originally published May 1995

What Did Heisenberg Tell Bohr about the Bomb?

In 1941 Werner Heisenberg and Niels Bohr met privately in Copenhagen. Almost two years later at Los Alamos, Bohr showed a sketch of what he believed was Heisenberg's design for a nuclear weapon

by Jeremy Bernstein

In September 1943 Niels Bohr learned that the gestapo in Copenhagen intended to arrest him. A few weeks later, on the 29th, he, his wife and several others hoping to escape from Denmark crawled in complete darkness to a beach outside Carlsberg. There they boarded a boat and crossed the Øresund in secret to Sweden. On October 6 the British flew Bohr alone from Sweden to Scotland. Later that same day he traveled to London and in the evening met with Sir John Anderson, the physical chemist in charge of the nascent British atomic bomb project. Anderson gave the Danish physicist a briefing on the Anglo-American program. According to Bohr's son Aage, who followed his father to England a week later and was his assistant throughout the war, Bohr was deeply surprised—shocked may be a better description—by how far the Anglo-American program had already progressed.

Bohr's alarm very likely had two sources. First, during the 1930s, when nuclear physics was developing, Bohr had said on several occasions that he thought any practical use of nuclear energy was all but impossible. That view was reinforced in the spring of 1939, when he realized an important detail concerning the fission of uranium. In December 1938 the German physical chemists Otto Hahn and Fritz Strassmann had discovered that uranium could be fissioned if it was bombarded with neutrons. (Hahn's former assistant Lise Meitner and her nephew Otto Frisch conjectured that the uranium nucleus had actually been split in the experiments and so coined the name "fission" for the process.) The experiments used natural uranium, 99 percent of which is in the isotope uranium 238. About seven tenths of a percent is in the isotope uranium 235, whose nucleus contains three fewer neutrons.

Chemically, the isotopes are indistinguishable. What Bohr realized was that because of their structural differences, only the very rare isotope uranium 235 had fissioned in the Hahn-Strassmann experiments. He concluded, then, that making a nuclear weapon would be almost impossible because it would require separating these isotopes—a daunting task. In December 1939 he said in a lecture, "With present technical means it is, however, impossible to purify the rare uranium isotope in su - cient quantity to realize the chain reaction." One can therefore well understand why Bohr was shocked to learn four years later that that was just what the Allies intended to do.

The second reason for Bohr's alarm can be traced back to a meeting he had had with the German physicist Werner Heisenberg in mid-September 1941, almost two years before his escape to Britain. By 1941 the Germans had occupied Denmark for more than a year. During that period, they established a so-called German Cultural Institute in Copenhagen to generate German cultural propaganda. Among its activities, the institute organized scientific meetings. Heisenberg was one of several German scientists who came under its auspices to Copenhagen, in this case to a meeting of astronomers. He had known Bohr since 1922 and had spent a good deal of time at Bohr's institute in Copenhagen, where Bohr had acted as a kind of muse for the creation of quantum theory. Now Heisenberg had returned as a representative of a despised occupying power, touting the certainty of its victory, according to some accounts.

Heisenberg's Visit

Heisenberg spent a week in Copenhagen and visited Bohr's institute on several occasions. During one of these visits, he and Bohr talked privately. Neither man seems to have made any notes, so one cannot be entirely sure what was said. Also, Bohr was a poor listener, so the two may well have talked past each other. Nevertheless, Bohr came away from the discussion with the distinct impression that Heisenberg was working on nuclear weapons. As Aage Bohr later recalled, "Heisenberg brought up the question of the military applications of atomic energy. My father was very reticent and expressed his skepticism because of the great technical di culties that had to be overcome, but he had the impression that Heisenberg thought that the new possibilities could decide the outcome of the war if the war dragged on." Now, two years later, Bohr was learning for the first time of the Allied nuclear weapons program. What had the Germans done during those two years? No wonder Bohr was alarmed.

It would be fascinating to know in detail what was meant by "new possibilities," but one can make an educated guess. By the mid-1940s physicists on both sides of the conflict realized that aside from fissioning uranium, there

JEREMY BERNSTEIN is professor of physics at the Stevens Institute of Technology and an adjunct professor at the Rockefeller University. He also serves as a vice president of the board of trustees of the Aspen Center for Physics. He has written some 50 technical papers, 12 books and numerous magazine articles. He has worked as a staff writer at the New Yorker magazine, taught nonfiction writing at Princeton University and won several science writing awards. He is a fellow of the American Physical Society, a Benjamin Franklin Fellow of the Royal Society of the Arts and a member of the French and American Alpine Clubs.

was an entirely separate route to making a nuclear weapon—the use of what later came to be known as plutonium. That element is somewhat heavier than uranium and has a di›erent chemistry, but given its nuclear structure, it is at least as fissionable. Unlike uranium, though, plutonium does not exist naturally and must be manufactured in a nuclear reactor by bombarding the reactor's uranium fuel rods with neutrons. Once made, the plutonium can be separated from its uranium matrix by chemical means.

From the moment this process was understood, any reactor became, in a certain sense, a component of a nuclear weapon. There is no doubt whatsoever that Heisenberg knew this fact well when he visited Bohr. He even gave lectures, whose texts have been preserved, describing such a possibility to highly placed German officials. Is this what he was trying to tell Bohr and, if so, why? There was such a lack of agreement between the two men as to what exactly was said that we will probably never know for sure.

As a corollary to this larger puzzle there is a smaller one. There is evidence that during the course of the Copenhagen meeting, Heisenberg gave Bohr a drawing. It is not clear whether Heisenberg made the drawing at the meeting or beforehand. Being familiar with how theoretical physicists communicate, I would imagine he drew the sketch on the spot to help convey an idea. In any case, under circumstances I will shortly describe, this drawing, or a replica, found its way to Los Alamos Laboratory in December 1943, where it created a considerable stir: it appeared to contain direct information about how the Germans were planning to make nuclear weapons. Before I describe how the drawing got to Los Alamos, let me tell how I learned of its existence. There is a relation.

The Mysterious Sketch

Beginning in November 1977, I conducted a series of interviews with the physicist Hans Bethe. Those sessions lasted on and off for two years and resulted in a three-part profile for the New Yorker magazine and a subsequent book. The interviews, which I taped, followed the chronology of Bethe's life. Bethe, who was born in Strasbourg in 1906, emigrated to the U.S. in 1935 and has been at Cornell University ever since. He became an American citizen in 1941, by which time, as he recalled, he was "desperate to do something—to make some contribution to the war effort." He, like Bohr, was at first certain that nuclear weapons were entirely impractical and went to work on the development of radar at the Massachusetts Institute of Technology.

In the summer of 1942 J. Robert Oppenheimer convened a study group at the University of California at Berkeley to investigate nuclear weapons. By this time Bethe was acknowledged as one of the leading nuclear theorists in the world, so Oppenheimer naturally asked him to participate. On the way to California by train, Bethe stopped in Chicago to pick up Edward Teller. There Bethe got the chance to see Enrico Fermi's developing nuclear reactor and, in his words, "became convinced that the atomic bomb project was real, and that it would probably work." He spent that summer working on the theory of nuclear weapons and in April 1943 went to Los Alamos, which had just opened as a laboratory. Eventually he became head of its theory division.

Now to the drawing. On November 29, 1943, Bohr and his son Aage sailed from Glasgow on the Aquitania for New York City. They arrived on December 6. Bohr was assigned the code name of Nicholas Baker, and Aage became James Baker; they were also given bodyguards. On December 28, after having had high-level meetings in Washington, D.C., with many offcials—including Major General Leslie R. Groves, the commanding offcer in charge of the Manhattan Project—Bohr departed for Los Alamos. On the 31st, presumably just after arriving at the laboratory, he met with a select group of physicists. The principal purpose of this meeting was for Bohr to tell the attending physicists what he knew about the German e›ort to make a nuclear weapon—in particular what he had learned from Heisenberg.

During one of my interviews with Bethe, he described this meeting, though not in any detail, and told me about the drawing. This is what he said to me (I have it on my tapes): "Heisenberg gave Bohr a drawing. This drawing was transmitted by Bohr later on to us at Los Alamos. This drawing was clearly the drawing of a reactor. But our conclusion was, when seeing it, these Germans are totally crazy. Do they want to throw a reactor down on London?" Only after the war did the Los Alamos scientists learn that the Germans knew perfectly well, at least in principle, what to do with a reactor—use it to make plutonium. But Bohr was concerned that one could actually use this reactor as some sort of weapon.

As far as I know, until I described this matter in the New Yorker, no one had ever mentioned such a drawing in print. In fact, my article on Bethe was frequently cited as the source for this odd sidelight on the Bohr-Heisenberg relationship. Hence, I found myself as a kind of a footnote to a footnote to history. My authority was shaken, though, at the start of 1994, during one of my periodic visits to the Rockefeller University in New York City, where I am an adjunct professor. Abraham Pais, a biographer of both Einstein and Bohr and a professor of physics emeritus at the university, called me into his offce. I have known Pais for 40 years but had not seen him in a while. This visit, then, was his first opportunity to tell me about a call he had received several months earlier.

It was from Thomas Powers, who at that time was writing Heisenberg's War. Powers had learned about the drawing from my book on Bethe. He was struck by the fact that at first glance it seemed as if Heisenberg had given to Bohr, in the middle of a war, a drawing of a highly classified German military project. That was such an extraordinary thing for Heisenberg to have done, if he did do it, that Powers wanted to check the matter out. He therefore got in touch with Aage Bohr in Copenhagen (his father had died in 1962). In a letter dated November 16, 1989, Aage Bohr wrote, "Heisenberg certainly drew no sketch of a reactor during his visit in 1941. The operation of a reactor was not discussed at all."

Stunned, Powers next contacted Bethe, who repeated to him exactly what he had told me 10 years earlier. In a quandary, Powers had called Pais, and now Pais was asking me. But Pais had done his own investigation. He had spoken with Aage Bohr, who once again insisted that there had never been any such drawing. Pais had also checked the archives in Copenhagen where all Bohr's private papers and journals are stored. Nowhere, he told me, did he find any mention of this drawing. Now it was my turn to be stunned. It is one thing to be a footnote to a footnote to history, but it is quite another to be a footnote to a footnote to incorrect history.

I promised Pais I would look into the matter myself, although, in truth, when I left his offce I did not have the foggiest idea of how I would go about it. Obviously, contacting Bethe again would not get me much further. Nothing could be more direct than what he had told me and repeated to Powers. I would need witnesses independent of Bethe and Aage Bohr. That much was clear. But who? Oppenheimer was dead. Niels

Bohr was dead. Groves was dead. Who else could have seen that drawing?

The Investigation

I began, in fact, with less information than I have so far given the reader. All Bethe had told me was that Bohr had "transmitted" a drawing to Los Alamos. He had not related any specific details about the December 31 meeting, so initially I had no idea who might have been there. Indeed, I did not even have the specific date. All that I learned subsequently. But I did know physicists who were at Los Alamos at the time and who might have seen or heard about the drawing. Two came to mind. One was Victor Weisskopf, an old friend, who had been close to Oppenheimer.

The other was Rudolf Peierls. Peierls and Otto Frisch had in March 1940 made the first correct calculation—in principle—to determine the amount of uranium 235, or the critical mass, needed to make a bomb. (The fact that this mass turned out to be pounds rather than tons is what really prompted the Allied e›ort.) Peierls, along with Frisch, was at Los Alamos as of early 1944. I have also known Peierls for many years and have frequently discussed with him the history of nuclear weapons. So it was quite natural for me to write him as well. This I did in early February, and soon after, both men answered.

Peierls replied that he had never seen the "famous sketch" yet did not think that either Bethe or Aage Bohr had deliberately lied. He proposed that perhaps Niels Bohr had kept knowledge of the sensitive document from his family or that perhaps Heisenberg had only shown the sketch to Bohr, who might then have redrawn it. He suggested I contact Bethe about this possibility. Weisskopf also wrote proposing I contact Bethe once more, because he, too, had never seen or heard about the drawing.

Neither of these letters was what I had hoped to receive. Clearly, I had to write Bethe to tell him what I had learned and to see if he could shed any further light on the situation. But then I had an inspiration. I would call Robert Serber. Serber, a professor of physics emeritus at Columbia University who lives in New York City, is also an old friend. After receiving his Ph.D. in 1934 from the University of Wisconsin, he had won one of five National Research Council Fellowships in physics and chose to go work with Oppenheimer at Berkeley. During the next few years, he had become very close to Oppenheimer.

After a brief interlude at the University of Illinois from 1938 until 1942, Serber returned to Berkeley to work on the bomb with Oppenheimer. He was there in the summer of 1942 when Bethe and Teller arrived. By March 1943 he had moved, with the first batch of scientists, to Los Alamos. One of his early tasks was to give a series of introductory lectures on bomb physics to the arriving scientists. These lessons were collected into what came to be called The Los Alamos Primer, declassified in 1965 and first published in its entirety in 1992. If anyone knew about the drawing, it would be Serber because he was in constant contact with Oppenheimer throughout this period.

I called Serber, and immediately I knew I had struck a gold mine. Not only did he remember the drawing vividly, but he also remembered the precise circumstances under which he had seen it. He had been summoned to Oppenheimer's offce on December 31, where a meeting was already in progress. Oppenheimer showed him a drawing with no explanation and asked him to identify it. This was the kind of intellectual game Oppenheimer liked to play. Serber looked at it and said it was clearly the drawing of a reactor. Oppenheimer replied that in fact it was a drawing of Heisenberg's reactor and had been given to the assembled group by Bohr. Bohr, who was, as Serber recalled, standing next to Oppenheimer, did not disagree.

That is what Serber told me. But he also said he had some written material related to this meeting. A few days later copies of two documents arrived: a letter from Oppenheimer to General Groves sent the day after the meeting and a two-page memorandum written by Bethe and Teller on the explosive possibilities of the reactor. Unfortunately, although these documents were very suggestive, they did not, at least when I first read them, settle the issue completely. The Bethe-Teller memorandum did hold significant clues, but I will return to them later. Oppenheimer's letter made no mention of the drawing or of Heisenberg or of the Germans. But the last sentence clearly implied that Bohr had spoken to Groves in Washington about these matters. Perhaps something in Groves's own archives might prove enlightening.

Meanwhile I had at last written to Bethe, and on March 2, I received his answer. It begins, "I am quite positive there was a drawing. Niels Bohr presented it to us, and both Teller and I immediately said, 'This is a drawing of a reactor, not of a bomb.'… Whether the drawing was actually due Heisenberg, or was made by Bohr from memory, I cannot tell. But the meeting on 31 December 1943 was especially called to show us what Niels Bohr knew about the Germans' idea of a bomb."

Bethe o›ered a theory to explain the mystery: "Heisenberg thought that the main step to a bomb was to get a reactor and to make plutonium. A reactor, however, could also be used as a power source. Niels Bohr was very ignorant about the whole subject. Heisenberg probably wanted to show Bohr that the Germans were not making a bomb but merely a reactor. Bohr misunderstood completely, and only on 31 December 1943 was it finally explained to him that this was not a bomb. That drawing made a great impression on me. Again, I am surprised that Viki [Weisskopf] and Aage have forgotten about it. What does Serber say?"

I was able to write Bethe and tell him what Serber had said. I also wrote Teller to ask for his recollections of the meeting. I was not sure I would get an answer and never have. But I had also written again to Weisskopf, sending him copies of the memorandums from Serber. On February 23, I received a typically gracious Weisskopf letter, acknowledging that he had indeed seen the sketch but later forgotten about it.

I now had, I thought, enough material to return to Pais. I played for him my Bethe tape and gave him copies of all the documents. He was about to return to Copenhagen, where he spends about half the year with his Danish wife. He promised me that he would speak to Aage Bohr at an opportune moment. That happened late in June. By the 30th Pais had written to tell me what had happened. He and Aage Bohr had met, discussed the letters and reviewed the tapes. Still, Aage Bohr felt certain that Heisenberg never gave any such drawing to his father. So I wrote to Aage Bohr directly. In February of this year his assistant, Finn Aaserud, wrote, "Aage Bohr maintains that it is entirely impossible that Bohr brought with him to the U.S. a drawing from the 1941 meeting with Heisenberg and indeed that the discussion at Los Alamos you refer to had anything to do with the 1941 encounter at all."

Where does this leave us? I have asked myself this question many times since receiving Pais's letter last June. I was at a loss until recently, when I took another look at the memorandum that Bethe and Teller prepared for Oppenheimer and Bohr and eventually for Groves. It suddenly struck me that in the first sentence of the second paragraph of this report Heisenberg's imprint stands out like a sore thumb. It reads, "The proposed pile [reactor] con-

sists of uranium sheets immersed into heavy water." In other words, Bethe and Teller were not considering any old reactor design but rather a very particular one that Bohr had described to them. This design is actually the faulty reactor Heisenberg invented in late 1939 and early 1940, which he clung to until nearly the end of the war!

It is almost unthinkable that in the few short weeks from when Bohr learned about the Allied project to when he arrived at Los Alamos he would have produced his own design possessing the same flaws as did Heisenberg's. He must have gotten this idea from Heisenberg, either verbally or in the form of a drawing. Where else could it have come from?

The Evidence

Let me explain. Any reactor requires fuel elements, the uranium, and what is known as a moderator, a device that slows the speed of neutrons hitting the fuel. Neutrons traveling near the speed of sound are vastly more e›ective in causing fission than are the rapidly moving neutrons produced by the fissioning itself. So the fuel elements in a reactor are embedded in the moderator. But a designer must carefully choose from which material the moderator should be made and also how the fuel elements should be placed in it. The latter involves both art and science.

The trick is that the uranium itself can absorb neutrons without producing fission. This absorption becomes stronger as the neutrons are slowing down. If the geometry of the fuel elements is not well thought out, the uranium will absorb so many neutrons that a self-sustaining chain reaction will never take place. In fact, the most effcient design involves separated lumps of uranium embedded in a lattice within the moderator. How big these lumps should be, and how they should be arranged, involves art. But the worst possible solution is placing the uranium in sheets, or layers.

To return to the matter at hand, note that Bethe and Teller wrote, "The proposed pile consists of uranium sheets." Heisenberg chose just such a design because it involved easier calculations than did other schemes. Then there is the question of the moderator. Bethe and Teller stated that the sheets were to be "immersed into heavy water." This specification, once explained, also has Heisenberg written all over it. The role of the moderator is, as I have mentioned, to slow down the fissioned neutrons. The best materials for this purpose are the lightest because a collision between a neutron and an object having a similar mass results in the greatest energy loss. If the neutron collides with a heavier object it will bounce o› and change its direction but not its speed.

If mass were the only consideration, the ideal moderator would be hydrogen, whose nucleus is a single proton having a mass sensibly the same as the neutron's. But, in reality, ordinary hydrogen fails as a moderator because it absorbs neutrons. In contrast, "heavy hydrogen," which has an extra neutron in its nucleus, does not absorb neutrons. Heavy hydrogen is found in "heavy water." But in seawater, say, this heavy water is only about one part in 5,000. So to use it as a moderator, it must be separated from ordinary water—an expensive and diffcult process.

Carbon, on the other hand, is abundant and cheap, although somewhat less e›ective as a moderator. By late 1940 Heisenberg had concluded that only carbon and heavy hydrogen should be used as moderators. But in January 1941, Walther Bothe, who was the leading experimental nuclear physicist left in Germany, began working with graphite, the form of carbon commonly used in pencils. His experiments seemed to show that graphite absorbed neutrons too strongly to serve as an e›ective moderator. What Bothe did not realize was that unless the graphite is purified far beyond any ordinary industrial requirement, it will contain boron impurities. Boron soaks up neutrons like a sponge. One part boron in 500,000 of graphite can ruin that graphite as a moderator. All the same, because of Bothe's experiment, Heisenberg and other German physicists decided that heavy water was the only practical choice.

Needless to say, physicists who were responsible for the successful reactor program here made the same kinds of calculations. Like Heisenberg, they decided that a carbon reactor would need more natural uranium than a heavy-water reactor. Fermi and his colleague Leo Szilard had also done experiments on neutron absorption by carbon. But Szilard was a fanatic about the purity of the graphite, and so their graphite, unlike Bothe's, worked well as a moderator. Because carbon was so cheap compared with heavy water, they decided that it was the best moderator. Fermi's reactor, which first operated on December 2, 1942, had a lattice of uranium lumps embedded in carbon. All the German experimental reactors—none of which ever operated—used heavy-water moderators. Look again at the sentence in the Bethe-Teller memorandum: "The proposed pile consists of uranium sheets immersed into heavy water." It is as if someone had written "Made in Germany" on this design.

Putting everything together, there seems to be little doubt that Heisenberg attempted to describe a nuclear device to Bohr. It seems that this device was his version of a reactor. He may, or may not, have given Bohr a drawing, but Bohr clearly retained a visual memory of the design. Bohr, however, did not understand the difference between a reactor and a bomb at the time and assumed that Heisenberg was describing a bomb.

So Aage Bohr may be quite right when he says, as far as his father was concerned, there was no discussion of a reactor. He may also be right that Heisenberg never gave Bohr a drawing. None of the individuals I have contacted are sure that the drawing they saw was in Heisenberg's hand—only that it was a drawing of Heisenberg's reactor. This I think solves the puzzle, but it does not solve the mystery. What was the purpose of Heisenberg's visit in the first place? Those who admire Heisenberg have argued that it was to show Bohr that the Germans were working only on a "peaceful" reactor.

It also must be noted that when Heisenberg visited Bohr, he clearly knew that reactors could be used to manufacture plutonium and that plutonium could fuel a nuclear weapon. Why, then, did he visit Bohr? What message was he trying to convey? What was he trying to persuade Bohr to do, or not to do? What was he trying to learn? That is the real mystery, one we may never solve.

FURTHER READING

HANS BETHE: PROPHET OF ENERGY. Jeremy Bernstein. Basic Books, 1980.

NIELS BOHR'S TIMES: IN PHYSICS, PHILOS-OPHY AND POLITY. Abraham Pais. Oxford University Press, 1991.

THE LOS ALAMOS PRIMER: THE FIRST LEC-TURES ON HOW TO BUILD AN ATOMIC BOMB. Robert Serber. Edited by Richard Rhodes. University of California Press, 1992.

HEISENBERG'S WAR: THE SECRET HISTORY OF THE GERMAN BOMB. Thomas Powers. Alfred A. Knopf, 1993.