George Marx[✝]

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The Fermi-Szilárd nuclear reactor

Chadwick discovered the neutron in Rutherford's laboratory in 1932. Nuclear force and nuclear energy surpass chemical energy million times. These are not manifested in everyday life because nuclei, due to their positive electric charge, repel each other. Neutrons, though, are such nuclear particles, which sense the intensive nuclear force but at the same time they are electrically neutral. Consequently, the discovery of the neutron opened up new prospects in physics and technology.

The significance of the discovery of the neutron was recognized by Enrico Fermi, the professor of the University of Rome. He realized neutron-activation within three years: with the help of neutron irradiation the nuclei of otherwise stable elements could be made radioactive. This led to the practical utilization of radioactive tracing, invented by George de Hevesy. Fermi invited Edward Teller also to his laboratory in Rome. His students observed that slow neutrons are more likely captured by nuclei. Fermi also noticed that if uranium is irradiated with neutrons, a series of radioactivity could be observed. He explained this phenomenon by assuming that transuranic nuclei, heavier than uranium had been formed. In 1938 Enrico Fermi was awarded with the Nobel Prize in physics for working out neutron-activation and recognizing the favorable reaction rate of slow neutrons. After receiving the Nobel Prize in Stockholm, he did not return to Italy, because the country was drifting towards fascism that time, but sailed to the United States together with his wife. In New York he became a professor at the University of Columbia.

Otto Hahn intended to clarify the chemical nature of the transuranic elements produced by neutron capture, and he also wished to find their place in the Periodic Table. Germans are precise chemists. When one of the radioactive ”transuranic” elements was examined, it behaved chemically very similarly to barium. This is why Hahn added barium to the sample, then precipitated barium and radium, behaving alike, by using sulfuric acid, and separated the two elements with the help of finer chemistry. Then came the surprise: the new neutron-induced radioactivity remained with the barium! It was Lisa Meitner who explained that

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[✝] This lecture was given by Prof. George Marx (1927-2002) Hungarian physicist on 11th September 2001 at the Italian Embassy in Hungary (Budapest) during the celebration feast of the Fermi centenary. It has been published in Italian, Hungarian and English languages in the booklet containing the celebrating lectures. We reproduce here the English version.

uranium-nucleus which absorbs the neutron, did not become a heavier transuranic element, but split into two, and one of the fragments is the radioactive isotope of barium. Since the binding energy per particle at the middle of the Periodic Table is deeper, fission of heavy nuclei liberates energy.

Atomic fission was discovered in December 1938. Niels Bohr, the Nobel laureate researcher of the atom and the nucleus traveled to America in 1939. He gave lectures in several cities on the new scientific sensation: nuclear fission. He was talking about this same subject in Washington on 26 January 1939 at a conference on theoretical physics organized by Gamow and Teller. His lecture turned the time schedule upside down. After his talk, Bohr, Fermi, and Gamow spent hours at the blackboard with chalk in their hands, discussing how fission takes place. They also repeated the experiment in the neighbouring laboratory, for the first time in the U.S. The event is immortalized on a plaque. The Danish Bohr developed the theory of fission together with the American Wheeler. Their study was published in Physical Review on 1 September 1939. This was the day when the Second World War broke out.

Let us follow another thread of the same story running parallel. At that time Leo Szilárd was living as an emigrant in London. In the morning 11 September 1934 he was reading that day’s The Times in his hotel room which reported Lord Rutherford’s (the discoverer of nucleus) lecture given the previous day. Rutherford described that he had managed to transform nuclei successfully with the help of radioactive particles. During the process occasionally energy was released. The somewhat conservative Lord finished his lecture with a warning: “Occasionally at the transformation of the nucleus energy is released but anyone thinking about the practical use of it is talking moonshine.” Szilárd, however, was a daring mind who was stimulated to thinking the moment when an authority declared that something was impossible. On his way to work, at the corner of Holborn and Southampton Streets he stopped at the red traffic light and started pondering about Rutherford’s statement. When the light turned green, the idea was ready: if the capture of one neutron triggers off nuclear reaction, and from this particular reaction two neutrons are released, then two neutrons induce two further reactions, which will produce four neutrons and so forth. This chain reaction of neutrons makes the release of practical nuclear power possible! (His friends doubted that the discovery happened exactly this way, as it was widely known that Szilárd was never stopped by red traffic lights.)

Szilárd rushed to Lord Rutherford with his idea but the Lord cast the lunatic out right away. Szilárd was trying to convince others to provide him with financial support: he was eager to find the element that makes two neutrons out of one. Chemists, like Chaim Weizmann, the first future president of Israel, and Eugene P. Wigner, future Nobel laureate, knew about chemical chain-reactions (like fire) and took Szilárd's idea seriously. Nevertheless, they were unable to sponsor the experiments. So Szilárd obtained a patent for the idea of neutron chain-reaction under the number 440023 and upon his request it was classified as secret by the British Admiralty. Meanwhile, history was taking turn. Seeing Hitler's ambitions, Szilárd had a presentiment of the upcoming European war and emigrated to America in 1938. There he managed to raise enough money to start his search for n → 2n reaction. He investigated several elements but in vain. He did not measure uranium since Fermi claimed that uranium by capturing neutrons transforms into transuranium. In the end on the 21st December 1938 Szilárd withdrew his patent for the neutron chain-reaction in London. On 24th January 1939, however, he heard Bohr's lecture in Princeton on the fission of uranium nucleus caused by neutrons and started to think. Uranium consists of 61% neutrons. Yet the middle-sized nuclei originating from fission consist only of 54% neutrons. So it may easily occur that during fission some neutrons drop out! He hurried to his friends, Eugene P. Wigner and Edward Teller who grasped the realities of the idea. Thus Szilárd sent a telegram to the Patent Office in London telling that his patent withdrawal should be disregarded.

On 3rd March 1939 on the seventh floor of the Pupin Laboratory at the University of Columbia, the Hungarian Leo Szilárd and the Canadian Walter Zinn made an interesting observation. They bombarded uranium with slow neutrons and it emitted fast neutrons whose energy could originate merely from fission. The same evening Edward Teller was relaxing and playing Mozart on the piano when his phone rang. It was Szilárd's voice: "I've found the neutrons." He spoke Hungarian for security reasons. Fermi decided to carry out the experiment himself in the basement of the Pupin Laboratory at the University of Columbia, but he could not detect emitted neutrons because he used fast neutrons to initiate fission. Szilárd lent him his neutron-moderating paraffin and the following day Fermi and Anderson, with completely different equipment, also demonstrated that under the influence of slow neutrons the uranium nucleus splits into two, and several fast neutrons are produced at each fission. On 16th March 1939 Fermi, Anderson and Hanstein, furthermore Szilárd and Zinn sent their article to the Physical Review, reporting the neutron-multiplying effect of nuclear fission. They foresaw that their discovery had military significance, so they requested the journal to register the date of the arrival of their papers, but not to print either of the two.

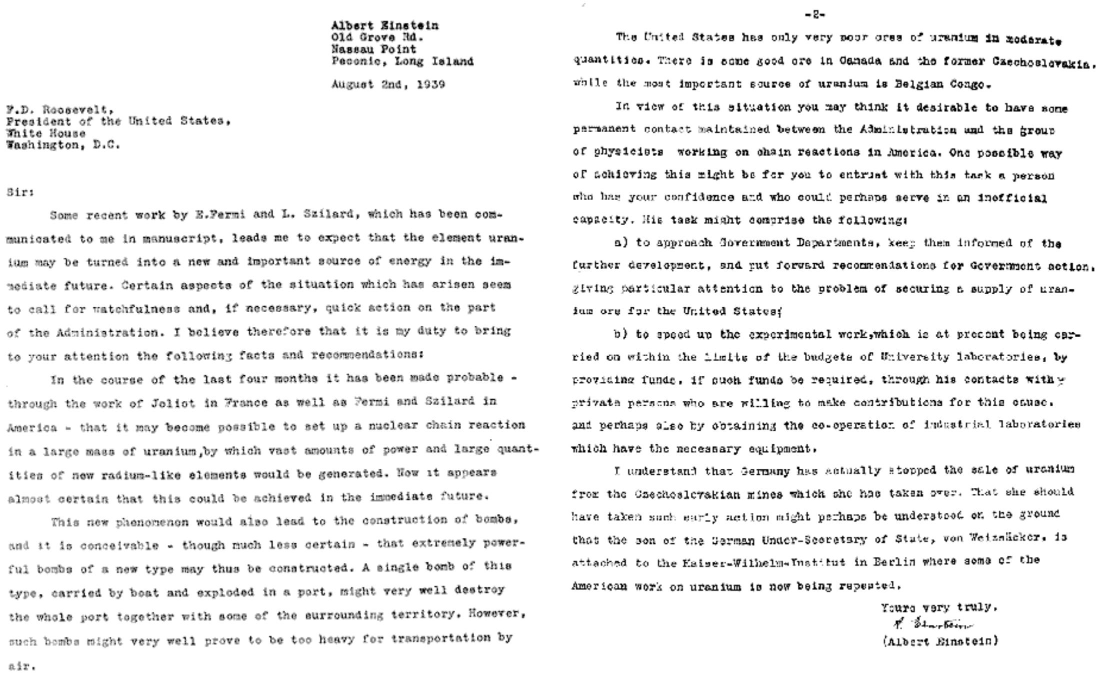
Meanwhile, Frederic Joliot-Curie carried out similar experiments in France and received the same results. Szilárd was aware of this, and tried to persuade Joliot-Curie out of the publication but without success. So at last, the Fermi study and the paper of Szilárd were published in the 15th

April issue of the Physical Review, while the paper of Joliot-Curie appeared in the Nature on 22nd April 1939. The news was reacted on by England, Germany and the Soviet Union too, initiating research on their utilization (atomic bomb). What was happening during his time in the United States?

In order to realize neutron chain reaction, scientists had to slow down fast neutrons originating from fission as only slow neutrons evoke fission with high efficiency. After investigating plenty of candidates (hydrogen, helium, water), graphite seemed to be the most promising moderator. Its density is high and it does not absorb neutrons.

Fermi calculated whether chain-reaction could take place in a homogenous mixture of uranium and graphite. The answer was ‘no’, since neutrons with medium energy were absorbed in the heavy isotope of uranium before being able to cause fission in the light one. Szilárd, though, calculated with uranium balls embedded in graphite blocks. If fission neutrons get out of uranium balls before crashing into uranium nuclei, (which means absorption), they could slow down in the graphite and thus slow neutrons split nuclei when arriving back into uranium. Szilárd managed to persuade Fermi too, that this arrangement was likely to work.

Fermi turned to the American Admiralty to gain financial support to perform neutron chain-reaction due to its military importance. This strange suggestion made by a citizen of the fascist Italy was refused. The historically more experienced Szilárd chose a more “personal” procedure.



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

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The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,

(Albert Einstein)

Fig. 1 Einstein’s letter to Roosevelt

Eugene P. Wigner knew Einstein well from Princeton. So Szilárd, together with Wigner, saw the already world-famous scientist about asking his personal intervention at the Queen of Belgium, not to supply uranium, mined in Congo, to the German army. After the visit Szilárd deemed it to be better to turn directly to the President. He dictated a letter addressed to President Roosevelt, took it to Einstein on the 2nd August 1939 with Edward Teller. Einstein read and signed it (Fig. 1). Leo Szilárd asked Alexander Sachs, Roosevelt's financial advisor, to deliver the letter personally.

This happened on the 3rd October. That time the war had already been going on, Hitler and Stalin invaded and divided Poland, so Roosevelt understood the military importance of the neutron chain reaction (atomic bomb). A committee was entrusted with the arrangements whose members included Fermi, Szilárd, Wigner and Teller, too. On the first meeting they granted six thousand dollar support so that Fermi and Szilárd could start the experiments, studying how uranium and graphite behaves towards neutron. The results were promising. Nevertheless, the Uranium Committee was reorganized in June 1940 for security reasons. Fermi, Szilárd and Teller were left out, being "untrustworthy" citizens of enemy countries at war western powers. American experts replaced them. One and a half years passed by and practically nothing happened. No wonder, there was peace in America.

On 7th December 1941 the American Pacific Fleet was attacked and mostly destroyed by Japanese aeroplanes in Pearl Harbour. The U.S. found itself at war. A decision was made within one day about the speeding up of the uranium programme and transferring it from the Atlantic coast to Chicago. On 18th June 1942 the uranium programme was put under military control. The construction of the first nuclear pile took place under the stand of a stadium, in secrecy. The director of the programme was Compton (a Nobel laureate American citizen). The assembly of the reactor was conducted by Fermi (a Nobel laureate Italian citizen), and the construction itself was led by Walter Zinn (a Canadian). The nuclear reactor was piled up by placing uranium and graphite blocks on a neutron source. Fermi measured how the number of neutrons changed. His results were used by Eugene P. Wigner (a Hungarian Nobel laureate) to calculate how high the reactor had to be, to make a self-sustaining neutron chain reaction. Edward Teller (a Hungarian citizen) was entrusted with radiation protection control. Leo Szilárd, living in Chicago that time, (also a Hungarian citizen) dropped in from time to time during lunch break and shared his ideas concerning what should be done in an other way (and often he was right!). He did not wish to dirt his hands by carrying graphite blocks - unlike Fermi and Zinn. He considered it to be "the assistants' task". This is how he deserved the description: "Leo

Szilárd is such an experimental physicist who has only head, but no hands”.

Fermi tried out 25 various uranium-graphite arrangements and from the observations Wigner calculated which the most favorable variation was. A 2x2x4 meter pile was built up in the room under the stand of a Sport Stadium by 2nd December 1942. Let us listen to Eugene P. Wigner’s account of that day:

“I was standing in the lounge under the Stagy Field Stadium and was watching Fermi. This Wednesday morning at around 8:30 nearly 50 people gathered in the 10x20 meter hall. There was a huge pile in the middle, constructed from black graphite blocks and wooden rods. Its base was square and the pile was tapering upwards. In it there was uranium-blocks laid. Fermi installed control rods over the pile to absorb neutrons. In case of emergency a “suicide squad” was to dash diluted solution of cadmic-salt from buckets into the pile (it would absorb neutrons) to stop the chain-reaction. They were standing on the top of the reactor. Serious work started at around 9:45. By 11:30 a self-sustaining chain reaction was almost established but the control rod dropped inside the reactor prevented it. Fermi sent all of us to have lunch.

We arrived back at 2. At one end of the balcony, Fermi was standing together with his two main assistants: Zinn and Anderson. He was holding a slide-rule in his hand. Compton, the director of the nuclear energy programme, was staying next to them. We, the other forty people gathered at the other end of the balcony, including my old friend, Leo Szilárd. At 3:30 in the afternoon Fermi ordered to raise the cadmium-covered control rod by 25 centimeter, and the number of neutrons was increasing. The neutron counter was going “pit-a-pat”. We were approaching the self-sustaining neutron chain-reaction more and more. When the control rod was completely pulled out, the counter was ticking faster than ever and so we knew that the nuclear chain reaction has been realized!

We freed the energy of the nucleus and kept it under control. The people were smiling and some clapping could be also heard but mostly we were concentrating for almost 30 minutes. The scene was not theatrical at all. Fermi kept the operation of the pile at a low level, so we were not threatened to be harmed. Still, the reactor was standing in front of us, functioning!

Some time before 4 o’clock Fermi ordered to end the reaction. The control rod was let back into the pile and the chain reaction stopped. We had all been expecting the experiment to work and it did. After all, when horses are put to a carriage and they are slashed, they set off and the carriage is expected to follow them. Fermi constructed the cart, he whipped the horses and the cart really did go. He was not the only one *being able to build the nuclear reactor, but certainly he was the only one who could realize it so quickly.*

Foreseeing this moment, I had bought a bottle of Chianti (Italian red wine) in Princeton 10 months earlier and brought it to Chicago. I bought it so soon because I had supposed that the war would prevent the import of Italian wine. It would have been more difficult to foresee the breakdown of the Chianti import than the successful functioning of the nuclear reactor. But I had already lived through a world war and experienced the disappearance of luxury items from markets. I kept the Chianti behind my back. At that moment I pulled it out of the brown paper bag, stepped forward and handed it to Fermi. He thanked, pulled out the cork and sent someone to get paper cups. The cups arrived and we tasted the Chianti. What a fantastic delight can good red wine cause!

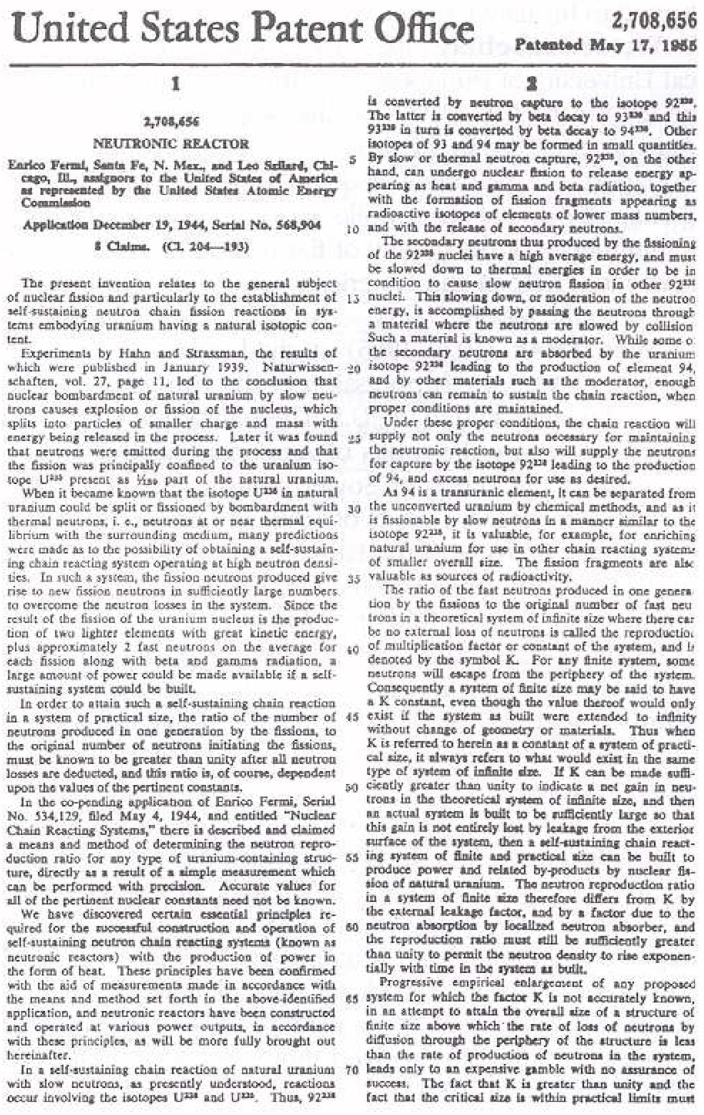
We clinked cups, calmly celebrating our success and wished that nuclear power would make people's lives happier and those harmful prejudices would diminish. Fermi signed the Chianti-label, then it went round in the room and we all signed it. No record was made of this historical event. Only the list of names on the label made it possible to reconstruct later who had been present at the start of the first atomic pile."

This is where we know that 38 Americans were there, also an Italian (Fermi), a Canadian (Zinn) and two Hungarians (Szilárd and Wigner). It is worth mentioning that Enrico Fermi was still an Italian citizen and Leo Szilárd was still a Hungarian citizen that time. They obtained American citizenship only in 1944 and 1943. (Wigner already received it in 1937.) During the events recounted above, Compton rushed to the telephone and called Washington to deliver the codified message:

"THE ITALIAN STEERSMAN ANCHORED IN THE NEW WORLD.
THE NATIVES GREETED HIM IN A FRIENDLY WAY".

The creation of the nuclear reactor was an Italian-Hungarian-American success story. The end of the story is known for everybody from history books.

Epilogue: The American patent, no. 2708656, of the neutron reactor was given to Enrico Fermi and Leo Szilárd 17th May 1955 on the basis of the application submitted on 19th December 1944 (Fig.2). By that time Fermi had already passed away (in 1954). The American state bought the patent from Szilárd for a symbolical $1. (Szilárd flew into a rage saying that either the real value of the reactor and the work invested should have been be paid or nothing at all.)



United States Patent Office

2,708,656

Patented May 17, 1955

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2,708,656

NEUTRONIC REACTOR

Enrico Fermi, Santa Fe, N. Mex., and Leo Szilard, Chicago, Ill., assignors to the United States of America as represented by the United States Atomic Energy Commission

Application December 19, 1944, Serial No. 568,904

8 Claims. (Cl. 204—193)

The present invention relates to the general subject of nuclear fission and particularly to the establishment of self-sustaining neutron chain fission reactions in systems embodying uranium having a natural isotopic content.

Experiments by Hahn and Strassman, the results of which were published in January 1939. Naturwissenschaften, vol. 27, page 11, led to the conclusion that nuclear bombardment of natural uranium by slow neutrons causes explosion or fission of the nucleus, which splits into particles of smaller charge and mass with energy being released in the process. Later it was found that neutrons were emitted during the process and that the fission was principally confined to the uranium isotope U^{235} present as $\frac{1}{139}$ part of the natural uranium.

When it became known that the isotope U^{235} in natural uranium could be split or fissioned by bombardment with thermal neutrons, i. e., neutrons at or near thermal equilibrium with the surrounding medium, many predictions were made as to the possibility of obtaining a self-sustaining chain reacting system operating at high neutron densities. In such a system, the fission neutrons produced give rise to new fission neutrons in sufficiently large numbers to overcome the neutron losses in the system. Since the result of the fission of the uranium nucleus is the production of two lighter elements with great kinetic energy, plus approximately 2 fast neutrons on the average for each fission along with beta and gamma radiation, a large amount of power could be made available if a self-sustaining system could be built.

In order to attain such a self-sustaining chain reaction in a system of practical size, the ratio of the number of neutrons produced in one generation by the fissions, to the original number of neutrons initiating the fissions, must be known to be greater than unity after all neutron losses are deducted, and this ratio is, of course, dependent upon the values of the pertinent constants.

In the co-pending application of Enrico Fermi, Serial No. 534,129, filed May 4, 1944, and entitled "Nuclear Chain Reacting Systems," there is described and claimed a means and method of determining the neutron reproduction ratio for any type of uranium-containing structure, directly as a result of a simple measurement which can be performed with precision. Accurate values for all of the pertinent nuclear constants need not be known.

We have discovered certain essential principles required for the successful construction and operation of self-sustaining neutron chain reacting systems (known as neutronic reactors) with the production of power in the form of heat. These principles have been confirmed with the aid of measurements made in accordance with the means and method set forth in the above-identified application, and neutronic reactors have been constructed and operated at various power outputs, in accordance with these principles, as will be more fully brought out hereinafter.

In a self-sustaining chain reaction of natural uranium with slow neutrons, as presently understood, reactions occur involving the isotopes U^{238} and U^{235}. Thus, 92^{238}

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is converted by neutron capture to the isotope 92^{239}. The latter is converted by beta decay to 93^{239} and this 93^{239} in turn is converted by beta decay to 94^{239}. Other isotopes of 93 and 94 may be formed in small quantities. By slow or thermal neutron capture, 92^{235}, on the other hand, can undergo nuclear fission to release energy appearing as heat and gamma and beta radiation, together with the formation of fission fragments appearing as radioactive isotopes of elements of lower mass numbers, and with the release of secondary neutrons.

The secondary neutrons thus produced by the fissioning of the 92^{235} nuclei have a high average energy, and must be slowed down to thermal energies in order to be in condition to cause slow neutron fission in other 92^{235} nuclei. This slowing down, or moderation of the neutron energy, is accomplished by passing the neutrons through a material where the neutrons are slowed by collision. Such a material is known as a moderator. While some o the secondary neutrons are absorbed by the uranium isotope 92^{238} leading to the production of element 94, and by other materials such as the moderator, enough neutrons can remain to sustain the chain reaction, when proper conditions are maintained.

Under these proper conditions, the chain reaction will supply not only the neutrons necessary for maintaining the neutronic reaction, but also will supply the neutrons for capture by the isotope 92^{238} leading to the production of 94, and excess neutrons for use as desired.

As 94 is a transuranic element, it can be separated from the unconverted uranium by chemical methods, and as it is fissionable by slow neutrons in a manner similar to the isotope 92^{235}, it is valuable, for example, for enriching natural uranium for use in other chain reacting systems of smaller overall size. The fission fragments are also valuable as sources of radioactivity.

The ratio of the fast neutrons produced in one generation by the fissions to the original number of fast neutrons in a theoretical system of infinite size where there can be no external loss of neutrons is called the reproduction of multiplication factor or constant of the system, and is denoted by the symbol K. For any finite system, some neutrons will escape from the periphery of the system. Consequently a system of finite size may be said to have a K constant, even though the value thereof would only exist if the system as built were extended to infinity without change of geometry or materials. Thus when K is referred to herein as a constant of a system of practical size, it always refers to what would exist in the same type of system of infinite size. If K can be made sufficiently greater than unity to indicate a net gain in neutrons in the theoretical system of infinite size, and then an actual system is built to be sufficiently large so that this gain is not entirely lost by leakage from the exterior surface of the system, then a self-sustaining chain reacting system of finite and practical size can be built to produce power and related by-products by nuclear fission of natural uranium. The neutron reproduction ratio in a system of finite size therefore differs from K by the external leakage factor, and by a factor due to the neutron absorption by localized neutron absorber, and the reproduction ratio must still be sufficiently greater than unity to permit the neutron density to rise exponentially with time in the system as built.

Progressive empirical enlargement of any proposed system for which the factor K is not accurately known, in an attempt to attain the overall size of a structure of finite size above which the rate of loss of neutrons by diffusion through the periphery of the structure is less than the rate of production of neutrons in the system, leads only to an expensive gamble with no assurance of success. The fact that K is greater than unity and the fact that the critical size is within practical limits must

Fig. 2 Patent of the Neutronic Reactor to E. Fermi and L. Szilárd

After Fermi's death, the Ministry of Energy of the U.S. founded the FERMI PRIZE. Eight persons were awarded between 1955 and 1963: an Italian (posthumous prize for Enrico Fermi), three Americans (Ernest Lawrence, Robert Oppenheimer, Glenn Seaborg), a German (Hans Bethe) and three Hungarians (John von Neumann, Leo Szilárd and Edward Teller).

By President Eisenhower's proposal the UNO established the ATOMS FOR PEACE prize whose reward surpassed that of the Nobel Prize. Niels Bohr was awarded first in 1957 for the successful creation of the atomic model and that of the nucleus. In 1958 the second prize was given to George de Hevesy for the discovery of radioactive tracer. Szilárd and Wigner received it in 1959 for the construction and the design of the nuclear pile, and in 1960 Alan Weinberg and Walter Zinn were awarded for its construction. An American, a Dane, a Canadian and three Hungarians bask in the glory. As if continuing the coded telegram sent on 2nd December 1942, Manson Benedict said when handing over the prizes in 1959 and 1960:

“THE SHIP WAS STEERED BY THE ITALIAN STEERSMAN,
WAS CONSTRUCTED BY A CANADIAN SHIPWRIGHT
USING A SCARCE AND VALUABLE MATERIAL
FOUND BY A HUNGARIAN EXPLORER”.

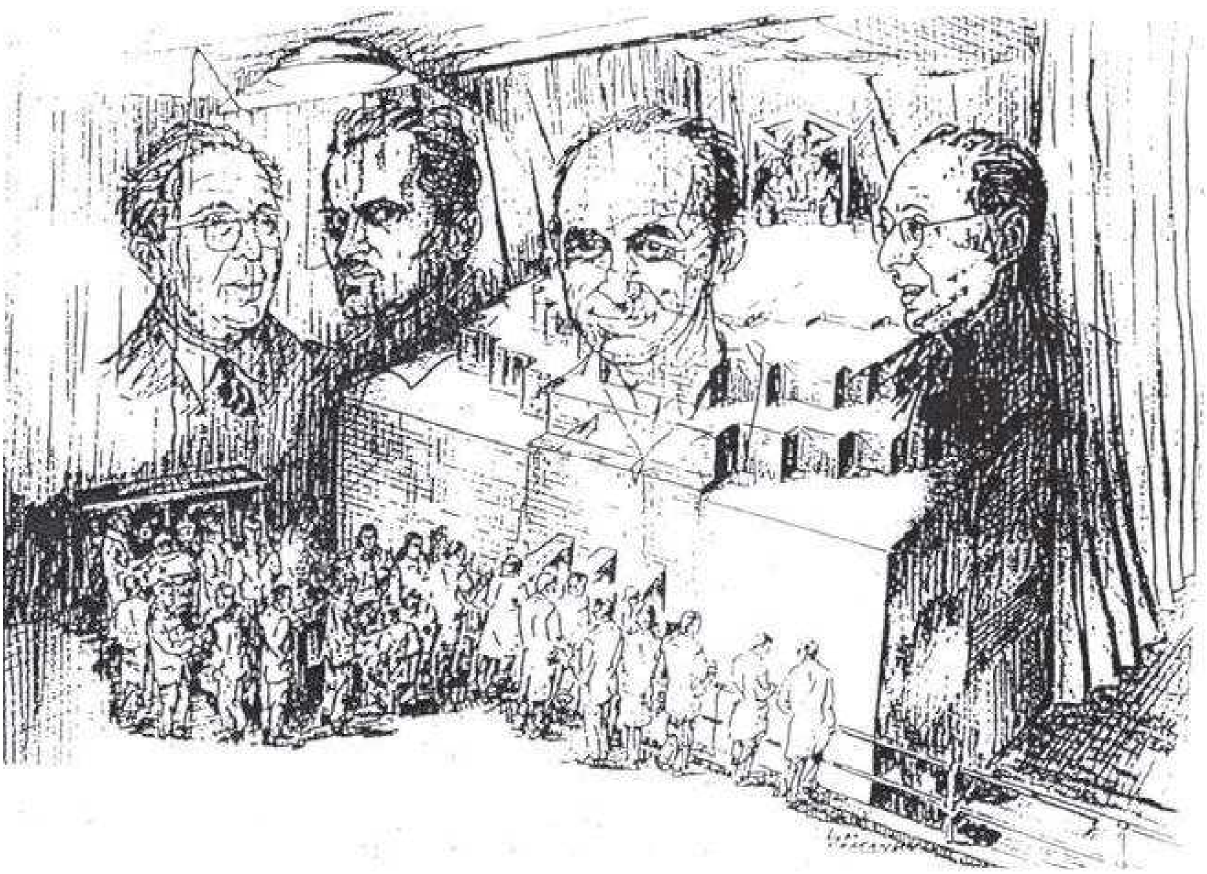

Fig. 3 Hand drawing of the Chicago pile
From left to right: L. Szilárd, A. Compton, E. Fermi, E.P. Wigner