on a nuclear chain reaction, were staying at the same hotel near Columbia when they met by chance for the first time. In March, 1939, Fermi had dismissed the idea of free neutrons, but by April, three laboratories, Fermi's at Columbia, Frédéric Joliot-Curie's in Paris, and Igor Kurchatov's in Leningrad, had all determined that each atomic fission event released two, three or four neutrons. Each neutron could split another uranium nucleus, thus creating a self-sustaining, exponentially-growing, chain reaction resulting in a spontaneous eruption of energy. Realizing that a chain reaction was possible, Fermi and Szilard began their efforts to create one.

Four years earlier, Fermi had found that slow neutrons were more effective at causing fission. He therefore needed a way to moderate the speed of the free neutrons. Water absorbed rather than slowed neutrons and heavy water[11], a very good moderator, was expensive and hard to get, so they decided to try graphite. He and Szilard designed a reactor and, with the help of the newly-formed U. S. Uranium Committee, bought a quantity of "pure" graphite blocks, which they stacked in a pile interlaced with uranium slugs, but the test was a failure. The graphite contained boron, which absorbed neutrons. They tried several different designs and sizes over the next two years, but none created a chain reaction; the number of free neutrons was too low[12]. By August, 1941, they were using six tons of uranium and thirty tons of now boron-free graphite, still without success. They were not certain that they could make their experiment work.

In December, 1941, just after the attack on Pearl Harbor, the Uranium Committee decided that they needed the newly-discovered plutonium. Because its production required a nuclear chain reaction, they gave Fermi's group high priority. The operation moved to the University of Chicago and was named, the Metallurgical Lab or Met Lab. There was now a Rad Lab at Berkeley and a Met Lab in Chicago.

The University of Chicago football stadium, which resembled a cross between a Crusader castle and a National Guard armory, was named after Amos Alonzo Stagg, the coach of the Chicago Maroons football team for forty years, and the inventor of the lateral pass[13]. In 1942 Fermi and Wigner, who had replaced Szilard, took over the squash court underneath the abandoned bleachers, but neglected to informed the president of the university that they were assembling a nuclear reactor on campus. They piled up 255 tons of graphite, and fifty tons of uranium around a wooden support structure. Fermi, stripped to the waist, was black and glistening; it was said he could have played Othello.

At the time, Fermi was reading Winnie the Pooh to improve his English and named the various geiger counters monitoring the reaction for characters in the Pooh stories: Tigger, Piglet, Kanga, and Roo. A Fermi protégé and the only woman on the project, Leona Woods[14], took careful measurements from the storied instruments as the pile grew.

Their nuclear reactor, called CP-1 for Chicago Pile #1, was a "…crude pile of black bricks and wooden timbers" shaped like a giant door knob ten feet high. On December 2, 1942, as cadmium control rods were carefully pulled from the graphite pile, the first self-sustaining nuclear chain reaction began producing very tiny amounts of plutonium. The message, "The Italian navigator has landed in the new world and the natives are friendly" was sent to Washington and in Chicago, Wigner produced a bottle of chianti. Later that day they continued their experiments.

There had always been a fear that a chain reaction could not be controlled and the pile would melt, catch fire, and blow up, spreading radioactivity over the campus. Emergency neutron-absorbing cadmium rods could be quickly lowered to stop the reaction[15] and a three-man "suicide squad" could throw buckets of cadmium nitride on the run-away reactor, but the rods and buckets were never used.

While Fermi and Szilard were experimenting with various piles at Columbia and solving the problem of contaminated graphite, the German army invaded Russia. The leading Russian nuclear physicist, Igor Kurchatov, had forgotten about nuclear chain reactions and was working on the protection of ships from magnetic mines; he had left his unfinished cyclotron in Leningrad.

Two distinct pathways to a nuclear weapon now existed: that laid out by Fisch and Peierls using pure U^{235} and that of Seaborg using plutonium. The problem of supplying plutonium was well on the way to being solved by CP-1, but an efficient method of separating U^{235} was yet to be developed.

[10] In 1938, Fermi and his family traveled to Stockholm to receive the prize and from there emigrated to America. Italy had just passed anti-Jewish laws which put his wife's life in danger.
[11] Heavy water consists of two atoms of deuterium (H^2) and one of oxygen. D_2O ($H^2{}_2O$) has different radioactive and chemical properties that are useful as a neutron moderator and a fuel for hydrogen bombs.
[12] Neutrons are lost from the surface of the uranium, are absorbed by various elements, such as U^{238} or impure graphite, or are otherwise prevented from causing additional fissions.
[13] Amos Alonzo Stagg stadium was demolished in 1957, but a statue, Nuclear Energy, by Henry Moore stands at the exact location of CP-1, in a square near the University of Chicago Library.
[14] On youtube there is an animated Lego video showing the building of Fermi's reactor, named CP-1, and the moment it went critical. The Lego figures of Enrico Fermi and Leona Woods, are scarily accurate. (https://www.youtube.com/watch?v=mTPiTJ2bKS0)
[15] The rods were suspended by ropes from the ceiling and one of the scientists stood at the ready with an ax.

The Separation of Isotopes

Unlike elements, isotopes cannot be separated by chemical means, but rather must be sorted by their mass, a much more complicated task. Due to its rarity, most physicists believed separation of the U^{235} isotope from its much more common U^{238} cousin would be so difficult that a bomb could not be made. Neils Bohr thought that it would "…take the entire efforts of a country…" to make a bomb and, in the end, he was nearly correct.

Frisch and Peierls' 1940 memorandum had been based on an optimistic estimate of isotope separation using thermal diffusion. In the end, this process was not efficient enough, but other processes were.

At Oxford, Franz Simon, another German Jewish refugee, was working on a method whereby different isotopes moved through a porous barrier at different rates. The heart of the process was a nickel membrane with one-hundred-million holes per square inch which used highly corrosive uranium hexafluoride (UF_6) and required pumps and pipes built of special materials, but in the end, UF_6 cascading through a sequence of thousands of diffusers, produced U^{235} on an industrial scale.

Another method of isotope separation was based on the fact that a beam of charged particles entering a magnetic field will be sorted by their weight. The device to do this is called a mass spectrometer and was first devised by J. J. Thomson at the turn of the century. In 1941 Lawrence created a device, called a calutron (Cal University cyclotron) that could produce one microgram of enriched U^{235} in one hour.

By 1942, processes to manufacture large amounts of both U^{235} and plutonium were on the drawing boards. The challenge now was to build the massive plants and make the bomb.