CIENCIA, SERENDIPIA E BOMBA ATÓMICA

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DOCUMENTOS ANEXOS AO RELATORIO

PAX

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> "Serendipity: the falculty of making fortunate finds by chance".
> English Dictionary. Geddes&Grosset (2001).
>
> "Serendipia: condición do descubrimento que se realiza grazas a unha combinación de accidente e sagacidade".
> Neoloxismo, aínda non aceptado pola Real Academia Galega da Lingua.

Como é sabido, e moi habitual que na aula presentemos os conceptos científicos como unha inexorable consecuencia do traballo dos homes e mulleres de ciencia, baseados, as máis das veces, no uso do "método científico" e desde unha perspectiva histórica case que lineal.

Non ten ocorrido así sempre nin moito menos. A *serendipia* –os descubrimentos accidentais- ten sido un xeito moi frecuente de chegar a leis, principios e achádegos que teñen sido fundamentais na evolución da ciencia ó longo dos séculos.

Son coñecidos os casos do principio de Arquímedes, a obtención de moitas substancias químicas e moitos fármacos, a lei da caída dos corpos, a vacinación contra a virola, a obtención do caucho sintético, a elucidación da estructura do benceno, a ordenación dos elementos por Mendeleiev, o descubrimento da radiación de fondo, etc.

Naturalmente, o azar que estivo presente nestes logros científicos estaba destinado a facerse presente diante de persoas que posuían unha especial predisposición. Digamos que estaban no lugar preciso e no tempo apropiado. Cremos, xa que logo, que este é un xeito de levar a ciencia á aula, o que nos permitiría, simultaneamente, ser fiel á Historia da Ciencia e establecer un relato máis humano dos logros científicos.

Por outra parte, ademais de facerlles máis amena a aprendizaxe, podemos así dar a entender ó noso alumnado que a adquisición de contidos científicos vailles permitir, nos momentos máis insospeitados, construír os seus verdadeiros coñecementos de ciencia. E quen sabe, pode que unha mestura de sagacidade e casualidade lles teña destinado algo importante no futuro.

Estamos a celebrar o Ano Internacional da Física, por cumplirse o centenario do famoso "ano mirabilis" de Einstein. Nese ano de 1905 aparece por primeira vez a relación de conversión entre enerxía e masa na que se considera a ecuación máis famosa da Historia. Véñense tamén de se cumplir os 60 anos dos ben tristes episodios de Hirosima e Nagasaki onde de xeito tan dramático e insensato foi posta a proba a validez da referida ecuación. No nacemento da "bomba atómica" xogou "a serendipia" un papel determinante, e pensamos que pode ser instructivo mostralo como exemplo desta forma en que ás veces se constrúe a ciencia.

Ademais do centenario da publicación dos transcendentais traballos de Einstein de 1905, cúmprense os 50 anos do seu pasamento, polo que tamén queremos con esta comunicación contribuír modestamente, e desde un acto de Enciga, a honrar a quen ten sido considerado como o personaxe máis importante do século XX.

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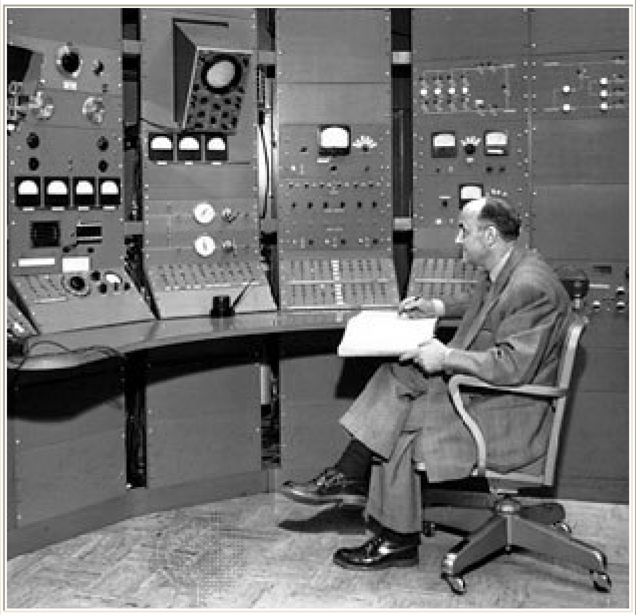
Fermi, Enrico



Enrico Fermi at the controls of the synchrocyclotron at the University of Chicago, 1951

UPI/Corbis-Bettmann

(b. Sept. 29, 1901, Rome, Italy--d. Nov. 28, 1954, Chicago, Ill., U.S.), Italian-born American physicist who was one of the chief architects of the nuclear age. He developed the mathematical statistics required to clarify a large class of subatomic phenomena, discovered neutron-induced radioactivity, and directed the first controlled chain reaction involving nuclear fission. He was awarded the 1938 Nobel Prize for Physics, and the Enrico Fermi Award of the U.S. Department of Energy is given in his honour.

Education and early career

Fermi was the youngest of the three children of Alberto Fermi, a railroad employee, and Ida de Gattis. Enrico, an energetic and imaginative student prodigy in high school, decided to become a physicist. At the age of 17 he entered the Reale Scuola Normale Superior, which is associated with the University of Pisa. There he earned his doctorate at the age of 21 with a thesis on research with X rays.

After a short visit in Rome, Fermi left for Germany with a fellowship from the Italian Ministry of Public Instruction to study at the University of Göttingen under the physicist Max Born, whose contributions to quantum mechanics were part of the knowledge prerequisite to Fermi's later work. He then returned to teach mathematics at the University of Florence.

In 1926 his paper on the behaviour of a perfect, hypothetical gas impressed the physics department of the University of Rome, which invited him to become a full professor of theoretical physics. Within a short time, Fermi brought together a new group of physicists, all of them in their early 20s. In 1926 he developed a statistical method for predicting the characteristics of electrons according to Pauli's exclusion principle, which suggests that there cannot be more than one subatomic particle that can be described in the same way. In 1928 he married Laura Capon, by whom he had two children, Nella in 1931 and Giulio in 1936. The Royal Academy of Italy recognized his work in 1929 by electing him to membership as the youngest member in its distinguished ranks.

This theoretical work at the University of Rome was of first-rate importance, but new discoveries soon prompted Fermi to turn his attention to experimental physics. In 1932 the existence of an electrically neutral particle, called the neutron, was discovered by Sir

James Chadwick at Cambridge University. In 1934 Frédéric and Irène Joliot-Curie in France were the first to produce artificial radioactivity by bombarding elements with alpha particles, which are emitted as positively charged helium nuclei from polonium. Impressed by this work, Fermi conceived the idea of inducing artificial radioactivity by another method: using neutrons obtained from radioactive beryllium but reducing their speed by passing them through paraffin, he found the slow neutrons were especially effective in producing emission of radioactive particles. He successfully used this method on a series of elements. When he used uranium of atomic weight 92 as the target of slow-neutron bombardment, however, he obtained puzzling radioactive substances that could not be identified.

Fermi's colleagues were inclined to believe that he had actually made a new, "transuranic" element of atomic number 93; that is, during bombardment, the nucleus of uranium had captured a neutron, thus increasing its atomic weight. Fermi did not make this claim, for he was not certain what had occurred; indeed, he was unaware that he was on the edge of a world-shaking discovery. As he modestly observed years later, "We did not have enough imagination to think that a different process of disintegration might occur in uranium than in any other element. Moreover, we did not know enough chemistry to separate the products from one another." One of his assistants commented that "God, for His own inscrutable ends, made everyone blind to the phenomenon of atomic fission."

Late in 1938 Fermi was named a Nobel laureate in physics "for his identification of new radioactive elements produced by neutron bombardment and for his discovery of nuclear reaction effected by slow neutrons." He was given permission by the Fascist government of Mussolini to travel to Sweden to receive the award. As they had already secretly planned, Fermi and his wife and family left Italy, never to return, for they had no respect for Fascism.

Meanwhile, in 1938, three German scientists had repeated some of Fermi's early experiments. After bombarding uranium with slow neutrons, Otto Hahn, Lise Meitner, and Fritz Strassmann made a careful chemical analysis of the products formed. On Jan. 6, 1939, they reported that the uranium atom had been split into several parts. Meitner, a mathematical physicist, slipped secretly out of Germany to Stockholm, where, together with her nephew, Otto Frisch, she explained this new phenomenon as a splitting of the nucleus of the uranium atom into barium, krypton, and smaller amounts of other disintegration products. They sent a letter to the science journal *Nature,* which printed their report on Jan. 16, 1939.

Meitner realized that this nuclear fission was accompanied by the release of stupendous amounts of energy by the conversion of some of the mass of uranium into energy in accordance with Einstein's mass-energy equation, that energy (E) is equal to the product of mass (m) times the speed of light squared (c^2), commonly written $E = mc^2$.

Work in the United States

Fermi, apprised of this development soon after arriving in New York, saw its implications and rushed to greet Niels Bohr on his arrival in New York City. The Hahn-Meitner-Strassmann experiment was repeated at Columbia University, where, with further reflection, Bohr suggested the possibility of a nuclear chain reaction. It was agreed that the uranium-235 isotope, differing in atomic weight from other forms of uranium, would be the most effective atom for such a chain reaction.

Fermi, Leo Szilard, and Eugene Wigner saw the perils to world peace if Hitler's scientists should apply the principle of the nuclear chain reaction to the production of an atomic bomb. They composed a letter, which was signed by Einstein, who, on Oct. 11, 1939, delivered it to Pres. Franklin D. Roosevelt, alerting him to this danger. Roosevelt acted on their warning, and ultimately the Manhattan Project for the production of the first atomic bomb was organized in 1942. Fermi was assigned the task of producing a controlled, self-sustaining nuclear chain reaction. He designed the necessary apparatus, which he called an atomic pile, and on Dec. 2, 1942, led the team of scientists who, in a laboratory established in the squash court in the basement of Stagg Field at the University of Chicago, achieved the first self-sustaining chain reaction. The testing of the first nuclear device, at Alamogordo Air Base in New Mexico on July 16, 1945, was followed by the dropping of atomic bombs on Hiroshima and Nagasaki a few weeks later.

Having satisfied the residence requirements, the Fermis had become American citizens in 1944. In 1946 he became Distinguished-Service Professor for Nuclear Studies at the University of Chicago and also received the Congressional Medal of Merit. At the Metallurgical Laboratory of the University of Chicago, Fermi continued his studies of the basic properties of nuclear particles, with particular emphasis on mesons, which are the quantized form of the force that holds the nucleus together. He also was a consultant in the construction of the synchrocyclotron, a large particle accelerator at the University of Chicago. In 1950 he was elected a foreign member of the Royal Society of London.

Fermi made highly original contributions to theoretical physics, particularly to the mathematics of subatomic particles. Moreover, his experimental work in neutron-induced radioactivity led to the first successful demonstration of atomic fission, the basic principle of both nuclear power and the atomic bomb. The atomic pile in 1942 at the University of Chicago released for the first time a controlled flow of energy from a source other than the Sun; it was the forerunner of the modern nuclear reactor, which releases the basic binding energy of matter for peaceful purposes. Element number 100 was named for him, and the Enrico Fermi Award was established in his honour. He was the first recipient of this award of $25,000 in 1954.

This article was written by Bernard Jaffe (d. 1986), a freelance science writer who was the author of *Men of Science in America* (1944).

The First Pile

By Corbin Allardice and Edward R. Trapnell

On December 2, 1942, man first initiated a self-sustaining nuclear chain reaction, and controlled it.

Beneath the West Stands of Stagg Field[1], Chicago, late in the afternoon of that day, a small group of scientists witnessed the advent of a new era in science. History was made in what had been a squash-rackets court.

Precisely at 3:25 p.m.,[2] Chicago time, scientist George Weil withdrew the cadmium-plated control rod and by his action man unleashed and controlled the energy of the atom.

As those who witnessed the experiment became aware of what had happened, smiles spread over their faces and a quiet ripple of applause could be hear. It was a tribute to Enrico Fermi, Nobel Prize winner, to whom, more than to any other person, the success of the experiment was due.

Fermi, born in Rome, Italy, on September 29, 1901, had been working with uranium for many years. In 1934 he bombarded uranium with neutrons and produced what appeared to be element 93 (uranium is element 92) and element 94. However, after closer examination it seemed as if nature had gone wild; several other elements were present, but none could be fitted into the periodic table near uranium where Fermi knew they should have fitted if they had been the transuranic elements 92 and 94. It was not until five years later that anyone, Fermi included, realized he had actually caused fission of the uranium and that these unexplained elements belonged back in the middle part of the periodic table.

Fermi was awarded the Nobel Prize in 1938 for his work on transuranic elements. He and his family went to Sweden to receive the prize. The Italian Fascist press severely criticized him for not wearing a Fascist uniform and failing to give the Fascist salute when he received the award. The Fermis never returned to Italy.

From Sweden, having taken most of his personal possessions with him, Fermi proceeded to London and thence to America where he has remained ever since. [3]

The modern Italian explorer of the unknown was in Chicago that cold December day in 1942. An outsider looking into the squash court where Fermi was working would have been greeted by a strange sight. In the center of the 30- by 60-foot room, shrouded on all but one side by a gray balloon cloth envelope, was a pile of black bricks and wooden timbers, square at the bottom and a flattened sphere on top. Up to half of its height, its sides were straight. The top half was domed, like a beehive. During the construction of this crude appearing but complex pile (the name which has since been applied to all such devices) the standing joke among the scientists working on it was: "If people could see what we're doing with a million-and-a-half of their dollars, they'd think we are crazy. If they knew why we are doing it, they'd know we are."

In relation to the fabulous atomic bomb program, of which the Chicago Pile experiment was a key part, the successful result reported on December 2nd formed one more piece for the jigsaw puzzle which was atomic energy. Confirmation of the chain reactor studies was an inspiration to the leaders of the bomb project, and reassuring at the same time, because the Army's Manhattan Engineer District had moved ahead on many fronts. Contract negotiations were under way to build production-scale chain reactors, land had been acquired at Oak Ridge, Tennessee, and millions of dollars had been obligated.

Three years before the December 2nd experiment, it had been discovered that when an atom of uranium was bombarded by neutrons, the uranium atom sometimes was split, or fissioned. Later, it had been found that when an atom of uranium fissioned, additional neurons were emitted and became available for further reaction with other uranium atoms. These facts implied the possibility of a chain reaction, similar in certain respects to the reaction which is the source of the sun's energy. The facts further indicated that if a sufficient quantity of uranium could be brought together under the proper conditions, a self-sustaining chain reaction would result. This quantity of uranium necessary for a chain reaction under given conditions is known as the critical mass, or more commonly, the "critical size" of the particular pile.

For three years the problem of a self-sustaining chain reaction had been assiduously studied. Nearly a year after Pearl Harbor, a pile of critical size was finally constructed. It worked. A self-sustaining nuclear chain reaction was a reality.

Construction of the Pile

Construction of the main pile at Chicago started in November. The project gained momentum, with machining of the graphite blocks, pressing of the uranium oxide pellets, and the design of instruments. Fermi's two "construction" crews, one under Zinn and the other under Anderson, worked almost around the clock. V.C. Wilson headed up the instrument work.

Original estimates as to the critical size of the pile were pessimistic. As a further precaution, it was decided to enclose the pile in a balloon cloth bag which could be evacuated to remove the neutron-capturing air.

This balloon cloth bag was constructed by Goodyear Tire and Rubber Company. Specialists in designing gasbags for lighter-than-air craft, the company's engineers were a bit puzzled about the aerodynamics of a square balloon. Security regulations forbade informing Goodyear of the purpose of the envelope and so the Army's new square balloon was the butt of much joking.

The bag was hung with one side left open; in the center of the floor a circular layer of graphic bricks was placed. This and each succeeding layer of the pile was braced by a wooden frame. Alternate layers contained the uranium. By this layer-on-layer construction a roughly spherical pile of uranium and graphite was formed.

Facilities for the machining of graphite bricks were installed in the West Stands. Week after week this shop turned out graphite bricks. This work was done under the direction of Zinn's group, by skilled mechanics led by millwright August Knuth. In October, Anderson and his associates joined Zinn's men.

Describing this phase of the work, Albert Wattenberg, one of Zinn's group, said" "We found out how coal miners feel. After eight hours of machining graphite, we looked as we were made up for a minstrel. One shower would remove only the surface graphite dust. About a half-hour after the first shower the dust in the pores of your skin would start oozing. Walking around the room where we cut graphite was like walking on a dance floor. Graphite is a dry lubricant, you know, and the cement floor covered with graphite dust was slippery."

Before the structure was half complete, measurements indicated that the critical size at which the pile would become self-sustaining was somewhat less than had been anticipated in the design.

Computations Forecast Success

Day after day the pile grew toward its final shape. And as the size of the pile increased, so did the nervous tension of the men working on it. Logically and scientifically they knew this pile would become self-sustaining. It had to. All the measurements indicated that it would. But still the demonstration had to be made. As the eagerly awaited moment drew nearer, the scientists gave greater and greater attention to details, the accuracy of measurements, and exactness of their construction work.

Guiding the entire pile construction and design was the nimble-brained Fermi, whose associated described him as "completed self-confident but wholly without conceit."

So exact were Fermi's calculations, based on the measurements taken from the partially finished pile, that days before its completion and demonstration on December 2, he was able to predict almost to the exact brick the point at which the reactor would become self-sustaining.

But with all their care and confidence, few in the group knew the extent of the heavy bets being placed on their success. In Washington, the Manhattan District had proceeded with negotiations with. I duPont de Nemours and Company to design, build, and operate a plant based on the principles of the then unproved Chicago pile. The $350,000,000 Hanford Engineer Works10 at Pasco, Washington, was to be the result.

At Chicago during the early afternoon of December 1st, tests indicated that critical size was rapidly being approached. At 4:00 p.m. Zinn's group was relieved the men working under Anderson. Shortly afterwards, the last layer of graphite and uranium bricks was placed on the pile. Zinn, who remained, and Anderson made several measurements of the activity within the pile. They were certain that when the control rods were withdrawn, the pile would become self-sustaining. Both had agreed, however, that should measurements indicate the reaction would become self-sustaining when the rods were withdrawn, they would not start the pile operating until Fermi and the rest of the group could be present. Consequently, the control rods were locked and further work was postponed until the following day.

That night the word was passed to the men who had worked on the pile that the trail run was due the next morning.

Assembly for the Test

About 8:30 on the morning of Wednesday, December 2nd, the group began to assemble in the squash court.

At the north end of the squash court was a balcony about ten feet above the floor of the court. Fermi, Zinn, Anderson, and Compton were grouped around instruments at the east end of the balcony. The remainder of the observers crowded the little balcony. R. G. Nobles, one of the young scientists who worked on the pile, put it this way: "The control cabinet was surrounded by the "big wheels"; the "little wheels" had to stand back."

On the floor of the squash court, just beneath the balcony, stood George Weil, whose duty it was to handle the final control rods. In the pile were three sets of control rods. One set was automatic and could be controlled from the balcony. Another was an emergency safety rod. Attached to one of this rod was a rope running through the pile and weighted heavily on the opposite end. The rod was withdrawn from the pile and tied by another rope to the balcony. Hilberry was ready to cut this rope with an axe should something unexpected happen, or in case the automatic safety rods failed. The third rod, operated by Weil, was the one which actually held the reaction in check until withdrawn the proper distance.

Since this demonstration was new and different from anything ever done before, complete reliance was not placed on mechanically operated control rods. Therefore, a "liquid-control squad," composed of Harold Lichtenberger, W. Nyer, and A. C. Graves, stood on a platform above the pile. They were prepared to flood the pile with cadmium-salt solution in case of mechanical failure of the control rods.

Each group rehearsed its part of the experiment.

At 9:45 Fermi ordered the electrically operated control rods withdrawn. The man at the controls threw the switch to withdraw them. A small motor whined. All eyes watched the lights which indicated the rod's position.

But quickly, the balcony group turned to watch the counters, whose clicking stepped up after the rods were out. The indicators of these counters resembled the face of a clock, with "hands" to indicate neutron clock. Nearby was a recorder, whose quivering pen traced the neutron activity within the pile.

Shortly after ten o¹clock, Fermi ordered the emergency rod, called "Zip," pulled out and tied.

"Zip out," said Fermi. Zinn withdrew "Zip" by hand and tied it to the balcony rail. Weil stood ready by the "vernier" control rod which was marked to show the number of feet and inches which remained within the pile.

At 10:37 Fermi, without taking his eyes off the instruments, said quietly:

"Pull it to 13 feet, George." The counters clicked faster. The graph pen moved up. All the instruments were studied, and computations were made.

"This is not it," said Fermi. "The trace will go to this point and level off." He indicated a spot on the graph. In a few minutes the pen came to the indicated point and did not go above that point. Seven minutes later Fermi ordered the rod out another foot.

Again the counters stepped up their clicking, the graph pen edged upwards. But the clicking was irregular. Soon it leveled off, as did the thin line of the pen. The pile was not self-sustaining --yet.

At eleven o'clock, the rod came out another six inches; the result was the same: an increase in rate, followed by the leveling off.

Fifteen minutes later, the rod was further withdrawn and at 11:25 was moved again. Each time the counters speeded up, the pen climbed a few points. Fermi predicted correctly every movement of the indicators. He knew the time was near. He wanted to check everything again. The automatic control rod was reinserted without waiting for its automatic feature to operate. The graph line took a drop, the counters slowed abruptly.

At 11:35, the automatic safety rod was withdrawn and set. The control rod was adjusted and "Zip" was withdrawn. Up went the counters, clicking, clicking, faster and faster. It was the clickety-click of a fast train over the rails. The graph pen started to climb. Tensely, the little group watched, and waited, entranced by the climbing needle.

Whrrrump! As if by a thunder clap, the spell was broken. Every man froze--then breathed a sigh of relief when he realized the automatic rod had slammed home. The safety point at which the rod operated automatically had been set too low.

"I'm hungry," said Fermi. "Let's go to lunch."

Time Out for Lunch

Perhaps, like a great coach, Fermi knew when his men needed a "break."

It was a strange "between halves" respite. They got no pep talk. They talked about everything else but the "game." The redoubtable Fermi, who never says much, had even less to say. But he appeared supremely confident. His "team" was back on the squash court at 2:00 p.m. Twenty minutes later, the automatic rod was reset and Weil stood ready at the control rod.

"All right, George," called Fermi, and Weil moved the rod to a predetermined point. The spectators resumed their watching and waiting, watching the counters spin, watching the graph, waiting for the settling down and computing the rate of rise of reaction from the indicators.

At 2:50 the control rod came out another foot. The counters nearly jammed, the pen headed off the graph paper. But this was not it. Counting ratios and the graph scale had to be changed.

"Move it six inches," said Fermi at 3:20. Again the change--but again the leveling off. Five minutes later, Fermi called: "Pull it out another foot."

Weil withdrew the rod.

"This is going to do it," Fermi said to Compton, standing at his side. "Now it will become self-sustaining. The trace will climb and continue to climb. It will not level off."

Fermi computed the rate of rise of the neutron counts over a minute period. He silently, grim-faced, ran through some calculations on his slide rule.

In about a minute he again computed the rate of rise. If the rate was constant and remained so, he would know the reaction was self-sustaining. His fingers operated the slide rule with lightning speed. Characteristically, he turned the rule over and jotted down some figures on its ivory back.

Three minutes later he again computed the rate of rise in neutron count. The group on the balcony had by now crowded in to get an eye on the instruments, those behind craning their necks to be sure they would know the very instant history was made. In the background could be heard Wilcox Overbeck calling out the neutron count over an annunicator system. Leona Marshall (the only girl present), Anderson, and William Sturm were recording the readings from the instruments. By this time the click of the counters was too fast for the human ear. The clickety-click was now a steady brrrr. Fermi, unmoved, unruffled, continued his computations.

The Curve is Exponential

"I couldn't see the instruments," said Weil. "I had to watch Fermi every second, waiting for orders. He face was motionless. His eyes darted from one dial to another. His expression was so calm it was hard to read. But suddenly, his whole face broke into a broad smile."

Fermi closed his slide rule---

"The reaction is self-sustaining," he announced quietly, happily. "The curve is exponential."

The group tensely watched for twenty-eight minutes while the world's first nuclear chain reactor operated.

The upward movement of the pen was leaving a straight line. There was no change in indicate a leveling off. This was it.

"O.K., 'Zip' in," called Fermi to Zinn who controlled that rod. The time was 3:53 p.m. Abruptly, the counters slowed down, the pen slid down across the paper. It was all over.

Man had initiated a self-sustaining nuclear reaction--and then stopped it. He had released the energy of the atom's nucleus and controlled that energy.

Right after Fermi ordered the reaction stopped, the Hungarian-born theoretical physicist Eugene Wigner presented him with a bottle of Chianti wine. All through the experiment Wigner had kept this wine hidden behind his back.

Fermi uncorked the wine bottle and sent out for paper cups so all could drink. He poured a little wine in all the cups, and silently, solemnly, without toasts, the scientists raised the cups to their lips--the Canadian Zinn, the Hungarians Szilard and Wigner, the Italian Fermi, the Americans Compton, Anderson, Hilberry, and a score of others. They drank to success--and to the hope they were the first to succeed.

A small crew was left to straighten up, lock controls, and check all apparatus. As the group filed from the West Stands, one of the guards asked Zinn:

"What's going on, Doctor, something happen in there?"

The guard did not hear the message which Arthur Compton was giving James B. Conant at Harvard, by long-distance telephone. Their code was not prearranged.

"The Italian navigator has landed in the New World," said Compton. "How were the natives?" asked Conant. "Very friendly."

List Of Those Present at

CHICAGO PILE EXPERIMENT

DECEMBER 2, 1942

Enrico Fermi

H. M. Agnew	G. Monk, Jr.
S. K. Allison	R. G. Nobles
H. L. Anderson	W. E. Nyer
W. Arnold	W. P. Overbeck
H. M. Barton	H. J. Parsons
T. Brill	G. S. Pawlicki
R. F. Christy	L. Sayvetz

A. H. Compton	L. Seren
R. J. Fox	L. A. Slotin
S. A. Fox	F. H. Spedding
D. K. Froman	W. J. Sturm
A. C. Graves	Leo Szilard
C. H. Greenewalt	A. Wattenberg
N. Hilberry	R. J. Watts
D. L. Hill	G. L. Weil
W. H. Hinch	E. P. Wigner
W. R. Kanne	M. Wilkening
P. G. Koontz	V. C. Wilson
H. E. Kubitschek	E. O. Wollan
H. V. Lichtenberger	Miss L. Woods
G. Miller	W. H. Zinn

Fermi's Own Story

By Enrico Fermi

It is ten years since man first achieved a self-sustaining atomic reaction.

Many people link this event only with the development of the atomic bomb and the subsequent efforts to develop the hydrogen bomb, reference to which has been made in the last few days by the Atomic Energy Commission.

The history of the first self-sustaining nuclear chain reaction, like that of all scientific achievements, begins with man¹s first philosophical speculations about the nature of the universe. Its ultimate consequences are still unpredictable.

The sequence of discoveries leading to the atomic chain reaction was part of the search of science for a fuller explanation of nature and the world around us. No on e had any idea or intent in the beginning of contributing to a major industrial or military development.

A partial list of the main stepping-stones to this development indicates many countries contributed to it.

The story begins in Paris in 1896 when Antoine Henri Becquerel discovered the existence of radioactive elements; that is, elements which spontaneously emit invisible, penetrating rays. Two years later, also in Paris, Pierre and Marie Cure discovered radium, for many years the best known of the radioactive elements.

In Zurich, Switzerland, in 1905, Albert Einstein announced his belief that mass was equivalent to energy. This led to speculation that one could be transformed into the other.

A most important discovery came in 1912 when Ernest Rutherford discovered the minute but heavy nucleus which forms the core of the atom. In ordinary elements this core is stable; in radioactive elements it is unstable.

Shortly after World War I, the same Rutherford achieved for the first time the artificial disintegration of the nucleus at the center of the nitrogen atom.

During the next decade, research progressed steadily, if unspectacularly. Then, in 1932, came a series of three discoveries by scientists working in three different countries which led to the next great advance.

Walter Bothe in Germany, and Frederic Joliot-Curie in Paris prepared the ground work that led James Chadwick of England to the discovery of the neutron. The neutron is an electrically neutral building block of the nuclear structure. The other build block is the positively charged proton.

The next step was taken in Rome in 1934. In experiments in which I was concerned it was shown that these neutrons could disintegrate many atoms, including those of uranium. This discovery was to be directly applied in the first atomic chain reaction eight years later.

The Discovery of Fission

The final stepping-stone was put in place in Berlin when Otto Hahn, working with Fritz Strassman, discovered fission or splitting of the uranium atom. When Hahn achieved fission, it occurred to many scientists that this fact opened the possibility of a form of nuclear (atomic) energy.

The year was 1939. A world war was about to start. The new possibilities appeared likely to be important, not only for peace but also for war.

A group of physicists in the United States‹including Leo Szilard, Walter Zinn, now director of Argonne National Laboratory, Herbert Anderson, and myself‹agreed privately to delay further publications of findings in this field.

We were afraid these findings might help the Nazis. Our action, of course, represented a break with scientific tradition and was not taken lightly. Subsequently, when the government became interested in the atom bomb project, secrecy became compulsory.

Here it may be well to define what is meant by the "chain reaction" which was to constitute our next objective in the search for a method of utilizing atomic energy.

An atomic chain reaction may be compared to the burning of a rubbish pile from spontaneous combustion. IN such a fire, minute parts of the pile start to burn and in turn ignite other tiny fragments. When sufficient numbers of these fractional parts are heated to the kindling points, the entire heap bursts into flames.

A similar process takes place I an atomic pile such as was constructed under the West Stands of Stagg Field at The University of Chicago in 1942.

The pile itself was constructed of uranium, a material that is embedded in a matrix of graphite. With sufficient uranium in the pile, the few neutrons emitted in a single fission that may accidentally occur strike neighboring atoms, which in turn undergo fission and produce more neutrons.

These bombard other atoms and so on at an increasing rate until the atomic "fire" is going full blast.

The atomic pile is controlled and prevented from burning itself to complete to complete destruction by cadmium rods which absorb neutrons and stop the bombardment process. The same effect might be achieved by running a pipe of cold water through a rubbish heap; by keeping the temperature low the pipe would prevent the spontaneous burning.

The first atomic chain reaction experiment was designed to proceed at a slow rate. In this sense it differed from the atomic bomb, which was designed to proceed at as fast a rate as was possible. Otherwise, the basic process is similar to that of the atomic bomb.

The atomic chain reaction was the result of hard work by many hands and many heads. Arthur H. Compton, Walter Zinn, Herbert Anderson, Leo Szilard, Eugene Wigner and many others worked directly on the problems at The University of Chicago. Very many experiments and calculations had to be performed. Finally a plan was decided upon.

Thirty "piles" of loss than the size necessary to establish a chain reaction were built and tested. Then the plans were made for the final test of a full-sized pile.

The scene of this test at The University of Chicago would have been confusing to an outsider‹if he could have eluded the security guards and gained admittance.

He would have seen only what appeared to be a crude pile of black bricks and wooden timbers. All but one side of the pile was obscured by a balloon cloth envelope.

As the pile grew toward its final shape during the days of preparation, the measurement performed many times a day indicated everything was going, if anything, a little bit better than predicted by calculations.

The Gathering on the Balcony

Finally, the day came when we were ready to run the experiment. We gathered on a balcony about 10 feet above the floor of the large room in which the structure had been erected.

Beneath us was a young scientist, George Weil, whose duty it was to handle the last control rod that was holding the reaction in check.

Every precaution had been taken against an accident. There were three sets of control rods in the pile. One set was automatic. Another consisted of a heavily weighted emergency safety held by a rope. Walter Zinn was holding the rope ready to release it at the least sign of trouble.

The last rod left in the pile, which acted as starter, accelerator and brake for the reaction, was the one handled by Weil.

Since the experiment had never been tried before, a "liquid control squad" stood ready to flood the pile with cadmium salt solution in case the control rods failed. Before we began, we rehearsed the safety precautions carefully.

Finally, it was time to remove the control rods. Slowly, Weil started to withdraw the main control rod. On the balcony, we watched the indicators which measured the neutron count and told us how rapidly the disintegration of the uranium atoms under their neutron bombardment was proceeding.

At 11:35 a.m., the counters were clicking rapidly. Then, with a loud clap, the automatic control rods slammed home. The safety point had been set too low.

It seemed a good time to eat lunch.

During lunch everyone was thinking about the experiment but nobody talked much about it.

At 2:30, Weil pulled out the control rod in a series of measured adjustments.

Shortly after, the intensity shown by the indicators began to rise at a slow but ever-increasing rate. At this moment we knew that the self-sustaining reaction was under way.

The even was not spectacular, no fuses burned, no lights flashed. But to us it meant that release of atomic energy on a large scale would be only a matter of time.

The further development of atomic energy during the next three years of the war was, of course, focused on the main objective of producing an effective weapon.

At the same time we all hoped that with the end of the war emphasis would be shifted decidedly from the weapon to the peaceful aspects of atomic energy.

We hoped that perhaps the building of power plants, production of radioactive elements for science and medicine would become the paramount objectives.

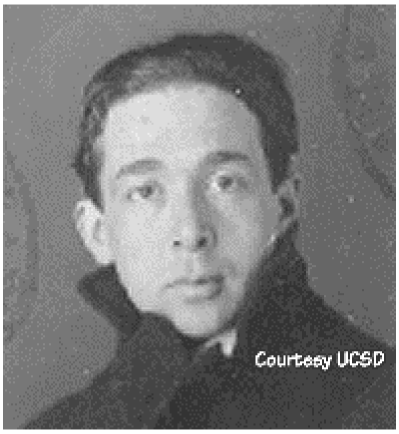
Unfortunately, the end of the war did not bring brotherly love among nations. The fabrication of weapons still is and must be the primary concern of the Atomic Energy Commission.

Secrecy that we thought was an unwelcome necessity of the war still appears to be an unwelcome necessity. The peaceful objectives must come second, although very considerable progress has been made also along those lines.

The problems posed by this world situation are not for the scientist alone but for all people to resolve. Perhaps a time will come when all scientific and technical progress will be hailed for the advantages that it may bring to man, and never feared on account of its destructive possibilities.

From *The First Reactor*, Published December, 1982 by the U.S Department of Energy

Leo Szilard - A Biographical Chronology



Leo Szilard, 1926 photo. Courtesy Szilard Papers, UCSD; used by permission. Contact Mandeville Special Collections Library, U.C. San Diego, for information on obtaining Szilard images.

Leo Szilard: Physicist, Molecular Biologist.
Born Budapest, Hungary, February 11, 1898.
Died La Jolla, California, U.S.A. May 30, 1964.

1898 Born February 11 in Budapest, Austro-Hungary, the son of a civil engineer.

1908 Student at Reáliskola, Budapest District VI, until graduation in 1916.

1916 Enrolled as engineering student at Budapest Technical University.

1917 Entered Austro-Hungarian Army as officer-candidate, artillery.

1918 Spared from probable death at battle front by chance illness. Honorably discharged from Austro-Hungarian army at end of WWI.

1919 Resumed engineering studies at Budapest Technical University. Left Hungary to escape repressive and anti-Semitic Horthy regime.

1920 Arrived in Berlin. Continued engineering studies at Technische Hochschule (Institute of Technology) in Berlin-Charlottenburg, then enrolled as physics student at University of Berlin.

1921 Took physics classes from Einstein, Planck, and von Laue.

1922 Independent dissertation on phenomenological thermodynamics praised by Einstein and awarded the notation "eximia," the highest honor. Received doctorate in physics from University of Berlin.

1923 Collaborated with Hermann Mark on x-ray diffraction experiments at Kaiser-Wilhelm Institutes for Chemistry, Berlin-Dahlem.

1924 Began 3-year appointment as Assistant to Nobel Laureate Max von Laue at the University of Berlin's Institute for Theoretical Physics.

1926 Began 7-year collaboration with Albert Einstein on the invention of home refrigerators without moving parts. Their joint inventions would include the annular linear induction pump, or Einstein-Szilard pump.

1927 Appointed Privatdozent (instructor) in Physics at University of Berlin.

1928 Began teaching seminars on quantum theory with John von Neumann. Hired as consultant by German General Electric Company (A.E.G.) to develop Einstein-Szilard refrigerator. Filed German patent application on the linear accelerator.

1929 Filed German patent application on the cyclotron. Met H.G. Wells. Published, in **Zeitschrift für Physik**, his classic analysis of Maxwell's Demon, in which he showed that the entropy of a unit of information was equal to $k \ln 2$.

1930 Met future wife Gertrude (Trude) Weiss. Attempted to organize an international movement of progressive intellectuals based on H.G. Wells' **Open Conspiracy**. Taught theoretical physics seminar with Erwin Schrödinger and John von Neumann. Taught seminar on nuclear physics and chemistry with Lise Meitner.

1931 Filed German patent application on the electron microscope. Prototype refrigerator using Einstein-Szilard pump successfully operated in A.E.G. Research Institute.

1932 During a visit to the United States, attempted to organize a scientific boycott of Japan to protest Japanese aggression in China. Development of Einstein-Szilard refrigerator abandoned due to invention of Freon and increasing economic Depression.

1933 Fled Germany March 31 to escape Nazi persecution. In Britain, aided fellow refugees and catalyzed the formation of the Academic Assistance Council. Ernest Rutherford quoted in London **Times** on September 12 as saying "anyone who looked for a source of power in the transformation of the atoms was talking moonshine." While walking through the streets of central

London after reading this article -- as he waited for a streetlight at the corner of Southampton Row -- Leo Szilard conceived the neutron chain reaction.

1934 On March 12, filed first British patent application on the neutron chain reaction. Request for laboratory space at Cambridge to investigate chain reactions rejected by Ernest Rutherford. Began experiments at London's St. Bartholomew's Hospital in search of a chain-reacting element, for which he suspected beryllium. Invented the Szilard-Chalmers reaction, a method for concentrating artificially produced radioactive isotopes.

1935 Received a refugee fellowship and continued his research in nuclear physics at the Clarendon Laboratory, Oxford. Concentrated on indium, which demonstrated puzzling isotopic activity.

1936 Assigned chain-reaction patent to British Admiralty to ensure patent would remain secret. Unsuccessfully attempted to convince colleagues, including Niels Bohr and Enrico Fermi, that atomic energy might be feasible, and if feasible was potentially so dangerous that research should be controlled.

1937 Continued research in nuclear physics at Oxford. Designed a betatron, in collaboration with James Tuck.

1938 Moved to New York City, in anticipation of outbreak of World War II. Concluded, after further experiments, that indium was incapable of chain-reacting.

1939 Predicted, immediately on learning of discovery of fission, that uranium might sustain a chain reaction. Began experiments at Columbia University, in collaboration with Walter Zinn, and demonstrated that neutrons were emitted in fission. Unsuccessfully proposed that results of fission experiments be kept secret because of danger of a German atomic bomb. Collaborated with Enrico Fermi on experiment testing uranium-water system. Proposed uranium-carbon lattice design for nuclear reactor. Unsuccessfully attempted to convince Fermi of likelihood of chain reaction and need to continue experiments. Visited Albert Einstein with Eugene Wigner (and later with Edward Teller) to discuss methods of averting German atomic bomb. Drafted, from Einstein's dictation, Einstein's August 2 letter to President Franklin D. Roosevelt.

1940 Received only $6,000 in research funds from government. With Enrico Fermi and Herbert Anderson, performed small-scale experiment with carbon demonstrating that uranium-carbon system might sustain a chain reaction. After German invasion of France, proposal for secrecy finally generally accepted by fellow scientists. In November, with Enrico Fermi, finally employed on government defense contract.

1941 With minimal government support, personally arranged for the industrial production of pure graphite and uranium necessary for a reactor.

1942 Moved to Chicago to begin employment at University of Chicago "Metallurgical Laboratory." Continued procuring pure graphite and uranium and designed reactor cooling systems. Declared by General Groves, head of newly-formed Manhattan Project, to be detriment to project who should be arrested and interned for duration of war. Witnessed successful demonstration of first nuclear chain reaction December 2.

1943 Advised colleagues on all aspects of reactor design. Correctly predicted that atoms dislocated by radiation damage ("Wigner disease") could release stored energy exothermically (the "Szilard complication"). (Effect caused 1957 Windscale nuclear accident in Britain.) Forced, by General Groves, to sell his atomic energy patent rights to the U.S. government.

1944 Proposed term "breeder" to describe reactor able to generate more fuel than it consumed. Became increasingly concerned about potential for post-war nuclear arms race.

1945 Unsuccessfully sought personal meetings with President Roosevelt, then Truman. Met with Secretary-of-State-designate James Byrnes. Co-authored Franck Report. Circulated petition among Project scientists opposing use of bomb on moral grounds. After end of war, organized successful opposition to May-Johnson bill, which placed atomic energy under military control. Testified before U.S. Senate committee on the implications of atomic energy.

1946 Founded, with Albert Einstein and others, the Emergency Committee of Atomic Scientists. Appointed Professor of Biophysics at the Institute of Radiobiology and Biophysics, University of Chicago.

1947 Decided to leave physics for biology. Attended Max Delbrück's "Phage Course" at Cold Spring Harbor, New York. "Letter To Stalin," proposing methods for reducing US-USSR tensions, published in **Bulletin of the Atomic Scientists**.

1948 Started own laboratory, with Aaron Novick, at University of Chicago, and began research in molecular biology. Invented the chemostat, an apparatus for continuous production of bacterial cultures under controlled conditions.

1949 Facilitated creation of "Midwestern Phage Group," with monthly meetings including Hershey, Lederberg, Luria, Watson, and others. Began publishing papers in biology.

1950 Publicly opposed development of Hydrogen bomb. Explained that such bombs could be coated with cobalt to increase radioactive fallout. With Aaron Novick, published "Experiments with the chemostat on spontaneous mutations of bacteria."

1951 Married his long-time friend Gertrud (Trude) Weiss, a public-health physician. With Aaron Novick, published paper describing phenotypic mixing in phage.

1953 Closed his Chicago biology laboratory and became a "roving theoretical biologist." Began year as visiting professor at Brandeis University.

1954 With Aaron Novick, proposed negative feedback regulation of enzyme activity. Became a Fellow of the American Academy of Arts and Sciences.

1955 Joint patent on nuclear reactor, with Enrico Fermi, issued by U.S. Patent Office.

1956 Became Professor of Biophysics at Enrico Fermi Institute for Nuclear Studies, University of Chicago.

1957 Began participation in "Pugwash" conferences, established to allow eminent scientists from East and West to discuss peace and world security. Attended first "Pugwash" conference in Pugwash, Nova Scotia. Offered Directorship of new Institute for Nuclear Physics in Berlin, but declined. Proposed to Jacques Monod that enzyme induction could be due to an anti-repressor.

1958 Attended second and third Pugwash conferences in Canada and Austria.

1959 Published theory of aging. Diagnosis of bladder cancer. Rejected standard treatment and designed his own radiation therapy.

1960 Underwent self-designed radiation therapy at Memorial Hospital, New York City. Cured of cancer. Atoms for Peace Award. Personal meeting with Soviet Premier Nikita Khrushchev, during Khrushchev's visit to New York, to propose methods of reducing US-USSR tensions, including Washington-Moscow "hotline. "

1961 Moved to Washington D.C. to seek "market for wisdom" in new Kennedy Administration. Elected to membership in National Academy of Sciences. Published short-story collection **The Voice of the Dolphins**. Honorary Doctor of Humane Letters, Brandeis University. Concluded that American government was incapable of change. Began national speaking tour "Are We On the Road to War?"

1962 Founded Council for Abolishing War (later renamed Council for a Livable World). Flew to Switzerland during Cuban Missile Crisis and attempted to avert World War III through personal diplomacy. In 1962 elections, Council support influenced outcome of close races, electing Senator George McGovern and others.

1963 Became Non-Resident Fellow of Salk Institute, La Jolla, California.

1964 Became a Resident Fellow of the Salk Institute. Completed paper on molecular basis of memory, "On Memory and Recall." Died in his sleep of a heart attack in La Jolla, California on May 30 at the age of 66.

EUGENE WIGNER

Eugene Wigner was a towering leader of modern physics for more than half of the twentieth century. While his greatest renown was associated with the introduction of symmetry theory to quantum physics and chemistry, for which he was awarded the Nobel Prize in physics for 1963, his scientific work encompassed an astonishing breadth of science, perhaps unparalleled during his time.

In preparing this memoir, we have the impression we are attempting to record the monumental achievements of half a dozen scientists. There is the Wigner who demonstrated that symmetry principles are of great importance in quantum mechanics; who pioneered the application of quantum mechanics in the fields of chemical kinetics and the theory of solids; who was the first nuclear engineer; who formulated many of the most basic ideas in nuclear physics and nuclear chemistry; who was the prophet of quantum chaos; who served as a mathematician and philosopher of science; and the Wigner who was the supervisor and mentor of more than forty Ph.D. students in theoretical physics during his career of over four decades at Princeton University.

The legacy of these contributions exists in two forms. First, there are the papers—in excess of five hundred—now included in eight volumes of his collected works.[1] His legacy also resides in the many concepts and phenomena that bear his name. There is, for example, the Wigner-Eckart theorem for the addition of angular momenta, the Wigner effect in nuclear reactors, the Wigner correlation energy, as well as the Wigner crystal in solids, the Wigner force, the Breit-Wigner formula in nuclear physics, and the Wigner distribution in the quantum theory of chaos.

His collection of essays *Symmetries and Reflections*[2] provides an insightful view of the many intellectual matters that concerned him during a busy career. The recollections of his life[3] recorded by Andrew Szanton when Wigner was in his eighties provide a special insight into the circumstances of his life and the incidents that brought him to the fore.

EARLY HISTORY

Wigner was born in Budapest on November 17, 1902, into an upper middle class, predominantly Jewish family. His father was manager of a leather factory, and clearly hoped that his son eventually would follow him in that post. He had two sisters. The family roots lay in both Austria and Hungary. The two major events that disturbed the tranquil course of his formative years were World War I and the communist regime of Bela Kun, which followed it. Since his father was of the managerial class, the family fled Hungary to Austria during the communist period and returned a number of months later, after the regime of Bela Kun had been deposed.

For his secondary school education, Wigner attended the Lutheran *gimnazium,* which had a dedicated and highly professional teaching staff. Wigner regarded himself an excellent student, but not an outstandingly brilliant one. Throughout his lifetime, he mentioned his debt to two individuals he met through that school. First was his mathematics teacher, Laslo Ratz, who recognized that the young Wigner had exceptional if not rare abilities in mathematics. The second was a somewhat younger student, John von Neumann, who came from a wealthy banking family and who indeed was recognized by Ratz to be a mathematical genius and to whom he provided private coaching. Wigner formed a close friendship with von Neumann that was to endure throughout their lifetimes. As students, they would often walk home together while von Neumann related to Wigner the wonders of advanced mathematics, which the former was absorbing.

TECHNISCHE HOCHSCHULE, BERLIN

While Wigner was strongly attracted to the field of physics, his father, who was of a very practical mind, insisted that instead he attend the Technische Hochschule in Berlin and focus on chemical engineering, so that he might be in a better position to earn a living in Hungary. Wigner followed his father's advice and in 1920 found himself in Berlin. There he spent a substantial part of the day mastering several fields of chemistry, as well as the arts and practice of chemical engineering, which he retained in full force for important use during World War II.

His heart, however, was still devoted to physics, which was in a state of major transition. He spent essentially all of his spare time at the University of Berlin attending seminars and colloquia, where he frequently found himself listening intently to discussions in the presence of the great figures of the time. His interest deepened. It should be added that von Neumann's parents had also insisted that von Neumann focus on chemical engineering, so that he would have a reliable practical background, although his major interest continued to be mathematics.

There was a small but prominent Hungarian community in academic circles in Berlin. Wigner soon formed relationships with its members, which remained close throughout their lifetimes. One of the special links was with Professor Michael Polanyi, a generation older, who gave very generously of his time and attention. He also met Leo Szilard, whom he often referred to as "the general," since Szilard enjoyed making decisions. Other Hungarians Wigner met through the Berlin connections were Dennis Gabor and Egon Orowan. He also renewed there a friendship with Edward Teller, whom he had known as a younger student in Budapest, and who was then working with Heisenberg in Leipzig.

RETURN TO BUDAPEST

Wigner returned to Budapest in 1925 to take a position in his father's leather factory. It was then that he learned of Heisenberg's highly innovative development of the matrix version of quantum mechanics. While he was not entirely happy with his work and circumstances in Budapest, he would have carried through indefinitely in order to be supportive of his family and its wishes.

RETURN TO BERLIN

A year or so after becoming re-established in Budapest, Wigner received an offer of a research assistantship in Berlin from Professor Karl Weissenberg, an X-ray crystallographer at the University of Berlin. When he discussed the matter with his father, the latter was not entirely pleased, although he recognized the intensity of his son's desire to become a professional scientist. Finally, his father decided to let his son return to Berlin, where the latter learned that Michael Polanyi had been instrumental in having the offer extended.

Since Wigner had a very fine command of mathematics, Weissenberg frequently posed problems of a semi-complex nature that had mathematical roots. This led the young novice to explore elementary aspects of symmetry or group theory as he struggled to try to satisfy Weissenberg's curiosity, as well as his own. In the meantime, Heisenbergs's matrix version of quantum mechanics was followed by Schroedinger's wave-like formulation.

Once caught up in symmetry theory, Wigner wondered if it had applications in the field of quantum mechanics. This led him to discuss the issue with von Neumann, who, after pondering the problem briefly, recommended that he read the papers of G. Frobenius and I. Schur on the irreducible representations of symmetry groups. Wigner soon became immersed in the field. He realized it opened a vast new area of mathematical physics for exploitation, the initial applications being to the degenerate states of symmetrical atomic and molecular systems. What many physicists came to call the "group theory disease" was born, with very far-reaching effects.

This initial work of Wigner on group theory and quantum mechanics[4,5] had a profound impact on all of fundamental physics and on Wigner's own subsequent development as a scientist. He understood that the superposition principle of quantum mechanics permitted more far-reaching conclusions concerning invariant quantities than was the case in classical mechanics. With the tools of group theory, Wigner derived many rules concerning atomic spectra that follow from the existence of rotational symmetry.

After a number of months, Weissenberg arranged for Wigner to become a research assistant to Professor Richard Becker, who had been newly appointed to a chair in theoretical physics at the university. Becker was very generous in allowing him to follow his own leads for self-development.

SHIFT TO GÖTTINGEN

In 1927 Richard Becker proposed that Wigner spend a period in Göttingen as an assistant to the very distinguished mathematician David Hilbert. Göttingen was at that time one of the greatest world centers of mathematics, with a continuous history in that field going back to the time of Karl Gauss. Moreover, it was very strong in theoretical physics. Unfortunately, Hilbert had become seriously ill and withdrew essentially permanently from professional work, so that Wigner found himself with a position with no formal responsibilities. He did form, however, friendly links with individuals such as James Franck. He also undertook a cooperative research program with Victor F. Weisskopf, then a student, with whom he published a paper on spectral line shape.

WIGNER'S SOLILOQUY

Having much time to himself in Göttingen because of the special circumstances he encountered there, Wigner decided to come to terms with himself and his new career. After much pondering, he came to three broad conclusions. First, he would devote his life to the further advancement of physics. Second, whenever possible, he would do his best to apply his knowledge of physics to the well being of mankind. Finally, having discovered that the field of group representations opened entirely new vistas in the applications of quantum mechanics, he would follow that area of development as the main lead in his future work.

Just at this point, Leo Szilard earnestly requested that Wigner write a book on group theory and its applications that would be understandable to physicists, particularly members of the younger generation. Soon after Wigner published his first work in the field, the mathematician Hermann Weyl, became interested in the topic and wrote a book on the subject, which was rather inaccessible for most physicists. Thus, Wigner began writing his famous book *Group Theory and Its Application to the Quantum Mechanics of Atomic Spectra*,[6] a continuing classic. In a sense, Wigner reclaimed his birthright while rendering a service.

RETURN TO BERLIN

In 1928 Wigner returned to Berlin and continued his work there. Among his many contributions to the field of quantum mechanics during this period was a paper devoted to the theory of chemical reaction rates that he developed in cooperation with Michael Polanyi and Henry Eyring, a visitor from the United States. The approach used was generalized later by Eyring and applied to many chemical problems. Wigner and Eyring were to become colleagues once again during the 1930s while both were on the Princeton faculty.

PRINCETON BECKONS

In the autumn of 1928 Wigner, again out of the blue, received a most remarkable letter from Princeton University asking if he would be willing to serve for one year as a half-time lecturer in mathematical physics at what for him was an enormous salary. The offer undoubtedly had a complex origin. Oswald Veblen, a distinguished, worldly professor of mathematics at Princeton who hoped to make Princeton the American equivalent of Göttingen in mathematics and mathematical physics, decided that a great advance would be achieved if John von Neumann would join the Princeton faculty on a full-time basis. This idea was by no means far-fetched because von Neumann had decided as early as the mid-1920s that it was very likely that Europe would experience another great war that would be accompanied by a vicious wave of anti-Semitism. He concluded at that time that he would eventually explore possible openings in the United States. When Princeton tried to acquire him on a full-time tenured basis in 1928, he decided he was not yet ready to go that far in terminating his European links and suggested that he and Wigner share the appointment on a half-time basis. Princeton agreed, with the understanding that Wigner's appointment would not carry tenure. In any event, both Wigner and von Neumann found themselves settling in at Princeton on a part-time basis in 1930.

Von Neumann enjoyed his life in the United States immensely from the very beginning. He formed friendships easily, and was soon leading a very stimulating life with his vivacious Hungarian wife, who had joined him. For Wigner, in contrast, the transition was a relatively difficult one. He not only found the informalities of American life strange relative to those in Europe, which suited him so well, but had special difficulty adjusting to Princeton, which had its own somewhat closed social structure. He lived a fairly lonely existence, except for the professional links that grew out of mutual research interests with some members of the faculty.

Not least, Wigner brought with him to the United States the standards of polite social behavior that had developed among the members of the upper middle and professional classes in Europe. There is an almost endless lore of "Wignerisms" that have circulated within the community associated with him. It was essentially impossible not to obey his insistence that you pass through a door before him. Individuals, on wagers, invented ingenious devices, which usually failed, in attempts to reverse the procedure. On one occasion, he encountered an unscrupulous merchant who attempted to cheat him in a too obvious way. Wigner, angry and now somewhat seasoned in vernacular terminology, terminated the negotiation abruptly by saying, "Go to Hell, please!" He often received requests from other individuals to read a research paper written by the latter. If he found many errors, he was very likely to return it with the ambiguous comment, "Your paper contains some very interesting conclusions!"

During that first year, both the mathematics and the physics departments were sufficiently pleased with the arrangement involving von Neumann and Wigner that it was extended on the half-time basis for a five-year period.

As Wigner was preparing to return to Berlin at the end of January 1933, it was announced that President Hindenburg had appointed Adolph Hitler chancellor. Wigner was dismayed, since he knew that his appointments in Berlin would be canceled because of his Jewish background. He returned to Budapest instead of Berlin. During the following year, he decided it would be wise for him to become a U.S. citizen, and citizenship was granted in 1937.

PREWAR YEARS OF RESEARCH

Along with the many other investigations related to physics and chemistry, Wigner initiated advances in three major fields of physics in the prewar years, first at Princeton (1930-36), then during his two years at Wisconsin (1936-38), and after his return to Princeton. He helped open important parts of solid-state physics to applications of quantum mechanics. He was a true pioneer in unraveling the mysteries of nuclear physics, and he derived for practical use the irreducible unitary matrix representations of the continuous group associated with the Lorentz transformation. In each of these three cases, his work opened doorways to areas that were to expand continuously during the next half century as a result of his initial work.

In the field of solid-state physics, he and Seitz, his first graduate student, succeeded in developing an acceptable wave function for the ground state of metallic sodium.[7] When the results associated with it were joined with calculations of the exchange and correlation energies of a gas of free electrons carried out by Wigner, the so-called binding energy or energy of sublimation of the metal could be derived essentially from fundamentals using quantum mechanics. The field was opened further by Wigner in cooperation with several of his students, most notably John Bardeen, who later gained much fame for his primary contributions to the invention of the transistor and the explanation of low-temperature superconductivity. Among other individuals who worked with him in this area at that time was Conyers Herring, who subsequently served as a leading generalist in the field for half a century.

Immediately after the discovery of the neutron in 1932, Wigner studied the early measurements of neutron-proton scattering, the properties of the deuteron, the connection between the saturation property of nuclear binding energies and the short range nature of the inter-nucleon force, and the symmetry properties of the force.

Later in the 1930s, when beta-decay data and energy levels of light nuclei began to emerge, Wigner, together with Gregory Breit, Eugene Feenberg, and others, developed the supermultiplet theory[8] in which spatial symmetry played a key role in the description of nuclear states.

Soon after Fermi found the strong and sharp resonances in the bombardment of nuclei by neutrons, Breit and Wigner developed the very useful Breit-Wigner formula to describe the cross sections in terms of nuclear parameters. Underlying the formula was the concept of a short-lived transition state, somewhat analogous to Bohr's "compound nucleus" and to the transition state appearing in Wigner's conception of a chemical reaction.

In an epochal paper[9] published in 1939, Wigner turned his attention to the inhomogeneous Lorentz group. This group involves time-dependent symmetries, or symmetry groups that include time-translation invariance. The topic had not previously received serious study by mathematicians or physicists. He provided a complete answer to the two major questions he posed: (1) what are the unitary representations of the inhomogeneous Lorentz group and (2) what is their physical significance? In this case, an analysis of its irreducible representations provided a complete classification of all the then known elementary particles. This paper furnished a platform for the further development of relativistic quantum mechanics by Wigner and others in the post-World War II period.

In 1940 Wigner developed the algebra of angular momentum recoupling, using group theoretical methods prior to Racah's algebraic analysis in 1942. The paper,[10] far ahead of its time, had the rather esoteric title of "On the Matrices Which Reduce the Kronecker Products of Simply Reducible Groups." Wigner's friends advised him that the work was too esoteric to merit publication; it did not emerge in published form until twenty-five years later.

Incidentally, Dirac became a frequent visitor to Princeton starting in the early 1930s. Wigner had first met him at Göttingen and developed a strong liking for the very reserved Englishman. The two somewhat lonesome bachelors became close friends, each respecting the other's qualities. Dirac eventually came to meet Wigner's younger sister as a result of this friendship. They were married in 1937.

UNIVERSITY OF WISCONSIN, 1936-38

Although Wigner's non-tenured appointment at Princeton was extended beyond the initial five years, and he was promoted from visiting lecturer to visiting professor, it was not the tenured position he was looking for. He decided he was being rejected. As a result he found it necessary to search for another position during a period in the Great

Depression when there were very few tenured vacancies. Fortunately, he succeeded in obtaining such an appointment at the University of Wisconsin with the help of a colleague there, Gregory Breit, who fully appreciated his merits. The warmth of the reception he received at the university made him feel at home very rapidly and he was soon productively at work again. In close cooperation with Breit, he continued to focus attention on nuclear physics. Among other things, they proposed a transition-state picture of nuclear reactions and the previously mentioned Breit-Wigner formula for the scattering and absorption of particles such as neutrons and gamma rays by nuclei. In later years, Wigner strengthened the mathematical foundations on which the relationship was based, using what has come to be termed R-matrix theory.

He also found himself greatly attracted to Amelia Frank, one of the young women members of the faculty. The two were married in December 1936. Unfortunately, she soon developed incurable cancer and died just a few months after their marriage, casting him into a deep depression.

In the meantime, Princeton had come to regret its decision regarding the "dismissal" of Wigner. As a result, he was invited to return to a tenured professorship in 1938. He might have refused under other circumstances, since by this time he felt more than a sense of gratitude to his many friends at the University of Wisconsin. Under the circumstances, however, he decided that it was very important for his own mental health that he leave the surroundings associated with so much grief, and he accepted the appointment.

NUCLEAR FISSION

The return to Princeton brought with it two major developments that rapidly drew Wigner into applied research, this time with feverish energy. It was obvious to him and von Neumann, as a result of the so-called Munich Peace Pact in the autumn of 1938, that the Second World War they had long anticipated was now near at hand and that England, France, and the United States were ill prepared to face it. To protect his parents from the rising power of Hitler, he convinced them to come to the United States, a necessary move to which they never succeeded in adjusting.

A few months later came the announcement of the discovery of nuclear fission by Hahn and Strassmann in Berlin, along with evidence for the large amount of energy released in the process.

In the meantime, Enrico Fermi, who had carried out much of the pioneering work on neutron-induced reactions, had taken the opportunity provided by a Nobel award to leave Italy and accept an appointment at Columbia University in New York City. Moreover, Leo Szilard, who had moved from Berlin to England when Hitler took power, decided to join Fermi in New York, since he also feared that war was imminent.

Leo Szilard, convinced since the 1920s that it would not be long before one would learn to extract an enormous amount of energy from the atomic nucleus, came dramatically alive with the discovery of fission and soon had both Fermi and Wigner deeply immersed in the problem of determining whether a fission-induced chain reaction was possible. By the end of the winter of 1938-39, they decided that the probability of success was high, provided they could obtain the necessary material support. One of the consequences of their conviction was the framing of the letter that Einstein, Szilard, and Wigner sent to President Roosevelt in July 1939 describing the potentialities of a nuclear bomb and warning that, since fission had been discovered in Germany, it was most likely that the Germans would be the first to develop it. It took two and a half years, the start of World War II, and the bombing of Pearl Harbor for the national leadership finally to respond to the need to make adequate resources available.

In the interim, Fermi and a small group working with him at Columbia, along with the cooperation of Szilard and Wigner, succeeded in measuring the various significant parameters, such as the number of neutrons produced per fission, that would determine whether a chain reaction was possible.

In June 1941 Wigner married fellow physicist Mary Wheeler, whom he had met through professional meetings. The two were soon living as happy a domestic life as one could hope for under wartime conditions and were raising two bright, talented children. This union finally freed Wigner from the long periods of loneliness he had experienced since first coming to the United States. The next four decades were happy ones until Mary died of cancer in 1977. Two years later he married Eileen Hamilton, the recently widowed wife of the dean of graduate studies. The two shared close companionship until Wigner's death.

UNIVERSITY OF CHICAGO

By September 1941 there was no doubt about the feasibility in principle of developing a nuclear chain reaction. Moreover, the government decided to concentrate the initial effort of achieving that end at the University of Chicago under the leadership of Arthur H. Compton. Fermi was made director of the experimental research program and Wigner was placed in charge of a theoretical group that would follow developments and explore future possibilities. A strong chemistry group, which could achieve practical means of separating fissionable plutonium from the other by-products of nuclear fission, was also assembled. James Franck was placed in charge of that group, but a team led by Glenn Seaborg was given principal responsibility for carrying through the practical phases of the chemical work. The race was on!

The following few years gave Wigner an opportunity to put to use all of his experience and professional background, not least his careful training as a chemical engineer. While Fermi and his group moved ahead procuring materials of adequate purity and form for the construction of a graphite-moderated natural uranium reactor, Wigner formed a small staff, which, in addition to providing auxiliary help to Fermi, began to design large reactors that could produce practical quantities of plutonium. In his search among individuals not previously known to him, he found two scientists who became main players in his team. The two were Alvin M. Weinberg, a theoretical physicist who had just obtained his Ph.D. at the University of Chicago, and Gale Young, a practical mathematician who had been teaching at Olivet College.

Another major addition to the group was Edward Creutz who had previously joined the junior faculty at Princeton as an experimental nuclear physicist. Creutz realized soon after becoming part of Wigner's team in Chicago that the greatest service he could render was not as a nuclear physicist, but as a highly imaginative and flexible technical innovator. For he solved with speed and ingenuity many urgent problems related to metallurgy and radiation-induced effects that were barriers to progress and were beyond the range of traditionally experienced engineers.

Working with these partners and a small auxiliary staff, Wigner focused his attention on the design of large water-cooled, graphite, natural uranium reactors that would operate in the range of 500 megawatts, producing at optimum about 500 grams of plutonium per day.

By the time Fermi's reactor actually went critical on December 3, 1942, Wigner and his team had completed a task of almost unbelievable proportions, perhaps without equal in the annals of science and engineering. They had emerged with the effectively complete design of the full-scale Hanford production reactors. When the work began, a general outline was agreed on. The basic structure would consist of a lattice of natural uranium rods imbedded in channels extending through a graphite moderator. Some of the major design elements that needed to be determined as the group proceeded were the choice of coolant, dimensions of the lattice and reactor, and disposition of the control rods and cladding and tube materials. They also had to design the uranium fuel rods, determining whether they were to be hollow rods cooled internally or solid slugs cooled externally, all of which was accompanied by detailed analyses of matters such as pressure drops and heat transfer. Beyond this were issues related to the design of the outer shield and the method for loading and unloading. Wigner's personal imprint was on every aspect of the design. When the Dupont company later built the Hanford reactors, Wigner personally reviewed every blueprint.

The path Wigner and his team had to tread to reach their goal was not an easy one. Engineers brought into the program to provide independent advice offered alternative proposals for reactor design. In particular, there was strong support for a reactor that would be cooled by gaseous helium. It was necessary to demonstrate that such alternatives were substantially less desirable than a water-cooled system. Moreover, General Leslie Groves, who was in charge of the overall program, decided that responsibility for the final design and construction of the large plutonium-producing reactors should be given to the Dupont company and not to the staff of the Chicago laboratory.

Wigner felt this decision was wrong on two scores. Many valuable months would be lost while the inexperienced Dupont group became intimately familiar with the science and technology involved; his own team would inevitably be required to serve as frontline advisors, but would be in a completely subservient position. To appreciate the problems he faced and his frustrations, one can do little better than to read Wigner's memoir for the period (pages 24 to 130 of part A, volume V of Wigner's collected works) and the introductory essay by Alvin Weinberg preceding it. The experience left a permanent mark on Wigner, although he did admit later that the reactors built and operated by Dupont at Hanford in Washington state were highly successful.

When it became clear after the testing of the first atomic bomb at Alamogordo in July 1945 that the United States would soon possess an arsenal of nuclear weapons, Wigner joined a group of project scientists who requested that President Truman forego the use of such bombs in Japan. Although he was proud of his contribution to the release of nuclear energy, which he regarded as very important for the future of mankind, he was not comfortable that his work could also contribute to the death of many Japanese civilians. According to his daughter, he later found some solace in the thought that the use of the bombs had also shortened the duration of the war and thereby saved many lives on both sides.

DIRECTOR OF RESEARCH, CLINTON LABORATORIES, OAK RIDGE

Once the basic mission of the Chicago laboratory had been fulfilled and the war was nearing its end, Wigner began to make plans about the best way to explore peaceful uses of nuclear energy in the postwar period. He finally decided to spend a period in Tennessee as director of research at Clinton Laboratories, forerunner of Oak Ridge National Laboratory. A one-megawatt graphite research reactor had been constructed there in 1943 following the success of the Fermi test reactor. Initially, the laboratory at Oak Ridge had been under the management of the University of Chicago, however, it was turned over to the Monsanto Chemical Company at the end of the war.

Wigner planned a two-pronged approach. First, he would establish a training program in which some thirty-five young scientists and engineers could learn the principles involved in nuclear reactors. These individuals would become future leaders in reactor development. Second, he would assemble an expert team to design nuclear reactors that could produce useful power efficiently and as safely as possible, placing much emphasis on the so-called "breeder" reactor. A substantial part of his research team in Chicago, including Weinberg and Young, agreed to join him there and spend the next phase of their professional careers promoting the development of nuclear energy for peaceful purposes. A pithy account of the scientific and technical work carried out under Wigner's guidance during the year or so he was in residence at the laboratory is contained in Weinberg's introductory essay appearing in part A, volume V of the collected work mentioned above.

In the meantime, there was a great deal of legislative activity in Washington about the way the national nuclear energy program should be managed in peacetime. The debate was intense and protracted. The final result was the creation of a new civilian agency, the Atomic Energy Commission, which was put in charge of the operation on January 1, 1947. As the year progressed, Wigner eventually decided he was not really suited to serve as manager of a laboratory in such a complex, politicized environment. Many of the most important technical decisions would be made in Washington rather than in the laboratory. He left Oak Ridge at the end of the summer of 1947 and returned to Princeton to continue his academic career. Alvin Weinberg was eventually selected to be his successor. In the meantime, Wigner was pleased to serve as a valuable consultant to the laboratory.

In parallel with his continuing interest in the technology of nuclear reactors,[11] he became deeply involved with the problems of civil defense and spent much time at Oak Ridge working with a group that was interested in ways of achieving an effective level of defense as inexpensively as possible.

REMAINING ACADEMIC YEARS

On his return to Princeton University from the Clinton Laboratories, Wigner embarked on a long and fruitful period of research and graduate teaching. As mentioned above, he continued with his consulting on reactors and passionate involvement with civil defense. However, his main activity pertained to research, generally with his graduate students and research associates. Of Wigner's more than forty Ph.D. students, the large majority obtained their degrees during this postwar period. While he was perhaps not as venturesome as before the war, his style remained the same and his broad interests continued, particularly in nuclear physics, in the foundations of quantum mechanics, and in relativistic wave equations. He initiated and developed fully the R-matrix theory of nuclear reactions and became a founding father of the quantum theory of chaos. There was also much greater opportunity for him to engage in philosophical reflections and the writing of related essays during the decades of this period.

Wigner's deep interest in the foundations of quantum mechanics, especially the quantum theory of measurement, persisted longer than any of his other interests. It was already present in his "soliloquy" in the 1920s, as well as in his contributions to von Neumann's famous 1932 book on the mathematical foundations of quantum mechanics. It continued in his thoughts and published work until the end of his life. Wigner's monumental work on the representations of the inhomogeneous Lorentz group (1939) led after World War II to his work[12] with Newton on relativistic wave equations. Although this work enjoyed considerable success, important problems remained. Indeed, Wigner remained pessimistic until the end of his life about fully reconciling the present formulation of quantum mechanics with special and general relativity. Limitations on general measurability were pointed out in an important paper with G. S. Wick and A. S. Wightman.[13]

In the postwar years Wigner's interest in nuclear structure gradually waned, but his involvement in nuclear reactions grew and was, perhaps, responsible for more of his published work than any other subject. The various collective models for nuclear structure that gained popularity were not to Wigner's taste. However, he was deeply interested in understanding individual particle motion in nuclei and, with Vogt, used a method very similar to the Wigner-Seitz method for electron correlations in solids to show how the Pauli exclusion principle permitted the persistence of such motion despite the absence of a central field and despite the strength and short range of the nuclear forces.

The R-matrix theory of nuclear reactions arose out of Wigner's prewar work on the Breit-Wigner formula and has remained, for more than half a century, the most successful and widely used method for the description of resonance phenomena in nuclei. It was developed initially with Leonard Eisenbud,[14] but many other students and colleagues were involved in its elaboration. Wigner turned to it and its mathematics frequently.

The mathematics associated with R-matrices and R-functions fascinated Wigner beyond their direct application to resonance reactions. Although he remained a physicist throughout his life, deeply committed to the understanding of nature, he could be beguiled by mathematics. While contemplating the nature of the small random matrix elements involved in the myriad of compound nuclear levels encountered, for example, in the absorption of slow neutrons by uranium to produce slow fission, Wigner introduced an infinite Hermitian matrix that possessed random matrix elements. In this case the random matrix elements were related to the level widths involved in the problem. Using ideas he had gained from von Neumann, he was able to show[15] that a statistical distribution of level spacing still persisted in the midst of utter randomness. This "Wigner distribution" of spacing became a cornerstone of the quantum theory of chaos.

Perhaps because he was the individual who introduced the concept of symmetry into quantum mechanics and had developed well-entrenched concepts of how nature should behave, Wigner was quite taken aback when, in the mid-1950s experimental observations of the details of nuclear beta decay demonstrated that we live in a portion of the universe where inversion symmetry is not valid for the so-called weak interactions involved in such decay.

RETIREMENT

Although he retired as a professor of physics at Princeton University in 1971, Wigner's overall activities did not diminish. In fact, they broadened in important ways, since he was now relieved of some of the routine associated with academic life. Moreover, he was able, with essentially undiminished vigor, to focus as he wished on aspects of physics, philosophy, and technology that were of greatest interest to him personally. He continued his lifelong interest in the mathematical foundations of quantum mechanics with particular reference to the conclusions that could be drawn using the powerful techniques derived from group theory. Moreover, the gradual lightening of responsibilities as he approached retirement gave him the time to prepare the first edition of his collection of philosophical essays *Symmetries and Reflections*.[2] The increased freedom also permitted him to become more deeply involved in international meetings where broad issues related to science were discussed. This included, for example, the annual meetings of Nobel Prize recipients at a private estate on Lake Constance. He also became the leader of free-ranging philosophical discussion groups that met more or less annually under the auspices of the Unification Church.

To retain a link with the teaching side of academic life, he accepted appointments as visiting professor and lecturer at several institutions. Among the most prominent were a series of appointments in the physics department of the State University of Louisiana at Baton Rouge and in the summer school at Erice in Sicily.

He retained close consulting and working relations with his former colleagues at the Oak Ridge National Laboratory with special emphasis on research devoted to means of providing protection to civilians in the event of nuclear war. Linked to this, he devoted much attention to the work of the Federal Emergency Management Agency, which is responsible for preventing and providing emergency aid for national disasters.

Once signs of increasing personal and political freedom began to appear in his native Hungary, he resumed relationships with the cultural and scientific leaders there and encouraged the expansion of freedoms. In the process, he became something in the nature of a Hungarian national hero.

Wigner's vital forces began to display attrition for the first time only when he was well into his eighties, the principal sign being partial, but significant memory loss. He no longer traveled without a companion. Remarkably enough, he retained a fairly complete and detailed memory of matters related to science and technology long after he encountered difficulties in other areas.

In summary, Wigner laid the foundations for the application of symmetry principles to quantum mechanics, an achievement for which he earned the Nobel Prize. Based on these foundations, symmetry has come to play a central role in the development of physics during the second half of this century, granting that the developments have gone considerably beyond Wigner's own work. He was fond of symmetries, such as rotations in which observations remain unchanged when the symmetry transformation is applied uniformly to everything. He usually worked with quantum mechanical systems possessing a finite number of degrees of freedom in which the ground states exhibit the full symmetry of the physical system. In contrast, the ground state can be asymmetric in systems having an infinite number of degrees of freedom (that is, the symmetry is broken spontaneously). Theories involving spontaneously broken symmetries now underlie the description of magnetism, superconductivity, unified electroweak interactions, and many of the concepts employed in attempting to develop theories that will provide further unified understanding of the forces between fundamental particles. Posterity will long remember Wigner for giving powerful new tools to the theoretical physicist, as well as for his comparably basic work on the development of nuclear reactors.

Lise Meitner 1878-1968

Some Important Contributions

Discovered the process of nuclear disintegration called nuclear fission, with O. Hahn and F. Strassmann.

Named the process fission and gave its physical explanation, with O. R. Frisch.

Discovered element 91, protactinium, with O. Hahn.

Confirmed, with W. Orthmann, Chadwick and Ellis' observations of the continuous energy spectrum in nuclear beta decay which led Wolfgang Pauli to propose the existence of the neutrino. Recent developments.

Measured absorption of short wave length gamma rays and found agreement with the Klein-Nishina formula, witn H. H. Hupfield.

Described the process now known as internal conversion (decay electron directly ejecting a K electron) and discovered the radiationles transition now known as the Auger effect in 1923; see below where the paper describing this discovery is referenced. Auger independently discovered the effect in 1925.

Some Important Publications

O. Hahn and F. Strassmann, "Uber den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittel Neutronen enstehenden Erdalkalimetalle," *Die Naturwissenschaften* 27:11 (1939). Meitner does not appear as an author of this paper because, being a Jewish woman, she fled Berlin July 13, 1938 to escape Nazi persecution.

"Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction," *Nature* 143: 239 (1939) with O. R. Frisch.

"Products of the Fission of the Uranium Nucleus," *Nature* 143: 471 (1939) with O. R. Frisch and "New Products of the Fission of the Thorium Nucleus," *Nature* 143: 637 (1939) with O. R. Frisch.

"Die Muttersubstanz des Actiniums, ein neues radioaktives Element von langer Lebensdauer," *Physikalische Zeitschrift* 19: 208 (1918) with O. Hahn.

"Uber eine absolute Bestimmung der Energie der primaren beta -Strahlen von Radium E," *Z. Phys.* 60:143 (1930) with W. Orthmann.

"Uber das Absorptiongesetz fur kurzwellige gamma-Strahlung," *Z. Phys.* 67: 147 (1930) with H. H. Hupfield.

"Das beta-Strahlenspektrum von UX1 und seine Deutung," *Z. Phys.* 17: 54-66 (1923).

Some Honors

Element 109 named "Meitnerium" in 1992.

Foreign member, Swedish Academy of Science; elected 1945.

"Woman of the Year," Women's National Press Club, Washington, D.C. 1946.

Foreign Member, The Royal Society of London.

Leibniz Medal, Berlin Academy of Sciences, 1924.

Lieben Prize, Vienna Academy of Sciences, 1925.

Ellen Richards Prize, Association to Aid Women Scientists, 1928.

Prize for Science and Art, City of Vienna, 1947.

Max Planck Medal, German Physics Society, 1949.

Member of the Ordre pour le Merite, Civilian Class (W. Germany), 1957.

Schlozer Medal, University of Göttingen 1962.

Enrico Fermi Prize, Atomic Energy Commission (U.S.) with Hahn and Strassmann 1966.

Member of the Academies of Berlin, Copenhagen, Gothenburg, Goettingen, Halle, Oslo, Stockholm, and Vienna. [bmfrs1970of]

Honorary doctorates from Adelphi College, University of Rochester, Rutgers University, Smith College, and the University of Stockholm. [bmfrs1970of]

Otto Hahn Prize, 1954. [bmfrs1970of]

Jobs/Positions

1907-12 unpaid researcher, Chemical Institute, Berlin

1912-15 *Assisent* to Max Planck (first paid position), University of Berlin

1912-13 unpaid "guest", Kaiser-Wilhelm Institute fur Chemie (KWI), Berlin-Dahlem

1913-18 *Mitglied*, KWI, Berlin-Dahlem

1918-38 Head, Radiophysics Department, KWI, Berlin-Dahlem

1921 Visiting Professor, University of Lund, Sweden

1922 *Dozentur*, University of Berlin

1926 *Nichtbeamteter Ausserordentlicher Professor*, University of Berlin

1938-47 Nobel Institute for Experimental Physics, Sweden (Meitner was paid a "very modest stipend" from the Royal Swedish Academy of Sciences, but was not given an official title.) [96 RLS].

1946 Visiting Professor, Catholic University of America, Washington D.C.

1947-60 Research Professor, Royal Institute of Technology (KTH), Sweden

Education

Ph.D. University of Vienna 1905

References consulted

[1 CLH], [1Y N20], [7 MWR1], [11 EY1], [12A GKS], [17 MWR2], [26 SBM], [27 LDO], [37B TO], [96 RLS], [dosb1980of], [bmfrs1970of], [pt1960lm]

Additional Information/Comments

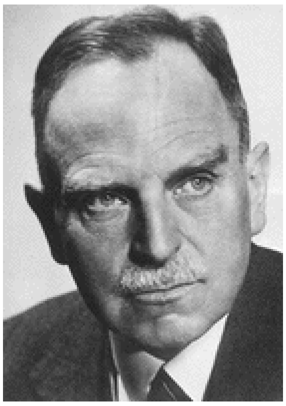
Meitner was the first woman physics professor in Germany.

Early in Meitner's career, an editor of the German encyclopedia *Brockhaus* asked her to submit an article on radioactivity. Meitner had already published several articles by that time, but went only by her last name. In her response to *Brochhaus*, however, Meitner included her first name as well. The editor replied, in Meitner's own words, that "he would not think of printing an article written by a woman" [pt1960lm].

From 1914 to 1916, Meitner volunteered as an x-ray nurse-technician in the Austrian army. She and Hahn often coordinated their leaves so that they could return to their lab and continue the search for protactinium.

Meitner may have been ahead of her time in the careful handling of radioactive substances. Ruth Sime described her rigid laboratory protocol as follows: "Chemical experiments and physical measurements were confined to separate rooms; people handling radioactive substances were required to follow uniform procedures... a roll of toilet paper hung next to the telephones and every door handle--and [people could] sit only on specially marked yellow chairs. No one ever shook hands in greeting, a suspension of the usual rules of German etiquette... Meitner was known for being especially strict and for insisting that strong activities be kept out of her physics section... Her precautions were effective: twenty-five years later her section could still be used for studying very weak activities

Otto Hahn – Biography



Otto Hahn was born on 8th March, 1879, at Frankfurt-on-Main. He attended the secondary high school there until he matriculated.

From 1897 Hahn studied chemistry at Marburg and Munich, taking his doctorate examination in 1901 at Marburg and submitting to Professor Theodor Zincke a thesis on organic chemistry.

He obtained a post as assistant in the Chemical Institute at Marburg, staying there two years, after which he worked under Sir William Ramsay at University College, London, from the autumn of 1904 to the following summer. His work here was rewarded by the discovery of a new radioactive substance, radiothorium, while working on the preparation of pure radium salts.

From the autumn of 1905 to the summer of the following year Hahn was at the Physical Institute of McGill University, Montreal (Canada) working under Professor Ernest Rutherford. Here he discovered radioactinium and conducted investigations with Rutherford on alpha-rays of radiothorium and radioactinium.

On his return to Europe Hahn moved to Berlin, to the Chemical Institute (Emil Fischer) of the University and there he qualified as a university lecturer in the spring of 1907, which year also saw his discovery of mesothorium.

At the end of 1907, Dr. Lise Meitner came to Berlin from Vienna and then began more than thirty years' collaboration. Their joint work embraced: investigations on beta-rays, their absorbability, magnetic spectra, etc.; use of the radioactive recoil, discovered shortly before by Hahn, to obtain new radioactive transformation products.

Between 1914 and 1918 Hahn's work was interrupted by his service in the First World War, but he resumed his research with Professor Meitner in 1918, and discovered protactinium, the long-lived mother substance of the actinium series. Hahn's own particular sphere was chemistry and he further discovered uranium Z, the first case of a nuclear isomerism of radioactive kinds of atoms. Using radioactive methods he investigated the absorption and precipitation of the smallest quantities of substances, normal and abnormal formation of crystals, etc. Hahn used the emanation method to test substances superficially rich or poor, and he elaborated the strontium method to determine the age of geological periods.

Following the discovery of artificial radioactivity by M and Mme. Joliot-Curie and the use of neutrons by Fermi for atomic nuclear processes, Hahn again collaborated with Professor Meitner and afterwards with Dr. Strassmann on the processes of irradiating uranium and thorium with neutrons.

Hahn and Prof. Meitner had also worked together on the discovery of an artificially active uranium isotope, which represents the basic substance of the elements neptunium and plutonium, first revealed later in America.

Hahn's work has won recognition in many learned circles. In 1912 he became scientific member of the Kaiser Wilhelm Institute for Chemistry and has been Director of this Institute since 1928. 1933 saw his appointment as Visiting Professor at Cornell University, Ithaca, New York. From 1st April, 1946, he has officiated as President of the Kaiser Wilhelm Society and from 28th February, 1948, has served as President of the Max Planck Society in Western Germany, being created Honorary President of the same Society in May, 1960.

His most spectacular discovery came at the end of 1938. While working jointly with Dr. Strassmann, Hahn discovered the fission of uranium and thorium in medium heavy atomic nuclei and his first work on these subjects appeared on 6th January and 10th February, 1939, in *Naturwissenschaften*. Since that time and until 1944 Hahn continued investigation on the proof and separation of many elements and kinds of atoms which arise through fission.

Hahn has been granted membership of the Academies of Berlin, Göttingen, Munich, Halle, Stockholm, Vienna, Boston, Madrid, Helsinki, Lisbon, Mainz, Rome (Vatican), Allahabad, Copenhagen, and the Indian Academy of Sciences.

In 1913 Hahn married Edith, *née* Junghans and they had one son, Hanno, born in 1922, killed by accident in 1960.

Fritz Strassmann (1902 - 1980)

Fritz Strassmann was born on February 22, 1902, in Boppard, Germany. He earned his Ph.D. from the Technical University of Hannover in 1929. In 1934, he joined Otto Hahn and Lise Meitner in their investigation of the bombardment of uranium with neutrons. His expertise in analytical chemistry was contributed to the team's recognition of the lighter elements produced from neutron bombardment. He replaced Lise Meitner, who had to flee Nazi Germany, and in 1938, Hahn and Strassmann conducted experiments that proved nuclear fission.

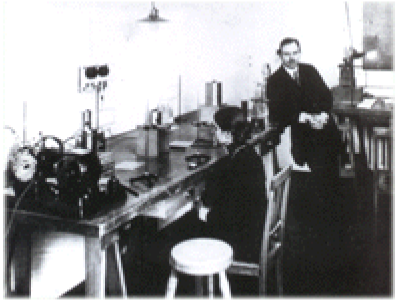
Strassmann later worked at the Kaiser Wilhelm Institute and, from 1945 to 1953, was director of the chemistry department at the Max Planck Institute. In 1946, Strassmann became professor of inorganic and nuclear chemistry at the University of Mainz, where he established the Institute of Inorganic Chemistry (later the Institute of Nuclear Chemistry).

Strassmann was on the ALSOS list, the Manhattan Project's military intelligence effort to capture known, enemy nuclear scientists in an attempt to learn how far Germany had progressed in its efforts to develop a nuclear weapon.

In 1966, for recognition of their work on nuclear fission, Strassmann, Hahn and Meitner shared the Enrico Fermi Award. He died in Mainz on April 22, 1980.

Otto Hahn, Lise Meitner and Fritz Strassmann

In 1938 Otto Hahn (1879–1968), Lise Meitner (1878–1968), and Fritz Strassmann (1902–1980) were the first to recognize that the uranium atom under bombardment by neutrons, actually split.



Lise Meitner and Otto Hahn in their laboratory. 3

With doctorate in hand from the University of Marburg in Germany, Hahn intended to make a career as an industrial chemist in a company with international business connections. He traveled to England to improve his English-language skills and found a job as an assistant in William Ramsay's laboratory at University College, London. Hahn quickly demonstrated his great skill as an experimentalist by isolating radioactive thorium. After working with Ernest Rutherford in Montreal, he joined Emil Fischer's institute at the University of Berlin, where he rose through the faculty ranks.

Otto Hahn 3

Hahn went in search of a collaborator with whom to pursue studies in experimental radioactivity and teamed up with Lise Meitner. She had come to Berlin to attend Max Planck's lectures in theoretical physics after receiving her doctorate in physics from the University of Vienna in 1905—the second doctorate in science from that university granted to a woman. In the first year of the Hahn–Meitner partnership they had to work in a remodeled carpenter's shop because the university did not yet accept women on an official basis. In 1912 their research group was relocated to the new Kaiser Wilhelm Gesellschaft, where Fritz Haber was head of the physical chemistry institute, Hahn was head of the radioactivity institute, and from 1918, Meitner was head of the radioactivity institute's physics department. During World War I, Hahn served in the German gas warfare service headed by Haber, and Meitner volunteered as an X-ray nurse for the Austrian army.

Lise Meitner honored on a postage stamp. 3

The discovery of the neutron by James Chadwick in 1932 gave new impetus to radioactivity studies because this uncharged atomic particle could penetrate the secrets of the atomic nucleus more successfully. Meitner, Hahn, and another chemist, Fritz Strassmann, who had worked with the partners since 1929, were deeply involved in identifying the products of neutron bombardment of uranium and their decay patterns. It was generally expected that elements close in atomic number—quite possibly elements with higher atomic numbers than uranium—would be produced. In 1938 Meitner had to leave Berlin because the Nazis were closing in on all people of Jewish ancestry. She soon found a congenial setting for her research at the Nobel

Institute in Stockholm. Her nephew, the physicist Otto Frisch, was located at Niels Bohr's institute in Copenhagen. Meanwhile, Hahn and Strassmann found that they had unexpectedly produced barium, a much lighter element than uranium, and they reported this news to Meitner. She and her nephew worked out the physics calculations of

Meitner's laboratory benchtop. [3]

the phenomenon based on Bohr's "droplet" model of the nucleus and clearly stated that nuclear fission of uranium had occurred. It was quickly recognized that barium was among the stable isotopes that were the products of the radioactive decay of transuranic elements that must have been initially formed after neutron bombardment of uranium. News of the splitting of the atom and its awesome possibilities was brought by Bohr to scientists in the United States and ultimately resulted in the Manhattan Project.

Neither Hahn, Meitner, nor Strassmann engaged in nuclear weapons research during World War II. At the end of the war Hahn was astonished to hear that he had won the Nobel Prize for chemistry in 1944 and that nuclear bombs had been developed from his basic discovery. Later, as director of the Max Planck Gesellschaft (the postwar successor to the Kaiser Wilhelm Gesellschaft), he spoke vigorously against the misuse of atomic energy. Meitner—who many thought should have received the Nobel Prize with Hahn—continued to do nuclear research in Sweden and then England. Strassmann nurtured the study of nuclear chemistry in Mainz, Germany.

Fritz Strassmann [3]

HISTORY OF THE NUCLEAR FISSION

Enrico Fermi of Italy—Nobel Prize winner and famous for creating the world's first nuclear chain reaction. Arthur Holly Compton of the United States—Nobel Prize winner famous for his discoveries about electrons and cosmic rays. Niels Bohr of Denmark—Nobel Prize winner famous for his insights into the structure of atoms. Otto Hahn of Germany—Nobel Prize winner famous for his discovery of nuclear fission.

The list continues: Einstein of Germany, Curie and Joliot of France, Meitner and Frisch of Austria, Wheeler and Alvarez of the United States. Most of them winners of the Nobel Prize; all of them superb scientists. An international community, joined in an effort to answer an ancient question—how does matter behave? A community that in 1939 came to focus on one narrow question—what happens to a uranium atom when a neutron hits it?

In the audio you can listen to these illustrious men and women describe the historic events which brought them to understand nuclear fission. You will not be listening to actors but to the people who actually made history.

This is a first-person account. It is not a physics lesson; you should not expect to learn all about the physics of nuclear fission. What you *can* expect is a better understanding of how science is done. This exhibit gives a glimpse into the scientific process, the lives of some renowned individuals involved in that process, and their role in solving a particular problem. As you listen and read, you will hear them describe themselves—their frustrations, their successes, their prejudices, their world view. They tell of how they related to science as human beings.

Can atoms be split apart? Does each atom have inner workings? Parts which can be separated? Parts which can perhaps be put to some use? These questions had already come to mind in 1898, when J. J. Thomson isolated the electron. That was the first solid proof that atoms are indeed built of much tinier pieces. Thomson speaks of the electron in this recorded passage...

Thomson: Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen, which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science.

Ideas about the atom were refined by one of Thomson's students, Ernest Rutherford. He showed that the mass in an atom is not smeared out uniformly throughout the atom, but is concentrated in a tiny, inner kernel: the nucleus. Rutherford wanted to understand the nucleus, not for any practical purpose, but because he was attracted to the beauty of its simplicity. Fundamental things should be simple not complex. Here is how he explains himself in 1931...

RUTHERFORD: The bother is that a nucleus, as you know, is a very small thing, and we know very little about it. Now, I had the opinion for a long time, that's a personal conviction, that if we knew more about the nucleus, we'd find it was a much simpler thing than we suppose, that these fundamental things I think have

got to be fairly simple. But it's the non-fundamental things that are very complex usually. I am always a believer in simplicity being a simple person myself.

A young man working with Rutherford in 1911 was Niels Bohr. They created a halfway successful model of the atom called the Rutheford-Bohr model. They imagined a nucleus at the center with electrons orbiting around it. Twenty-five years later, Bohr described his collaboration with Rutherford...

BOHR: If, twenty-five years ago, I had the good fortune to give a modest contribution to this development, it was, above all, thanks to the hospitality I then, as a young man, enjoyed in the famous laboratories of England. In particular, I think with grateful emotion of the unique friendliness and straightforwardness with which Rutherford, in the midst of his unceasing creative activity, was always prepared to listen to any student behind whose youthful inexperience he perceived a serious interest.

To Bohr, studying the atom was a friendly pursuit of truth. The public was not so sure. Rutherford and other scientists had already happened to notice that energy is intensely concentrated within the nucleus. Newpapers began to talk about the chances of unlocking that energy. Reporters said atoms might run the world's industry someday, after our supply of coal and oil ran out. On the other hand, H. G. Wells wrote a novel featuring atomic bombs. The *St. Louis Post-Dispatch* in 1903 describes atomic energy...

Most physicists ignored that sort of wild journalism. All they wanted was to get a better picture of the nucleus. One big step came in 1932, when Cockcroft and Walton, in Rutherford's laboratory, built a machine that could shoot a beam of protons at very high speeds. They fired protons, like bullets, into metal targets. The collisions transformed some of the nuclei in the target atoms. Some of the atoms' mass was converted into energy. The Cockcroft-Walton experiment demonstrated for the first time a concept that Albert Einstein had proposed almost thirty years earlier. He had theorized that energy and mass are equivalent; they can be converted into one another. Let's hear Einstein tell about it...

EINSTEIN: It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing—a somewhat unfamiliar conception for the average mind. Furthermore, the equation E is equal to mc^2, in which energy is put equal to mass, multiplied with the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally.

The *New York Times* reacted to experiments like those by Cockcroft and Walton with enthusiasm...

***NEWS ARTICLE:** "Science has obtained conclusive proof from recent experiments that the innermost citadel of matter, the nucleus of the atom, can be smashed, yielding tremendous amounts of energy and probably vast new stores of gold, radium and other valuable minerals."*

But the Cockcroft-Walton work—and every other nuclear physics experiment during the thirties—used up far more energy than it released. So physicists doubted that nuclear energy could be put to practical use anytime soon, if ever. Rutherford made this opinion public in 1933 at a scientific meeting, and his remarks were published in the scientific journal *Nature*:

NEWS ARTICLE: *"These transformations of the atom are of extraordinary interest to scientists but we cannot control atomic energy to an extent which would be of any value commercially, and I believe we are not likely ever to be able to do so... Our interest in the matter is purely scientific, and the experiments which are being carried out will help us to a better understanding of the structure of matter."*

A few physicists were not so sure that nuclear energy could never be controlled. Leo Szilard thought of a possible way to do it. If he could find some sort of nucleus that would emit *two* neutrons whenever it was bombarded with one neutron, he might be able to set off a chain reaction. Szilard wanted to investigate various elements, including uranium. But he was not able to get money to do experiments.

It was only in 1938 that many scientists began to focus their attention on uranium, the heaviest of known elements. Leading the pack were two German chemists, Otto Hahn and Fritz Strassmann. For over thirty years, Hahn had been working with another talented scientist, Lise Meitner. However, Meitner was of Jewish ancestry, and had to flee Nazi Germany. Otto Hahn recalls...

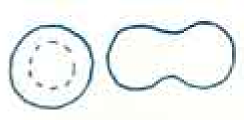
HAHN: Miss Meitner—Professor Meitner—had left our laboratory on July 1938 on account of these Hitler regime things and she had to go to Sweden. And Strassmann and myself, we had to work alone again and in the autumn of '38 we found strange results.

Enrico Fermi had begun this line of work, when he showed that neutrons work better than protons for penetrating and transforming a nucleus. By 1938, Hahn and Strassmann were among a number of scientists who were trying to find out what products are formed if you shoot neutrons into heavy elements. They hoped to find elements even heavier than uranium. Such altogether new elements would surely have scientific interest, and perhaps even practical uses. But the substances Hahn and Strassmann produced looked like radium or barium, two known and almost chemically identical elements...

HAHN: We made precipitations, Strassmann and myself, where we could be absolutely sure that there could be nothing else but either radium or barium.

But physicists did not suppose a heavy element like uranium could be transformed into a light element like barium. You might be able to knock off four protons from the nucleus of the uranium atom and create radium. But to get from uranium to barium, the neutron would have to chip off 100 particles! That seemed flatly impossible. Barium was out of the question...

HAHN: Therefore, we could conclude that the substances could be really only



radium because barium was prohibited by the physicists that we didn't dare to think it barium in those times. We always tried to explain what is wrong in our experiments, not to say we do have barium, but we always thought it can't be there and therefore we have to say, "What is the nonsense we are doing?" So really, it is so, that we poor chemists—isn't it the same with you?—we are so afraid of these physics people.

Hahn wrote to Meitner in December of 1938 describing the "strange results" he and Strassmann had found. Meitner was equally baffled—at first. Later that month, shortly before Christmas, her nephew Otto Frisch visited her in Sweden. Frisch was a physicist who worked at Niels Bohr's famous Institute for Theoretical Physics in Denmark. Years later, Frisch recalled his visit to Meitner in December of 1938...

FRISCH: Lise Meitner was in Sweden and was lonely so I offered to come and visit her, and we met in the west of Sweden in a small place near Goteborg, and when I came she was brooding over a letter of Hahn. And then we sort of kept rolling this thing around and saying, "Barium, I don't believe it. There's some mistake. You couldn't chip a hundred particles off a nucleus in one blow. It's fantastic. It's quite impossible, a single neutron could do that." And I still don't know how we got to the concept of fission, but I remember Lise Meitner drawing a dotted circle on a piece of paper and saying, "Couldn't it be this sort of thing?" Now she always rather suffered from an inability to visualize things in three dimensions, whereas I had that ability quite well. And I had, in fact, apparently come around to the same idea, and I drew a shape like a circle squashed in at two opposite points. And Lise Meitner then said, "Well, yes, that is what I mean. " Apparently she had, so to say, looked at the nucleus from the poles on, and with the dotted line was indicating the equator being pushed inwards.

Meitner and her nephew continued their discussion outdoors...

FRISCH: We walked up and down in the snow. I was wearing skis and she said probably she could get along just as fast on her feet, which she did, and gradually we came to the idea that perhaps one should not think of the nucleus being cleaved in half as with a chisel but rather that perhaps there was something in Bohr's idea that the nucleus was like a liquid drop.

Now Meitner and Frisch understood what had happened in Hahn and Strassmann's experiment. The neutrons which they had shot into uranium had indeed been captured by the uranium nucleus. But then the nucleus changed shape, vibrated, and came apart entirely. This was not the usual slight transformation of a nucleus. The picture did fit neatly with a recent theory of Niels Bohr's. He believed that a nucleus behaves like a liquid drop, and a liquid drop hit hard enough, might stretch until it broke in two. Now, if that happened to a nucleus, a lot of energy would be released—atom for atom, far more energy than any process seen till then. Frisch continues the story of his visit...

FRISCH: I think I stayed there for about another day or so. We had Christmas dinner with some Swedish friends, and we discussed a few details. We agreed that

we would have to write a paper about this, but we left it to be done separately somehow. It was eventually done in the way that I drafted a paper and read it off to Lise Meitner over the long-distance telephone between Copenhagen and Stockholm, and she would stop me and make comments and suggestions. So it was a slightly expensive way of writing a paper.

My recollection is that when I came back to Copenhagen I found Bohr just on the point of parting, of leaving for America, and I just managed to catch him for five minutes and tell him what we had done. And I hadn't spoken for half a minute when he struck his head with his fist and said, "Oh, what idiots we have been that we haven't seen that before. Of course this is exactly as it must be." And he added, "This is very beautiful," and, had we written a paper? So I said no, we were in the process of writing one.

On his way to America by ocean liner, Bohr developed a more complete explanation of fission. He worked with a colleague, Leon Rosenfeld, who was making the trip with him. Rosenfeld later recalled their efforts...

ROSENFELD: When we met on the boat, he said, "I have in my pocket a paper that Frisch has given me which contains a tremendous new discovery, but I don't yet understand it. We must look at it." Bohr accepted the conclusions because it was an argument directly following from the experiments. But he did not understand why the nucleus would split. And then during the trip that took six days, I suppose or so, he got hold of the solution, and it turned out to be extremely simple.

Meanwhile, back in Denmark, Frisch wanted to check by experiment the idea that uranium can split in two. Several methods could be used to study sub-atomic particles. The easiest was to look at electrical effects in an ionization chamber, using an amplifier and oscilloscope. Invisible particles passing through the chamber would show up as pulses on the screen of the oscilloscope. The hallmark of fission would be the size of the pulses: the two halves of a split atom would have far greater energy than any known particle. Frisch describes his work...

FRISCH: I rigged up a pulse amplifier for the special purpose, and I also built a small ionization chamber; but the whole thing only took me about two days, and then I worked most of the night through to do the measurements because the counting rates were very low. But by three in the morning I had the evidence of the big pulses. And I went to bed at three in the morning, and then at seven in the morning I was knocked out of bed by the postman who brought a telegram to say that my father had been released from concentration camp.

By this time Frisch and Meitner had finished writing their joint paper, in which they interpreted the Hahn-Strassmann results as nuclear fission. Frisch meanwhile wrote a second paper about his new experiments which confirmed their guess...

FRISCH: They were both sent to *Nature* at the same day but *Nature* published one after the other. And I might still mention that the word "fission" occurs in the first

paper and was suggested to me by an American biologist, William A. Arnold, whom I asked what you call it when a cell divides itself.

On the same day that Frisch sent his two scientific papers on fission out for publication—January 16, 1939—Niels Bohr's ocean liner docked in New York. Enrico Fermi was on the pier to meet him. The Italian physicist had arrived in New York two weeks earlier. The Fascist government had allowed him to leave Italy to personally accept the Nobel Prize in Stockholm. Fermi, whose wife was of Jewish ancestry, had decided not to return, but to instead take a post at Columbia University. The next day Bohr came up to Columbia, and there he happened to run into Herbert Anderson, a physics graduate student. Anderson never forgot the meeting...

ANDERSON: Bohr came to Columbia and he was looking for Fermi, and as he walked into one of the laboratories, expecting to see Fermi there, he didn't find Fermi, but he found me. And, although he didn't know who I was, he was so full of his news, that he grabbed me by the shoulder and he said, "Listen, young man, I want to tell you about something that's very important, that's recently happened in physics." Bohr doesn't speak very loud, he whispers, you see. He has to get very close to you, then he whispers in your ear, and he said, "Let me tell you about fission." And so, of course, I was overwhelmed by having such a great man pick me out of everybody and tell me, give me this news, almost for the first time. And so he began to explain about fission, and about how neutrons are captured in uranium, and how the thing got excited and then came apart. And released a lot of energy. Well then he had to leave and so he left.

Anderson went to Fermi's office to tell him that Bohr was looking for him. But Fermi had already heard the news. Anderson continues the story...

ANDERSON: And Fermi said, "Oh, he says, I know. Let me explain to you about fission." So he went to the board and he began to show me. But of course, Fermi is much more vivid, and much clearer and I could always understand him much better. He was evidently very interested in this thing. I decided then and there that this is a very exciting subject and just right—maybe I could get a thesis out of it, which is all graduate students think about. I realized that Fermi had just arrived and that although he had achieved considerable fame as a theoretical physicist, I somehow had the idea that his first love was really experimental physics and it seemed to me at the time that what he really needed was a laboratory, some equipment and a good graduate student, and I had all three.

Anderson and Fermi made a sort of agreement...

ANDERSON: I would teach him about Americanisms and he would teach me physics and I would lend him the apparatus and we would work together. Well, you know, things weren't very hard to do in those days. So he says, "Why don't we get the electrode of your ionization chamber, put some uranium on it, let's go down to the cyclotron, and let's see if we can see all this energy release." And so we got busy just that afternoon. But there was a meeting, a theoretical physics meeting in Washington, the next day. And Fermi was supposed to go to that. And so he left and I began to wonder what to do and I remembered that Dunning was in and I came to Dunning, and I said, "Why don't we see if we can see this fission?"

John Dunning was a physics professor who Anderson had been working with already. Dunning remembers...

DUNNING: I went up to the 13th floor and brought down one of the old standard stand-by neutron sources, the radon plus berylium sources that had been used so much before. We put it next to the chamber containing the uranium and in considerable excitement we saw with even this very weak source about one big pulse, a huge pulse, on the oscilloscope every minute. The rate, however, was so slow that I had doubts whether this was really real or whether it was maybe a bad electrical contact. So we had another device, and installing that right next to the chamber, the rate went up according to my notes to something like seven or so with that device, huge pulses. We finally quit about 11 p.m. My notebook contains this phrase: "Believe we have observed new phenomenon of far reaching consequences."

Meanwhile Bohr and Fermi went to the theoretical physics conference in Washington, DC. One physicist in close touch with Bohr was John Wheeler.

WHEELER: Bohr felt that he owed it as a responsibility to Frisch and Meitner that word of their work-in-progress and their concepts should not really be released until they had had the proper scientific opportunity to publish it. And it was not until the second day of the conference that an issue of *Die Naturwissenschaften* was handed to him which had just come in, which had the work of Hahn and Strassmann; so then he could tell about it. And then of course everybody got started on the experiments.

Not only scientists, but also science reporters picked up the news. Across the continent in Berkeley, California, physics professor Luis Alvarez was particularly interested to hear of the discovery...

ALVAREZ: I remember exactly how I heard about it. I was sitting in the barber chair in Stevens Union having my hair cut, reading the *Chronicle*, and in the second section, buried away some place, was an announcement that some German chemists had found that the uranium atom split into pieces when it was bombarded with neutrons—that's all there was to it. So I remember telling the barber to stop cutting my hair and I got right out of the barber chair and ran as fast as I could up to the Radiation Laboratory. And my student, Phil Abelson, had been working very hard to try and find out what transuranium elements were produced when neutrons hit uranium. And he was so close to discovering fission that it was almost pitiful. I mean, he would have been there, guaranteed, in another few weeks—when I arrived panting from the Student Union with my news about fission, and I played it kind of dramatically. I saw Phil there and I said, "Phil, I've got something to tell you but I want you to lie down first." So, he lay on the table (right alongside the control room of the cyclotron). "Phil, what you are looking for are not transuranium elements, but they are elements in the middle of the periodic table." I showed him what was in the *Chronicle*, and, of course, he was terribly depressed.

Hahn and Strassmann's paper arrived in Paris at the laboratory of Frederic Joliot. With his wife, Irene Curie, Joliot had made important nuclear discoveries. Lew Kowarski was in the laboratory, and remembers Joliot's reaction to the paper...

KOWARSKI: It was on the 16th of January, and *Naturwissenschaften*, the famous number, arrived in the morning mail. Joliot probably had his first glimpse of the Hahn and Strassmann article in my presence, and it was, of course, a bombshell.

Don't forget that Kowarski is describing Joliot's reaction to the Hahn-Strassmann experiments; the Paris group had not yet heard how Frisch and Meitner had explained the strange results, in terms of uranium fission. But Joliot followed an almost identical path, as Kowarski explains...

KOWARSKI: Immediately, everything was understood. For the next few days, nobody talked of anything else. Joliot immediately had the ideas about splitting of the uranium atom in two. Then he designed his famous experiment, which is, I think, one of the most elegant experiments I know of in the history of science, and which he performed before my eyes. It was that simple, took a few days. So here it was. Fission was proved as physical reality. We still didn't know that Frisch had already observed it two weeks before.

Within weeks, the whole world knew about fission. Speculation about the vast stores of energy in the nucleus prompted a *New York Times* editorial in February 1939...

"The possibility of harnessing the energy of the atom crops up again. Rutherford...and other distinguished physicists did their best in late years to discourage speculations on the subject, because bombardment was so inefficient that more energy was expended on the atom than ever came out of it. Now the picture is changed... Romancers have a legitimate excuse for returning to Wellsian utopias where whole cities are illuminated by energy in a little matter."

As soon as they realized that atoms can be split, physicists began to talk over the possible consequences. John Dunning recalls...

DUNNING: I well remember that on January 25, 1939 there was a session at the faculty club at Columbia around the lunch table. Bohr had been talking very enthusiastically about fission possibilities in Princeton and it seemed clear that this had to be really got at. Immediately, the question arises as an experimentalist, not a theorist, shouldn't there be secondary neutrons created? Or evaporated? If there were enough of these, then the long-sought-for key to a self-sustaining nuclear energy release might indeed be here. World War II was pretty clearly in the offing at that time and all of us recognized the far-reaching consequences that might be possible if fission could really be developed.

Being able to split uranium did not necessarily mean you could get a chain reaction and release a lot of energy. That question had to be answered before anything else. It was exactly the question that Leo Szilard had been asking for years. Now Szilard was in

New York, another refugee from Fascism, and he was urging people to attack the problem. Herbert Anderson recalls...

ANDERSON: Well, Fermi came back and the first thing he did when he came back to Columbia, was he got hold of me, took me in the office, and then began to write down on the blackboard all the experiments we ought to do. And, of course, the thing that was the most important, if you were going to make a chain reaction, is to make sure that neutrons come out. Of course, so far all that was known is that a lot of energy is released. But Szilard had already pointed out that to make a chain reaction you had to have more neutrons emitted than were absorbed. But, of course, Fermi realized that the two fragments of the fission would be very heavily neutron rich and it was quite likely that there would be some extra neutrons boiled off in the process. And so, he immediately designed an experiment which he wanted me to do with him to see where the neutrons were emitted. And so, we launched on a career of trying first of all to see whether neutrons were emitted and in what number. Experiments were also being done (in fact, they always seemed to be about a week or so ahead of us) by Joliot, Halban and Kowarski working in Paris.

The Paris team, like Fermi, knew that a chain reaction would come only on one condition: if each uranium atom, when it split, spat out fresh neutrons. Joliot asked Kowarski to try to think of a way to detect them...

KOWARSKI: I went home for lunch. And here is one of those classical cases when scientists describe how they got ideas. I perfectly remember which place on what street it was that I had the idea. The idea seemed so stupidly simple. If you observe any neutrons of higher energy, that proves it. It's rather elementary.

The Paris and New York teams both found that neutrons do come out from split uranium atoms. Yes, a chain reaction was possible. Now the basic nuclear physics was in hand, and people could begin to ponder what to do with it. Over three years later, beneath the bleachers of the football stadium at the University of Chicago, Fermi led a team of physicists who released the first chain reaction. The physicist in charge at Chicago was Arthur Holly Compton. Here is his description of this historical moment...

COMPTON: We entered the balcony at one end of the room. On the balcony a dozen scientists were watching the instruments and handling the controls. Across the room was a large cubical pile of graphite and uranium blocks in which we hoped the atomic chain reaction would develop. Inserted into openings in this pile of blocks were control and safety rods. After a few preliminary tests, Fermi gave the order to withdraw the control rod another foot. We knew that that was going to be the real test. The geiger counters registering the neutrons from the reactor began to click faster and faster till their sound became a rattle. The reaction grew until there might be danger from the radiation up on the platform where we were standing. "Throw in the safety rods," came Fermi's order. The rattle of the counters fell to a slow series of clicks. For the first time, atomic power had been released. It had been controlled and stopped. Somebody handed Fermi a bottle of Italian wine and a little cheer went up. One of the things that I shall not forget is

the expressions on the faces of some of the men. There was Fermi's face—one saw in him no sign of elation. The experiment had worked just as he had expected and that was that. But I remember best of all the face of Crawford Greenewalt. His eyes were shining. He had seen a miracle, and a miracle it was indeed. The dawn of a new age. As we walked back across the campus, he talked of his vision: endless supplies of power to turn the wheels of industry, new research techniques that would enrich the life of man, vast new possibilities yet hidden.

Leo Szilard recalled...

SZILARD: There was a crowd there and when it dispersed, Fermi and I stayed there alone. Enrico Fermi and I remained. I shook hands with Fermi and I said that I thought this day would go down as a black day in the history of mankind. I was quite aware of the dangers. Not because I am so wise but because I have read a book written by H. G. Wells called *The World Set Free*. He wrote this before the First World War and described in it the development of atomic bombs, and the war fought by atomic bombs. So I was aware of these things. But I was also aware of the fact that something had to be done if the Germans get the bomb before we have it. They had knowledge. They had the people to do it and would have forced us to surrender if we didn't have bombs also. We had no choice, or we *thought* we had no choice.

Enrico Fermi in 1952 summed up the feelings of all people today...

FERMI: It was our hope during the war years that with the end of the war, the emphasis would be shifted from weapons to the development of these peaceful aims. Unfortunately, it appears that the end of the war really has not brought peace. We all hope as time goes on that it may become possible to devote more and more activity to peaceful purposes and less and less to the production of weapons.

Additional Reading and Links

Unless otherwise noted, the level is appropriate for middle-school students and above.

Web Sites

Students and teachers can find a wealth of related materials on the Web. An investigation of what is available may include searches for:

- Names of the scientists involved: Meitner, Hahn, Strassman, Bohr, etc.
- Nobel speeches of Fermi, Compton, Einstein, Bohr, Hahn, Curie, etc.
- Key words: Nuclear fission, transmutation

Alsos History of Fission
An excellent scientific review, mainly 1932-1945.

Nuclear Chemistry and the Discovery of Fission
The story of the 1938 work, especially the chemical side. Site includes other nuclear chemistry (neutron,

plutonium, etc.) and an instructor's guide.

Trinity Nuclear Weapons History
Online archive of documents, mainly from 1945 forward

Los Alamos Lab History

Fission Movie *(QuickTime animation)*

Federation of American Scientists
Founded by atomic scientists in 1946, the FAS provides a gateway to current nuclear arms issues.

Alsos Digital Library for Nuclear Issues and its items relating to fission
Large annotated list of books, Websites and other materials.

History of Physics Syllabi
Includes reading lists for courses on 20th-century physics and nuclear affairs.

More History of Physics Exhibits
Award-winning exhibits on Einstein, M. Curie, W. Heisenberg, E.O. Lawrence, Andrei Sakharov and other pioneers.

More History of Physics Links *from the Center for History of Physics*

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

Lise Meitner and O.R. Frisch

Nature, **143,** 239-240, (Feb. 11, 1939)

On bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behavior together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar properties to those of osmium was assumed to be eka-osmium (Z = 94) rather than osmium (z = 76) or ruthenium (z = 44).

Following up an observation of Curie and Savitch[3], Hahn and Strassmann[4] found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation[5], however showed that it was impossible to separate those bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium* (Z = 56) *are formed as a consequence of the bombardment of uranium* (Z = 92) *with neutrons.*

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission, within a short time, of a large number of charged particles may be regarded as excluded by the small penetrability of the 'Coulomb barrier', indicated by Gamov's theory of alpha decay.

On the basis, however, of present ideas about the behaviour of heavy nuclei[6], an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.

In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension has been used[7] and its value has been estimated from simple considerations regarding nuclear forces. It must be remembered, however, that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of c. 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium[8], the other will be krypton ($Z = 92 - 56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains.

It is possible[8], and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short periods (10 sec. and 40 sec.) so far ascribed to ^{239}U might be masurium isotopes ($Z = 43$) decaying through ruthenium, rhodium, palladium and silver into cadmium.

In all these cases it might not be necessary to assume nuclear isomersim; but the different radioactive periods belonging to the same chemical element may then be attributed to different isotopes of this element, since varying proportions of neutrons may be given to the two parts of the uranium nucleus.

By bombarding thorium with neutrons, activities are which have been ascribed to radium and actinium isotopes[8]. Some of these periods are approximately equal to periods of barium and lanthanum isotopes resulting from the bombardment of uranium. We should therefore like to suggest that these periods are due to a 'fission' of thorium which is like that of uranium and results partly in the same products. Of course, it would be especially interesting if one could obtain one of those products from a light element, for example, by means of neutron capture.

It might be mentioned that the body with the half-life 24 min[2] which was chemically identified with uranium is probably really ^{239}U and goes over into eka-rhenium which appears inactive but may decay slowly, probably with emission of alpha particles. (From inspection of the natural radioactive elements, ^{239}U cannot be expected to give more than one or two beta decays; the long chain of observed decays has always puzzled us.) The formation of this body is a typical resonance process[9]; the compound state must have a life-time of a million times longer than the time it would take the nucleus to divide itself. Perhaps this state corresponds to some highly symmetrical type of motion of nuclear matter which does not favor 'fission' of the nucleus.

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Physical Evidence for the Division of Heavy Nuclei under Neutron Bombardment

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From chemical evidence, Hahn and Strassmann conclude that radioactive barium nuclei (atom number Z = 56) are produced when uranium (Z = 92) is bombarded by neutrons. it has been pointed out that this might be explained as a result of a "fission" of the uranium nucleus, similar to the division of a droplet into two. The energy liberated in such processes was estimated to be about 200 Mev, both from mass defect considerations and from the repulsion of the two nuclei resulting from the "fission" process.

If this picture is correct, one would expect fast-moving nuclei of atomic number 40 to 50 and atomic weight 100 to 150, and up to 100 Mev energy, to emerge from a layer of uranium bombarded with neutrons. In spite of their high energy, these nuclei should have a range in air of a few millimeters only, on account of their high effective charge (estimated to be about 20), which implies very dense ionization. Each such particle should produce a total of about 3 million ion pairs.

By means of a uranium-lined ionization chamber, connected to a linear amplifier, I have succeeded in demonstrating the occurrence of such bursts of ionization. The amplifier was connected to a thyratron which was biased so as to count only pulses corresponding to at least 5×10^5 ion pairs. About 15 particles per minute were recorded when 300 milligram of radium, mixed with beryllium, was placed one centimeter from the uranium lining. No pulses at all were recorded during repeated check runs of several hours total duration when either the neutron source or the uranium lining was removed. With the neutron source at a distance of four centimeters from the uranium lining, surrounding the source with paraffin wax enhanced the effect by a factor of two.

It was checked that the number of pulses depended linearly on the strength of the neutron source; this was done in order to exclude the possibility that the pulses are produced by accidental summation of smaller pulses. When the amplifier was connected to an oscillograph, the large pulses could be seen very distinctly on the background of much smaller pulses due to the alpha particles of uranium.

By varying the bias of the thyratron, the maximum size of pulses was found to correspond to at least 2 million ion pairs, or an energy loss of 70 Mev of the particle within the chamber. Since the longest path of a particle in the chamber was 3 centimeters, and the chamber was filled with hydrogen at atmospheric pressure, the particles must ionize so heavily that they can make 2 million ion pairs on a path equivalent to 0.8 cm of air or less. From this it can be estimated that the ionizing particles must have an atomic weight of at least about seventy, assuming a reasonable connection between atomic weight and effective charge. This seems to be conclusive physical evidence for the breaking up of uranium nuclei into parts of comparable size, as indicated by the experiments of Hahn and Strassmann.

Experiments with thorium instead of uranium gave quite similar results, except that surrounding the neutron source with paraffin did not enhance, but slightly diminished the effect. This gives evidence in favor of the suggestion that also in the case of thorium some, if not all of the activities produced by neutron bombardment, should be ascribed to light elements. it should be remembered that no enhancement by paraffin has been found for the activities produced in thorium, except for one which is isotopic with thorium and is almost certainly produced by simple capture of the neutron.

Prof. Meitner has suggested another interesting experiment. If a metal plate is placed close to a uranium layer bombarded with neutrons, one would expect an active deposit of the light atoms emitted in the "fission" of the uranium to form on the plate. We hope to carry out such experiments, using the powerful source of neutrons which our high-tension apparatus will soon be able to provide.