

A LECTURE ON BOMB PHYSICS: FEBRUARY 1942

During the waning weeks of World War II in Europe, as Allied armies swept across a defeated, chaotic Germany, two teams of the world's leading nuclear scientists strove to complete their work. One team, sequestered at Los Alamos, hastened to assemble the first of three atomic bombs. The other, a group of German scientists and technicians who had recently fled the Allied bombing of Berlin for southern Germany, worked day and night trying to achieve what, unbeknownst to them, the Allies had achieved nearly two and a half years earlier: a critical self-sustaining nuclear reactor.

As they assembled what would be their last attempt at a reactor, the German scientists slowly realized that it would fail. Within hours after French troops swept through the area at the end of April 1945, the Alsos mission, a secret American science intelligence unit, halted the German nuclear effort and captured many of the German nuclear scientists, along with most of their equipment and technical papers. By VE day, 8 May, the Alsos mission had confirmed the nonexistence of a German atom bomb and had singled out ten of the German scientists for extended internment under American and British control.

After the ten scientists had languished at several locations in France and Belgium, on 3 July 1945 British authorities flew them to England, where they were held incommunicado for exactly six months at Farm Hall, an English country manor near Cambridge. Before the German scientists arrived, physicist R. V. Jones, a leading figure in British scientific intelligence, had the rooms

A talk delivered to top German research officials demonstrates that Heisenberg understood, several years before the end of World War II, the basics of how to obtain fissile materials for an atomic bomb.

Werner Heisenberg

Introduction by David Cassidy

Translation by William Sweet

outfitted with hidden microphones. A team of bilingual British military personnel monitored all of the scientists' conversations and recorded those that appeared of intelligence value in the state-of-the-art medium of the day: reusable shellacked metal disks.

Ever since that time a debate has raged among historians and scientists about how much the German scientists really understood about bomb physics. What follows is the complete text

of a nontechnical lecture that Werner Heisenberg, the leading figure in German nuclear research, delivered as part of a lecture series to senior German research officials on 26 February 1942. A second article, on page 32, excerpts materials from the Farm Hall transcripts themselves, focusing on items that shed more light on what Heisenberg and his colleagues understood as of August 1945 about making a bomb.

Heisenberg's lecture of 26 February 1942 was one of three such talks he delivered to top German brass during the war. It was part of a lecture series sponsored by the Education Ministry, which was in the process of taking over management of nuclear research from the military. A second talk, on 4 June, was for selected military commanders and Albert Speer, Hitler's director of war mobilization, and a third, on 6 May 1943, was at Hermann Göring's aeronautical research academy.

Except for Heisenberg's mistaken notion that a reactor would stabilize itself at a high energy level, his talk of 26 February is accurate about bomb physics in all essentials, as far as it goes. At Farm Hall, Heisenberg would remember the 26 February meeting as the time when he and others first convinced Education Minister Bernard Rust "that we had absolutely definite proof that it could be done." "It" most likely referred to making an atomic bomb.

Heisenberg's talk was entitled "The Theoretical Foundations for Obtaining Energy from Fission of Uranium." A note handwritten by Heisenberg on the document describes it as "(Manuscript of the lecture delivered 26 February 1942 at the House of German Research)." The two illustrations are from the published version of the subsequent talk he gave at Göring's academy but are assumed to be identical to the ones he used with his 26 February talk.

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WILLIAM SWEET is a contributing editor to *PHYSICS TODAY*. The translation of the lecture was done from the German text in Werner Heisenberg, *Gesammelte Werke/Collected Works*, volume AII, edited by W. Blum et al. (Springer-Verlag, Berlin, 1989), with the permission of the publisher. The second and third illustrations are also from that volume. The translated lecture will appear in an appendix to *Hitler's Uranium Club: The Secret Recordings at Farm Hall*, to be published this fall by AIP Press.

Der Reichsführer-SS

Tgb.Nr.
RF/H.

Berlin SW 11, den 22. Febr. 42
Himmler-SS Nr. 8
Führer-Hauptquartier
Eingangsnummer 1142
Nachdem die Anschrift
in Berlin zu ändern.

Lieber Parteigenosse Rust!

Ich danke Ihnen für Ihre freundliche Einladung zu der am 26. Februar im "Haus der Deutschen Wissenschaft" stattfindenden Tagung. Da ich zu dem angegebenen Zeitpunkt nicht in Berlin sein werde, ist es mir leider nicht möglich, an der Veranstaltung teilzunehmen.

Heil Hitler!

A. Himmler

NOTE FROM HEINRICH HIMMLER, leader of the SS and head of the state's terror apparatus, politely declining an invitation to the lecture about bomb physics that Heisenberg was to deliver on 26 February 1942. In the late 1930s, when Nazi physicist Johannes Stark attacked Heisenberg as a "White Jew" because of his support for relativity, Heisenberg directly asked Himmler for support. Heisenberg's mother also interceded with Himmler's mother, who moved in the same Munich social circles. On 21 July 1938 Himmler wrote to Heisenberg guaranteeing him his protection.

The lecture

At the beginning of the work on the uranium problem, done in the framework of the Army Weapons Bureau task force, the following experimental facts became known:

1) Normal uranium is a mixture of three isotopes: U-238, U-235 and U-234, which are found in natural minerals approximately in the relationship 1:1/140:1/17 000.

2) The uranium nuclei can, as [Otto] Hahn and [Fritz] Strassmann discovered, be split by means of neutron irradiation; specifically, the nucleus of U-235 by neutrons of all (including low) energies (Bohr), and the nuclei of U-238 and U-234 only by means of fast neutrons.

3) Each fission releases, per atomic nucleus, an energy of about 150 to 200 million electron volts. This energy is about 100 million times greater, per atom, than the energies released in chemical reactions. Furthermore, in each fission reaction a few neutrons are ejected from the atomic nucleus.

From these facts can be concluded: If one managed, for example, to split all the nuclei of 1 ton of uranium, an enormous energy of about 15 trillion kilocalories would be released. It had been known for a long time that such high amounts of energy are released in nuclear transmutations. Before the discovery of fission, however, there was no prospect of inducing nuclear reactions in large quantities of material. For in artificially induced reactions in high-voltage facilities, cyclotrons and so on, the expenditure of energy is always much greater than the energy produced.

The fact that in the fission process several neutrons are ejected opens the prospect, on the other hand, that the transformation of large quantities of material could be effected in a chain reaction. The neutrons ejected in fission would, for their part, split other uranium nuclei, more neutrons would be produced, and so on; by repeating

this process many times one obtains an ever greater increase in the number of neutrons, which only stops when a large proportion of the substance has been transformed.

Before addressing the question of whether this program can be carried out in practice, it will be necessary to study more closely the various processes that can generate a neutron from uranium. A neutron liberated in fission can either, if it has enough energy, after traveling a short distance, collide with another uranium nucleus, split it and generate another neutron, or it can—and unfortunately this is much more likely—just give up energy in the collision to the nucleus, without splitting it, whereupon the neutron continues on its way with less energy. In this case the energy of the neutron will be so small after a few collisions that only the following possibilities exist for its destiny: In the course of colliding

with an atom it can get stuck in the nucleus, in which case further propagation is impossible; or—and this unfortunately is rather improbable—it can collide with a nucleus of U-235 and split it. Then further neutrons are generated in the process, and the events just described can begin again. Some of the neutrons can escape from the surface of the uranium bulk and thereby be lost.

The exact description of the probabilities of each process taking place was an important programmatic point in the work of the task force, and Mr. [Walther] Bothe will report on the results.

For our purposes it is sufficient to state that in natural uranium, neutron absorption (in which a neutron is captured by U-238, yielding the new isotope U-239) is much more common than fission or propagation. Therefore the chain reaction we are looking for cannot take place in natural uranium, and one has to sniff out new ways and means of effecting initiation of the chain reaction.

The behavior of the neutrons in uranium can be compared to the behavior of a population, such that the fission process has an analog in marriage and neutron capture in death. In normal uranium the death toll greatly outweighs the number of births, so that the existing population always will have to die out after a short time.

An improvement in the fundamentals obviously is possible only if one succeeds in (1) raising the number of births per marriage, (2) boosting the number of marriages or (3) reducing the probability of death.

Possibility (1) does not exist in the neutron population, because the number of neutrons per fission is established by natural laws and constants that cannot be influenced. (For the determination of these important constants, take note of the talk by Mr. Bothe.)

There remain therefore only paths (2) and (3). An increase in the number of fissions can be reached if one

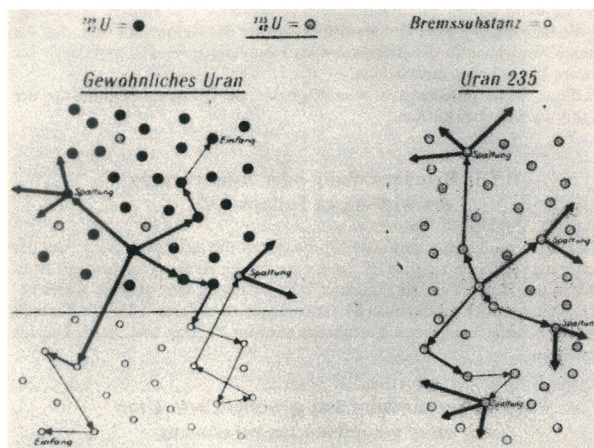
enriches the uranium in the fissionable but much rarer isotope U-235. If in fact one succeeded in producing pure U-235, then the conditions would come into play that are portrayed on the right side of the first figure [this page]. Every neutron would, after one or more collisions, cause another fission, provided it did not escape from the surface. The probability of death by neutron capture is vanishingly small compared with the probability of propagation. So if one just assembles a certain amount of U-235, so that neutron loss through the surface stays small compared with internal multiplication, then the number of neutrons will increase enormously in a very short time and the whole fission energy of 15 trillion kilocalories per ton is released in a fraction of a second. The pure isotope U-235 undoubtedly represents, then, an explosive material of unimaginable force. Granted, this explosive is very hard to obtain.

A big part of the work of the Army Weapons Bureau task force has been devoted to the problem of enrichment, that is, the production of pure U-235. American research also appears to be oriented in this direction, with considerable emphasis. In the course of this session Mr. [Klaus] Clusius will report on the status of this question, and so I will not have to go into it any further.

There remains to be discussed now only the third possibility for initiating the chain reaction: reduction of the death toll, that is, the probability of neutron capture. According to general principles of nuclear physics it can be assumed that the probability of capture becomes large only at very specific neutron energy levels. (The investigations of the past year have yielded valuable results on just this point.) If one succeeded in quickly slowing the neutrons, without too many collisions, to the region of lowest possible energies (that is, the energy region given by thermal motion), then one could reduce the death toll substantially. In practice one can effect a rapid diminution of neutron speed by adding suitable braking substances [or moderators], that is, substances whose nuclei—when hit by a neutron—take away part of the neutron's energy. If one adds enough braking substance, then one can bring the neutrons without danger into the region of lowest energies. But unfortunately most braking substances have the property of also capturing neutrons, so that too much braking substance will increase the probability of capture, that is, the death toll. These relations are portrayed schematically on the other [left] side of the first figure [above].

It is a question, accordingly, of finding a moderator that quickly removes energy from a neutron without, as far as possible, absorbing it.

The one substance that does not absorb at all, helium, unfortunately cannot be used because of its low density. The most suitable material almost certainly is deuterium, which is available in its simplest combination—and also in sufficient proportion—in water. Admittedly, heavy water is not easy to obtain in large quantities. The task force has initiated thorough investigations into the production of heavy water and other substances that are



FISSION REACTIONS in pure uranium-235 (right) and unenriched uranium above a layer of moderator (left) are depicted in this first figure from Heisenberg's talk. *Spaltung* means "fission" and *Einfang* "capture."

possibilities, such as beryllium and carbon.

Pursuant to an idea of [Paul] Harteck, it has proved advisable to separate the uranium and the moderator [in a reactor], so that the kind of arrangements result that are seen in the layered ball shown in the second and third figures [see page 30], which was built as a small-scale experiment at the Kaiser Wilhelm Institute [for Physics at Berlin-Dahlem].

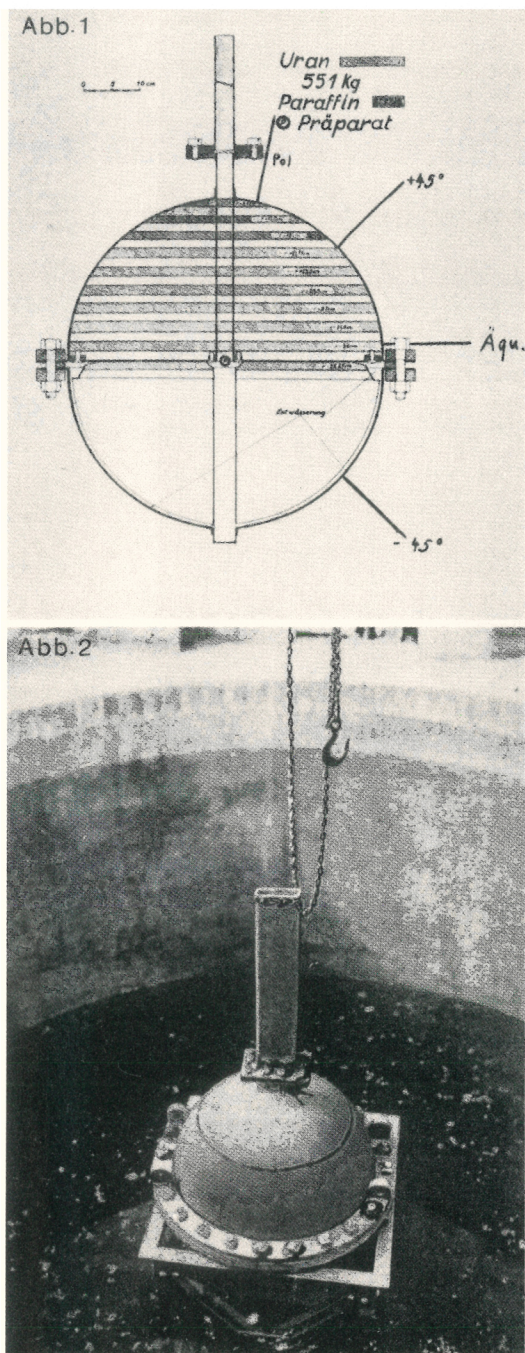
Whether this kind of layering of natural uranium and moderator can lead to a chain reaction and therewith to the liberation of large energies, that is, whether the "death rate" can be reduced enough for the "birth rate" to outweigh it, so that an increase in the population begins, has to be regarded as a completely open question, since the properties of the few substances that can be used as moderators are given and cannot be changed.

To illuminate this point was again one of the most important assignments of the task force.

Let us now assume for a moment that this question has been resolved in a positive sense; then it still has to be investigated how this particular arrangement behaves with greater multiplication of the neutron population. It turned out that multiplication does not stop only when a greater part of the uranium is transformed, but much sooner. The ever greater propagation leads in fact to a strong warming, and with the warming—since the neutrons move faster and therefore spend less time in the neighborhood of a uranium nucleus—the probability of fission gets smaller. The warming has as a consequence, then, a diminution in the number of "marriages" and hence in the multiplication; because of that, at a certain temperature the neutron multiplication will be exactly balanced by absorption.

So the layered arrangement as described will stabilize itself at a certain temperature. As soon as energy is drawn from the machine, cooling and a renewed multiplication set in, and the drawn energy in turn is replaced by fission energies; the machine stays for all practical purposes at the same temperature.

One arrives with this at a machine that is suitable for heating a steam turbine and that can put its very large energies over a period of time at the disposal of such a thermal power machine. One can therefore think of practical applications for such machines in transportation, especially in ships, which would acquire enormous range from the huge energy reserve contained in a relatively



LAYERED REACTOR built at the Kaiser Wilhelm Institute for Physics in Berlin-Dahlem. Top: In the design for the reactor, sheets of uranium metal are seen to alternate with sheets of paraffin. Bottom: The actual reactor, seen externally in a container of water.

found in which the chain reaction can take its course has still—as stated—to be determined by experiment. But also, when such a mixture is found, a large quantity of this mixture must still be amassed to allow the chain reaction really to run, since with smaller quantities the loss of neutrons through the surface always will be greater than the internal multiplication. Experiments with very small quantities of substance are therefore from the outset insufficient for deciding the suitability of the mixtures for the chain reaction. Without generous support of the research work—with materials, radioactive sources, funds—as obtained from the Army Weapons Bureau, it would not have been possible to progress. But even with the larger quantities—for example, of heavy water—that have been made available, the chain reaction still cannot take place. Therefore we must still touch on the question of how one can recognize in a small-scale experiment whether in the chosen mixture the “birth rate” is outweighing the “death rate.”

To resolve this question effectively, one introduces into the mixture a neutron source about which it is known how many neutrons per second it emits. If the number of neutrons escaping from the mixture is greater than the number introduced with the source, then one can conclude that multiplication is outweighing absorption and that a suitable mixture has been found.

Experiments conducted in Leipzig in the last few years have shown that a certain mixture of heavy water and uranium actually has the desired properties. To be sure, the surplus of the “birth rate” over the “death rate” was so small in these experiments that it was canceled by additional absorption in the container material. But the container material can be dispensed with later or can be replaced by something else.

To the extent one can extrapolate from laboratory-scale experiments to large-scale experiments, the experiments unequivocally support the possibility that with a layering of uranium and moderator a machine can be built as indicated.

The results to date can be summarized as follows:

1) Obtaining energy from uranium fission is undoubtedly possible if enrichment in the U-235 isotope is successful. Production of pure U-235 would lead to an explosive of unimaginable force.

2) Natural uranium also can be used for energy production in a layered arrangement with heavy water. A layered arrangement of these substances can transfer its great energy reserve over a period of time to a thermal power machine. Such a reactor provides a means of liberating very large, usable quantities of energy from relatively small quantities of substance. An operational machine can also be used to obtain a hugely powerful explosive; over and above that, it promises a number of other scientifically and technically important applications, which go beyond the scope of this talk.

[A concluding sentence refers to the three figures.] ■

small quantity of uranium. That such a machine does not burn any oxygen would be a particular advantage if used in submarines.

As soon as such a machine is in operation, the question of how to obtain explosive material, according to an idea of [Carl Friedrich] von Weizsäcker, takes a new turn. In the transmutation of the uranium in the machine, a new substance comes into existence, element 94, which very probably—just like U-235—is an explosive of equally unimaginable force. This substance is much easier to obtain from uranium than U-235, however, since it can be separated from uranium by chemical means.

Whether a mixture of uranium and moderator can be