

The Fission Vision

The new era really began in 1933, when Leo Szilard had the inspired idea that a chain reaction could be initiated by the bombardment of an element with neutrons.

—Michael White and John Gribbin, *Einstein: A Life in Science*

[In London] while living on his savings, Szilard had no other scientific or academic burdens and deadlines. No family. No close friends. No household chores. When he wanted to think about the chain reaction, he could. And did. For days and nights at a time.

—William Lanouette with Bela Silard, *Genius in the Shadows: A Biography of Leo Szilard, the Man Behind the Bomb*

It is September 12, 1933, and London's morning paper, the *Times*, carries an article about a speech by Britain's celebrity scientist, Ernest Rutherford. The great physicist (now *Lord Rutherford*) describes "the discoveries of the last quarter century." He talks of "bombarding atoms" and about the "transformation of elements." This is news to most readers of the *Times*; elements are supposed to be unchangeable. When it comes to the atom as a source of power (as imagined in H. G. Wells's popular science-fiction novel *The World Set Free*), Rutherford dismisses the idea, saying, "The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine."

Leo Szilard (SIL-ard), newly arrived in England, reads the morning news. A 35-year-old Hungarian who served in the Austro-Hungarian army during

Leo Szilard, shown here near Oxford, England, in 1936, had broad abilities. He submitted 29 applications to the German patent office, many in partnership with Einstein.





Hungary's capital, Budapest, is a combination of the hilly Obuda ("Old Buda") and Buda on the west bank of the Danube River and the flat, modern city of Pest on the east bank. The cities were unified in 1873, about the time this panorama was painted.

the Great War (that's World War I), Szilard was saved from sure death when the flu kept him from a battle in which his fellow soldiers all perished.

After the war, in 1919, Szilard left his native Budapest to study at the University of Berlin. There, he intended to pursue engineering, but Max Planck, Max von Laue, and Albert Einstein were among the physics professors. Szilard was smart enough to change his major to physics.

When the university didn't offer a course he wanted to take, Szilard persuaded Einstein to teach it in a seminar. When Max von Laue gave him a problem to pursue, young Szilard decided it wouldn't lead anywhere. So, after just a year of university physics, he discovered an "unsolvable" physics problem and solved it in an original paper. Then he was afraid to show it to von Laue (after all, he was supposed to do what his teacher had told him to do). Instead, he showed Einstein what he had found.

"That's impossible," said Einstein. "That cannot be done."

"Well, yes, but I did it," said Szilard, who explained his ideas to Einstein, and "[Einstein] liked this very much."

The next day, Szilard had the courage to take his paper to von Laue, who accepted it as a Ph.D. thesis. Not long after that, Szilard joined the faculty at the University of Berlin.

Szilard has a mind that dazzles. When he isn't experimenting or theorizing in physics, he invents things.

The "unsolvable" problem was posed by James Clerk Maxwell. It involved an imaginary demon that seems to defy the second law of thermodynamics. Curious? Read chapters 37 and 38 of *Newton at the Center*, book two in this series.

Besides that, he keeps trying to save humanity (mostly by being involved with do-good organizations). Szilard cares deeply about moral issues. Many of Europe's Jewish physicists believe that the Nazis are a momentary madness. They assume they can wait out Hitler. Szilard thinks otherwise. He stuffs all his savings into his shoes and leaves Germany. So that's why he is in London in 1933. He is living on those savings, hoping to find productive work. Years later, the French biologist Jacques Monod will describe Szilard as a "short fat man . . . his eyes shining with intelligence and wit . . . generous with his ideas." But in 1933 he is still slim and boyish with thick, curly dark hair and a soulful, Bohemian air.

By nature, Szilard is a contrarian. He loves to take the opposite view of whatever he hears. And, that morning in 1933 when he reads the *Times*, Szilard finds Rutherford's thoughts on nuclear energy "rather irritating because how can anyone know what someone else might invent?" Rutherford must be wrong, he says to himself. But why? Szilard's mind focuses on atoms and nuclei and their potential power; he thinks of little else.

Hitler youth parade in Germany in the 1930s. To many boys, the drills, uniforms, and hype made military life seem heroic and war patriotic. Hardly anyone considered the morality or purpose of it all.



Many...people took a very optimistic view of the situation. They all thought that civilized Germans would not stand for anything really rough happening. The reason that I took the opposite position was... [because] I noticed that Germans always took a utilitarian point of view. They asked, "Well, suppose I would oppose this thinking, what good would I do?...I would just lose my influence."...You see, the moral point of view was completely absent, or very weak....And on that basis I reached in 1931 the conclusion that Hitler would get into power, not because the forces of the Nazi revolution were so strong, but rather because I thought that there would be no resistance whatsoever.

—Leo Szilard, quoted in *Leo Szilard: His Version of the Facts*



The original “Eureka!” moment struck Greek philosopher/mathematician/engineer Archimedes while he was taking a bath, as depicted here in a sixteenth-century woodcut. Read about it in chapter 17 of book one, *Aristotle Leads the Way*.

“In the days that followed, [Szilard] pondered Rutherford’s declaration in a routine favored for serious thought: long soaks in the bathtub and long walks in the park,” says his biographer William Lanouette. “Szilard walked and wondered that chilly September, seeking with each quick step a way to disprove the ‘expert’ Rutherford.”

Standing on a London street corner, Szilard has a “Eureka!” moment. Here are his words describing it:

As the light changed to green and I crossed the street, it suddenly occurred to me that if we could find an element which is split by neutrons and which would emit two neutrons when it absorbs one neutron, such an element, if assembled in sufficiently large mass, could sustain a nuclear chain reaction.

(Read that paragraph a few times to be sure you have it.)

Szilard has imagined the two steps needed to free the energy in an atom’s nucleus: one, a nuclear chain reaction, and two, a critical mass of the right element to set off and sustain it. Does he envision the process we now call “fission,” the splitting of nuclei? Yes, he seems to, but Szilard’s ideas are not yet clearly expressed. And he doesn’t know which

When it comes to chain reactions, getting the mass just right is critical. Some neutrons leak from the surface of whatever you’re testing. Those leaked neutrons are out of the game; they can’t cause further fission events. So, if you start with a small chunk of an element, you may not have enough neutrons to maintain fission. A big chunk will go off prematurely. A just-right amount is called a “critical mass.”

element will provide nuclei that can be easily split.

He does realize that neutrons are a key to the process. Szilard writes, “It occurred to me that neutrons, in contrast to alpha particles, do not ionize [electrically charge] the substance through which they pass.”

Neutrons, being neutral, are not repelled by the positive electric charge of protons, so they can move into the nucleus freely. Szilard pictures what might happen if one neutron enters a nucleus: That added neutron should create an isotope that is unstable, which means it would split spontaneously. If it did, then there might be two neutrons, which could split the nuclei of two other atoms, and so on—creating a chain reaction. The trick in making this happen is finding an element that splits into two or more fragments plus two neutrons when one neutron invades its nucleus.

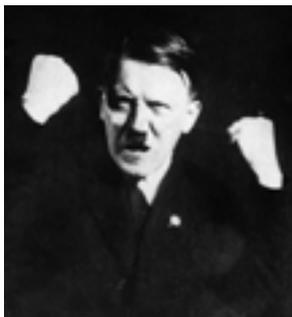
Of course, this is all speculative. No one has tested his idea. And no one knows which element (if any) would work. Szilard has considered leaving physics to become a biologist, but now chain reactions become an obsession. On March 12, 1934 (five months after Rutherford’s speech), he files a 15-page patent application on neutrons and transmutation (the changing of one element into another). Later, he amends it, adding a description of a nuclear chain reaction. Then, because he is aware that what he has described could lead to a bomb, Szilard assigns the patent to the British Admiralty where he knows it will stay secret.

Now he is torn. He wants to tell his physicist friends so they can do experiments that will lead to fission, the splitting of nuclei. (No one but Szilard seems to think it can be done.) He also wants to be sure his ideas stay secret from most German scientists. He knows they would be capable of producing a bomb.

So he tries to get others to understand what he is after, but he doesn’t quite tell them enough to have them realize what he’s talking about. He writes to Sir Hugo Hirst, the founder of General Electric in the United Kingdom, and mentions the H. G. Wells book. “I have reason to believe that in so far as the industrial applications of the present

Don’t confuse these words: During **FISSION**, the nucleus of a heavy atom splits into two or more parts, releasing energy and two or three neutrons. Nuclear bombs are fission bombs.

During **FUSION**, light nuclei combine to make a heavier nucleus, releasing energy. The energy from fusion makes the Sun shine and provides the power in a hydrogen bomb.



To those who believed in a greater Germany, Hitler had charisma. This photograph was taken in 1932.

discoveries in physics are concerned, the forecast of the writers may prove to be more accurate than the forecast of the scientists.” In other words, novelist Wells may have it right when he says the atom can produce cheap, usable power. What must Sir Hugo think? After all, Lord Rutherford doesn’t imagine it possible. Szilard, with his Hungarian accent and vaguely stated ideas, must seem like a mad scientist rather than a visionary physicist.

When he attempts to interest other physicists, Szilard doesn’t get anywhere, either. He contacts Austrian physicist Lise Meitner in Berlin, hoping she will do experiments to pin down the right element: an element with a nucleus that can be split, leading to a chain reaction. Szilard even goes to the Cavendish Lab and asks Lord Rutherford to give him lab space so he can do his own experiments. But when he talks to Rutherford, Szilard doesn’t explain himself well. Perhaps he is intimidated—he doesn’t have his usual self-confidence. “I was thrown out of Rutherford’s office,” he later tells his friend Edward Teller (another Hungarian physicist).

For the next four years, Szilard searches for an element that will foster a chain reaction; he does experiments at the universities of Oxford, Rochester, and Illinois. (A letter of recommendation from Einstein gets Szilard a Rockefeller Fellowship bringing him to the United States in 1938, but he doesn’t explain the chain reaction idea to Einstein.)

Szilard experiments with beryllium. That element doesn’t work. Neutrons do not split the nuclei of its atoms. Then he tries indium. No luck there, either. Uranium and thorium are the elements he is searching for, but he doesn’t know that, although he does mention both of them in his amended patent application.

Meanwhile, a few physicists are walking a new path. They are focusing on the nucleus as a way to create elements. The physicists are: Ernest Rutherford in England, Irène and Frédéric Joliot-Curie in France, Lise Meitner and Otto Hahn in Germany, and Enrico Fermi in Italy. They are racing against one another.



When physicist Lise Meitner arrived in Berlin in 1907, women weren’t even allowed in scientific laboratories.

Frédéric and Irène Joliot-Curie (below) shared a passion for artificial radioactivity. In their breakthrough experiment, the nucleus of an aluminum atom (13 protons, 14 neutrons) absorbed an alpha particle (two protons, two neutrons). One neutron was expelled (and a positron was emitted), leaving a nucleus of 15 protons and 15 neutrons. That’s a radioactive isotope of atomic number 15: phosphorus (P).



Fermi and Szilard: Neat Must Work with Messy

Fourteen-year-old Enrico Fermi was browsing near a statue of Giordano Bruno (the philosopher who was burned at the stake in 1600 for his scientific beliefs). It was market day in Rome, and outdoor stalls were filled with paintings, books, food, clothing—a mishmash of things. Enrico was grieving. His older brother had just died, and they had been inseparable. The boy needed something to think about other than his brother. So when he found two old books on physics (written in Latin), he bought them. Then he read them straight through. From then on, there was no question about it: He would be a physicist.

A few years later, when Fermi applied for a fellowship at the University of Pisa, the examiner who read his competitive essay was astounded. He said the work would do credit to a doctoral



In this courtyard at the University of Pisa, politics and scientific ideas have been and are actively debated.

candidate. Enrico was 17. Two years after that, he was teaching his professors. In a century filled with outstanding physicists, Enrico Fermi was among the greatest. He became a leading force among the physicists who built the first nuclear bomb. Here are a few comments from his peers:

J. Robert Oppenheimer said that Fermi had “a passion for clarity. He was simply unable to let things be foggy. Since they always are, this kept him pretty active.”



Student Emilio Segrè (left) met Professor Enrico Fermi (right), just four years older, and quickly switched from engineering to physics. In 1927, the newly acquainted young men spent this day at the beach with a friend.

“My greatest impression of Fermi’s method in theoretical physics was its . . . simplicity. . . . He stripped it of mathematical complications and of unnecessary formalism. In this way, often in half an hour or less, he could solve the essential physical problem involved,” said Hans Bethe.

“His teaching was exemplary, minutely prepared, clear, with emphasis on simplicity and understanding of the basic ideas, rather than generalities and complications. . . . We would knock at his office door, and if free, he would take us in, and then he would be ours until the question was resolved,” said Jack Steinberger.

“Fermi was a rigorous academic whose life centered on a brilliant physics career; he had little interest in politics. . . . A homebody, . . . he awoke at 5:30 each morning and spent the two hours before breakfast polishing his theories and planning the day’s experiments,” writes William Lanouette in *Scientific American*.

As for Szilard, Lanouette says, “The bachelor Szilard rarely taught, published infrequently and dabbled in economics and biology. . . . A late sleeper, he often appeared at Columbia only in time for lunch, after which he would drop in on colleagues, posing insightful questions and suggesting experiments *they* should try.” This “odd couple” had to work together to build a bomb. It wasn’t easy for either of them.

Like the ancient alchemists, each is trying to transmute (change) elements in the laboratory. By inserting extra particles into the nucleus, they hope to get new elements. The winner of the race will gain international acclaim and probably a Nobel Prize.

In Paris, in 1933, Irène and Frédéric Joliot-Curie shoot alpha particles at aluminum and produce a radioactive isotope in their laboratory. It's a big achievement. Marie and Pierre Curie won the 1903 Nobel Prize in physics for their work in natural radioactivity; their daughter and son-in-law receive the 1935 prize in chemistry for artificially creating radioactive elements.

At about the same time, the talented Enrico Fermi, a professor at the University of Rome, begins a series of experiments by propelling electrons at nuclei. Nothing much happens. Then he tries sending protons; they are repelled by the positive electric charge of the protons in the nucleus. After James Chadwick discovers neutrons, Fermi starts tossing neutrons at nuclei—and something does happen.

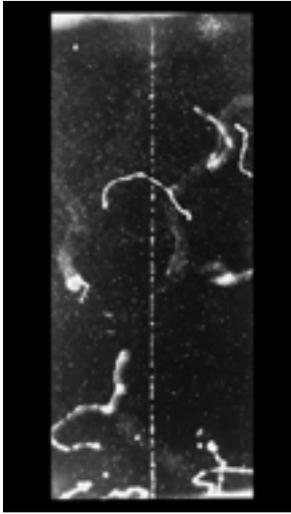
Since the neutron has no charge, it is *not* repelled by nuclei (just as Szilard hypothesized). Neutrons don't need to overcome an electrical barrier, as protons do. The strong force attracts and welcomes them. Rutherford thinks the neutron is too lethargic—slow-moving—to start any action. Lise Meitner has already discovered that neutrons are more likely to be absorbed by a nucleus when they move slowly.

Fermi discovers the same thing accidentally when he does his experiments on a wooden table—and gets better results than on a marble table. He figures out that the nuclei of elements in wood (especially hydrogen) must slow the neutrons by colliding with them. He guesses that paraffin (wax) nuclei will do the same thing, so he puts paraffin filters between the neutron beam and the target. After Fermi describes his encouraging results, Lise Meitner writes to him (on October 26, 1934): “Enclosed is a small notice currently

Enrico Fermi's goal in 1934 was to produce new, heavier elements by adding neutrons. The process that he didn't understand then, and wasn't looking for, is nuclear fission. Elements 93 and 94 were discovered in 1940 by Emilio Segrè, Edwin McMillan, and Philip Abelson. Lise Meitner predicted these new elements, but she didn't have a laboratory to do the experimenting.

Being electrically neutral, [the neutron] encounters no electrostatic barrier to penetrating the nucleus. Indeed, slow neutrons often find their way into nuclei more efficiently than fast ones, much as a slow cricket ball is easier to catch.

—Philip Ball, *The Ingredients: A Guided Tour of the Elements*



In a 1923 experiment, high-speed beta particles (electrons) left faint, intermittent tracks in a cloud chamber. Slower electrons made the thicker squiggles. Electrons can be knocked out of atoms by X rays or gamma rays or emitted during radioactive beta decay.

The elements above number 92 (uranium) are called *transuranic* (“beyond uranium”) elements. They are all radioactive and synthesized (created in laboratories) except for trace amounts of natural neptunium (number 93) found in uranium ore.

in press . . . from which you can see that by quite different means I have arrived at similar conclusions . . . to yours.”

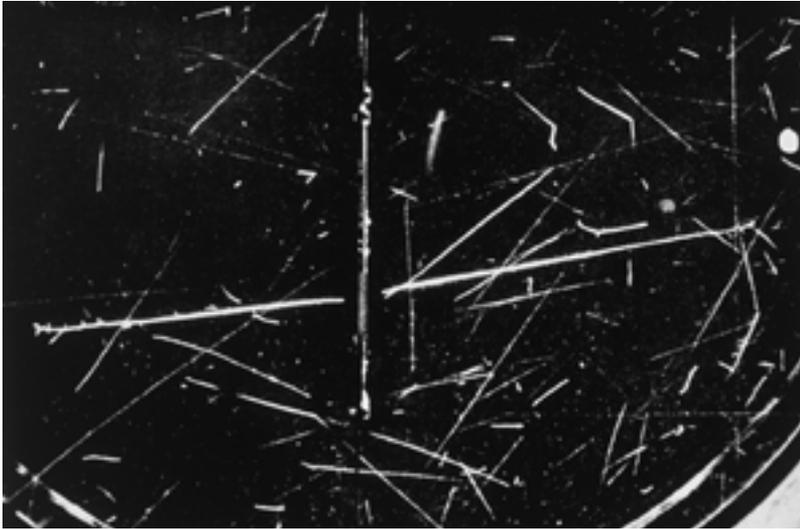
Fermi begins whamming all the elements he can put his hands on (except hydrogen and helium). His colleague Emilio Segrè says, “[We] discovered about forty new radioactive substances.” They are in unexplored territory, using neutrons to bring on radioactivity. When a nucleus is bombarded, beta particles (electrons) are sometimes emitted. This is weird. There are no electrons in the nucleus. How could this happen? It seems that electrons (and neutrinos) are created as a neutron converts to a proton during radioactive decay. Fermi has found an interaction that explains radioactivity. Called the “weak force,” it is one of nature’s four forces. The weak force (which is a whole lot stronger than gravitation) only operates inside the nucleus. (See page 378 for more on the four forces, or interactions.)

When Fermi decides to bombard nuclei of the metal uranium with neutrons, it is a fateful decision. He is hoping to create a still heavier element, *beyond* uranium, a “transuranic” element. He sends neutrons (slowed just a bit) off toward uranium atoms. Some are absorbed.

Has Fermi done what he set out to do: produce a new element in his laboratory? “We thought that we had produced transuranic elements,” Segrè will write later. “In this we were in error, at least in part; while it was true that transuranic elements were formed . . . what we had observed was something quite different.”

I. I. Rabi, a physicist who grew up in New York City, later describes the process: “When a neutron enters a nucleus, the effects are about as catastrophic as if the moon struck the earth. The nucleus is violently shaken up by the blow, especially if the collision results in the capture of the neutron. A large increase in energy occurs and must be dissipated, and this may happen in a variety of ways, all of them interesting.” But Rabi is writing later, in 1970, when what happens is understood.

In 1934, Fermi doesn’t know it, but **he has split the**



In this cloud chamber, a uranium nucleus split into two fragments, which shot off to the right and left. A single neutron caused the fission. Having no charge, it didn't leave any glowing "bread crumbs," but its presence is evidenced by the protons (short lines, every which way) that it disturbed.

uranium nucleus! He is playing with uranium fission. Since he isn't looking for fission, he doesn't discover the small "daughter" nuclei that recoil with high energy when he experiments. His detector has a window of aluminum foil that stops any secondary nuclei produced by fission. Fermi isn't aware that Szilard has been searching for an element that will sustain a chain reaction. Uranium is that element. So far, no one is making the right connections. (Actually, Ida Noddack, a German chemist, makes a good guess, but no one pays attention to the paper she writes. And Lise Meitner is making interesting conjectures, but she doesn't put the clues together.)

Still, what Fermi does is big news in the tight scientific world involved in nuclear research. (In 1938, Fermi will win a Nobel Prize in physics for his work on nuclear reactions produced by slow neutrons.)

The seeds of atomic power are now blowing in the scientific wind. In his 1935 Nobel acceptance speech, Frédéric Joliot-Curie calls for a next step in nuclear research. He talks about splitting the nucleus and says it could lead to explosive nuclear chain reactions and also to "the enormous liberation of usable energy." No one realizes that Fermi has already split a nucleus.

As for "usable energy" from the nucleus? Except for Leo

If it weren't for a piece of aluminum foil, Enrico Fermi might have discovered fission in 1934 and Germany (Italy's Axis ally) might have developed nuclear weapons in time to use them during the Second World War (and there might have been many, many more deaths).

Szilard, most scientists still agree with Ernest Rutherford that the idea is “moonshine.” Rutherford, *who discovered the nucleus*, dies in 1937 not knowing that a nuclear age is imminent.

The big experiment is coming: Lise Meitner, aware of Fermi’s work, suggests that her friends and collaborators,

A Prize-winner

When Lise Meitner was a schoolgirl in Vienna, women were not admitted to universities in Austria or almost anywhere else. It was said that women would become mentally ill, or sterile, if they tried to use their brains. In 1897 (in part because of pressure from women’s rights groups), rules began to change. Austrian universities opened their doors (just a crack) to women.

To get into a university, there were tough tests to pass in Greek, Latin, math, literature, history, and more. Most students spent eight years preparing for those university exams. Meitner studied frantically for two years. She was one of four women who passed the exam in 1901.

Meitner’s father insisted that she get a teaching degree, but she wanted to be a scientist, and she had Marie Curie’s example to



The center of Vienna, Meitner’s hometown, is the Graben (ca. late 1800s, above).

inspire her. She picked physics for her major; it was a good choice. Vienna had one of the best physics professors in the world: Ludwig Boltzmann. He became an inspiration to Lise Meitner. Here is how she described him:

His relationship to students was very personal. . . . He not only saw to their knowledge of physics, but tried to understand their character. Formalities meant nothing to him, and he had no reservations about expressing his feelings. The few students who took part in the advanced seminar were invited to his house from time to time. There he would play for us—he was a very good pianist—and tell us all sorts of personal experiences.

Otto Frisch wrote of his aunt, “Boltzmann gave her the vision of physics as a battle for ultimate truth, a vision she never lost.”

From Vienna, Meitner went to the University of Berlin to get a Ph.D. There, she studied with Max Planck. When she met Otto Hahn, they clicked as a team: He was a chemist who liked details; she was a physicist, a strong mathematician, and someone who liked big ideas. It was a collaboration that would last for almost 30 years.

They set up a nuclear physics laboratory at the Chemical Institute at the University of Berlin; it was in the basement because women weren’t allowed upstairs. Meitner began writing important papers. When she met Ernest Rutherford in 1908, he was startled.

Berlin chemists Otto Hahn and Fritz Strassmann, also bombard the nuclei of uranium atoms with neutrons. It is 1938, and, like Fermi, they expect to create heavy, transuranic elements.

So Hahn and Strassmann are puzzled when their experiment produces a radioactive form of a much *lighter* element, barium. An atom of barium (number 56) is not

“Oh, I thought you were a man!” he said.

Otto Hahn moved to the Kaiser Wilhelm Institute for Chemistry, and Meitner followed. In 1917, she was made head of her own laboratory. Two years later, she became the first woman in Germany to be named a professor. As a team, Hahn and Meitner were among the world’s leaders in radioactive research; they discovered a zoo of radioactive particles. On her own, Meitner wrote 56 scientific papers in a 13-year period.



Hahn and Meitner worked together for 30 years before war split them.

When the Nazis came to power, neither Planck nor Hahn took them seriously. They told Meitner she should stay in Germany. They thought they could protect her, but they couldn’t. First she lost her job. Then Hahn was pressured into not talking to her. She had waited too long; German laws now made it a crime for her to leave. Finally, with the help of friends (and an “arrangement” with a border

guard), she walked into Holland. Meitner’s biographer, Ruth Lewin Sime, writes, “Stateless, without a passport, she did not know where she would live or how she could travel. Except for a few summer clothes in two small suitcases, she had no belongings. And she had no money, none at all.” Niels Bohr helped Meitner get a job in Sweden, but she was separated from her life’s work.

Otto Hahn stayed in Germany where he eventually bent to the pressures of the Nazi regime. It was almost impossible to remain in Nazi Germany and not do so. Later, Hahn tried to make German scientists seem heroic in their inability to produce a bomb. He and Heisenberg suggested that they could have done it but didn’t because of moral scruples. No one knows if that is true. The British army captured 10 top German scientists, including Hahn and Heisenberg, after the Nazi defeat. They held them at Farm Hall, an English country manor. British Intelligence bugged the place, so we know of the astonishment of the German scientists when they found out that the Allies had built a bomb.

After the war, Hahn tried to write Meitner out of the fission story, and for a while he was successful. He pretended she had been his assistant, not his equal, and he never mentioned the role she had played in the discovery of fission. Hahn got a Nobel Prize; Meitner did not. But truth usually wins out. Today her role is widely appreciated. The Lise Meitner story is told well in *Lise Meitner: A Life in Physics* by Ruth Lewin Sime.

I remember that my reaction and probably that of many others was that Fermi's was really a silly experiment because neutrons were much fewer than alpha particles. What that simple argument overlooked of course was that they are very much more effective.

—Otto Frisch, as quoted in *The Making of the Atomic Bomb*



If fission fragments fly apart at great speed, why didn't anyone notice them? Because the energy in a single fission is "tremendous" compared to chemical energy but not to, say, the energy of a moving golf ball. It's the very quick, multiplying effect of a chain reaction that makes nuclear fission so powerful.

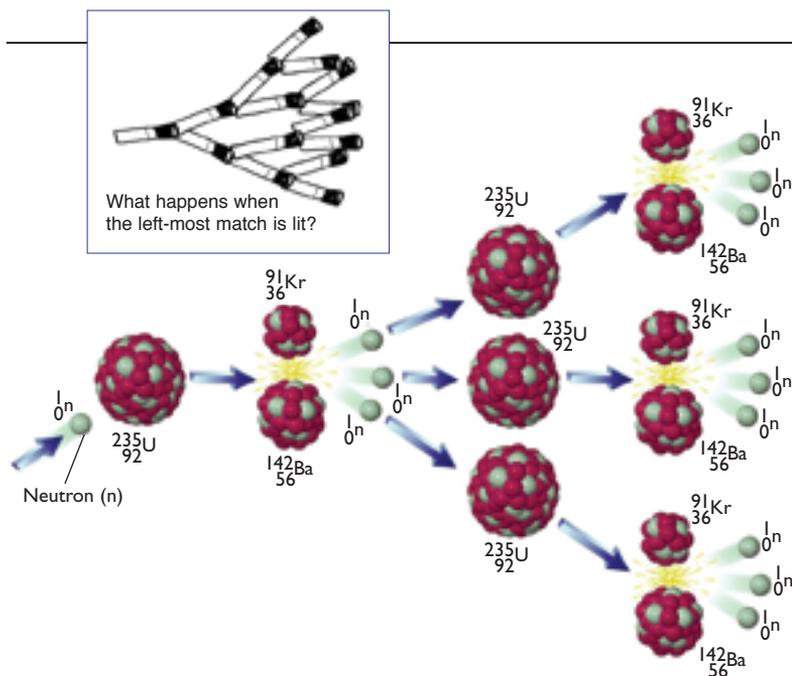
quite half as heavy as an atom of uranium (number 92). What can that mean? Hahn and Strassmann are superb chemists, but they can't interpret their results because they don't know much physics. They expect a heavy element; they get a light one. Lise Meitner is a physicist, but she is Jewish and has fled from Berlin to Stockholm. Hahn sends word of the experiment to her.

When Meitner learns of the results, she, too, is surprised. She needs to think it out. She meets with her nephew, Otto Robert Frisch (another physicist who has been rescued by Niels Bohr), and they take a walk in the Swedish woods. It is winter and cold. Meitner is on foot, and Frisch is on cross-country skis, but she keeps up with him. They talk and think, then sit on a tree stump and talk and think some more. "Gradually the idea takes shape that this was no chipping or cracking of the nucleus but rather a process to be explained by Bohr's idea that the nucleus is like a liquid drop; such a drop might elongate and divide itself," writes Frisch later.

In other words, Meitner and Frisch believe that the added neutron causes the uranium nucleus to stretch and develop a "waist" like a drop of water before it splits in two (left). In that thin waist, the uranium atom must have broken into two fragments. They believe Hahn and Strassmann have split an atom's nucleus (and they realize that Fermi probably did the same thing earlier).

But the combined mass of those two fragments is less than that of the original uranium nucleus. How can this be? Where has the missing mass gone? That is the dilemma.

In those snowy woods, Meitner and Frisch figure out that the missing mass has been converted into energy—just as Einstein said it would be in his famous equation $E = mc^2$. If that is true, the released energy was thousands of times greater than the chemical energy resulting from atomic-molecular reactions. The reason for the huge energy is that the two charged fragments are very close together and repel



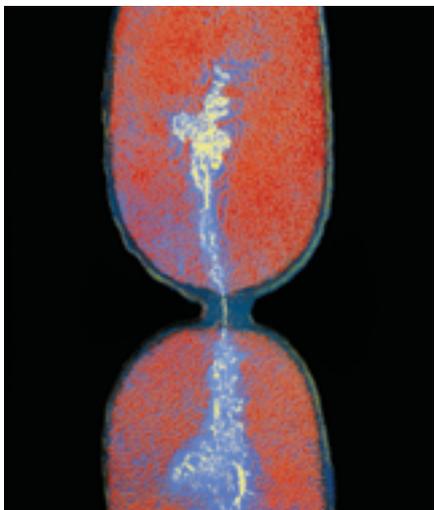
This simple diagram illustrates a chain reaction of uranium-235 fission, starting with a slow-moving neutron hitting one nucleus at the far left. The two fragments are krypton (number 36), a noble gas, and barium (number 56). Their atomic numbers add up to 92 (uranium's atomic number), but their combined atomic masses are less than uranium's. Each fragment releases a slow-moving neutron that strikes two more uranium nuclei, which split and release four neutrons that strike four uranium nuclei, and so on.

each other with tremendous force, flying apart with great speed. Is this a source of energy that is usable? They think so, and they both realize that, multiplied in a chain reaction, it would be very powerful.

Meitner and Frisch go on to hypothesize that when a nucleus splits, energy is not the only thing released. Neutrons may also be set free. For uranium, the average number of emitted neutrons is 2.5. Imagine those free neutrons entering another uranium atom; its bombarded nucleus will also split, releasing at least two neutrons (you now have four), and those four will split other nuclei, releasing more neutrons. That will start a chain reaction, which, if it is not controlled, can quickly expand exponentially.

Chain reactions are routine in chemistry. One thing leads to another. Picture a lightning bolt that sets a tree on fire; the fire spreads to two nearby trees, and then others, and soon a forest is gone (right). But a nuclear chain reaction is much faster and more powerful. Meitner and her nephew (and the savvy physics community) know that the





A salmonella bacterium divides into two daughter cells through a process that biologists first called “fission” in 1841. Physicists adopted the term nuclear fission, the splitting of a nucleus, in 1939.

amount of power let loose would be staggering. (The explosion of a TNT molecule releases 30 electron volts. The release of energy from the fission of one uranium nucleus is about 200,000,000 electron volts.) Is it really possible? Could each nucleus be a tiny bomb, which, when it splits, sends off energy along with neutrons to trigger its neighbors?

Meitner and Frisch need to confirm their theory. They talk with Bohr and outline an experiment they have in mind to verify their hypothesis and also to measure the energy liberated from the uranium atom. The experiment works; they get the results they expect. Lise Meitner, Otto Frisch, Otto Hahn, and Fritz Strassmann have discovered “nuclear fission.” (Frisch chooses the name “fission” after talking to a biologist who says that it is the word for the dividing of living cells.) Like so many things that seem difficult, once fission is understood, it is simple.

“Oh, what idiots we all have been! But this is wonderful!

Half a Haircut

Physicist Luis Alvarez (a future Nobel Prize-winner) was in a barbershop on the campus of the University of California at Berkeley reading the *San Francisco Chronicle* when he saw an article describing Bohr’s announcement. Alvarez leapt out of the barber chair with his hair half cut and ran to the university’s radiation laboratory.

The next day, the fission experiment was verified in California. J. Robert Oppenheimer, who had been skeptical about the possibility of nuclear fission, was quickly converted into a believer. (Take note of that name—

Oppenheimer. He was a professor who had been training young physicists at Berkeley and Caltech.)

Alvarez (right) and Oppenheimer were brought together by nuclear fission.



This is just as it must be!” Niels Bohr says as soon as he hears the news. It’s 1939, and Bohr is about to go to the United States to attend the Fifth Washington Conference on Theoretical Physics. A throng of great physicists will be there, including Szilard and Fermi, who meet for the first time.

At the Washington conference, Bohr makes the big announcement about fission. George Gamow, writing later of “the excitement of that day” in his book *Thirty Years That Shook Physics*, says, “That same night the experiment was repeated [in a Washington laboratory] and it was found that the fission of uranium by impact of one single neutron results in the emission of a few more new neutrons. The possibility of a branching chain reaction and the large-scale liberation of nuclear energy seemed open. With the newspaper reporters politely shown from the conference room, the pros and cons of fission chain reaction were carefully weighed. Bohr and Fermi, armed with long pieces of chalk and standing in front of the blackboard, resembled two knights at a medieval tourney. Thus did nuclear energy enter the world.”

A few days later, Enrico Fermi, standing in his office in the physics tower at Columbia University, looks out on New York City with all its people and activity, cups his hands, and says, “A little bomb like that, and it would all disappear.”

Leo Szilard now knows that uranium is the element he has been searching for, the element that will support a chain reaction.

Ready or not, the world will now have to deal with nuclear energy.

Enrico Fermi, the Joliot-Curies, Otto Hahn, and Fritz Strassmann all split nuclei with neutrons. But they didn’t know what they had done. Lise Meitner and Otto Frisch figured it out five years after Fermi’s first experiment.