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How Realistic Was the Threat of "Hitler's Atomic Bomb"?

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Abstract

Using factual information on background knowledge, costs, personnel numbers, resources, and facilities from the Manhattan Project, we examine the feasibility of the development of nuclear weapons in Germany in World War II. We conclude that, while for various reasons, a uranium bomb would have been technically and economically out of reach in Germany, a few plutonium bombs might have been possible had a coordinated aggressive project been initiated no later than about mid-1940. However, the German scientists involved never established an understanding of the functioning of an atomic bomb as contained in the Frisch–Peierls memorandum and were never asked to provide such a basis on which a decision on an atomic bomb program could be based. This means that a German atomic bomb program did not fail as is often assumed; rather, it was never started. The German uranium project was never more than a scientific mission to study the possibilities offered by the newly discovered source of nuclear power.

Keywords: World War II; nuclear weapons; reactor; atomic bomb; Uranverein; Manhattan Project; Werner Heisenberg

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1. Introduction

For 80 years, books and articles have been written about why Hitler did not have an atomic bomb. While different views have been expressed, one fact is beyond question: the special unit of the US Army tasked with finding evidence of nuclear activities, ALSOS, did not find traces of even a preliminary stage of bomb development. ALSOS secured materials, arrested scientists, and collected some 400 secret reports. Its scientific head, Dutch-born physicist Samuel Goudsmit, had the opportunity to interrogate the scientists and to investigate their laboratories. In his book *ALSOS*, he concluded that there was no meaningful German nuclear weapons program [1].

Later authors attempted to find the reasons why "Hitler's atomic bomb" did not exist. The next two books, by Robert Jungk and David Irving, were written without access to documents that were kept secret until the mid-1980s [2,3]. Upon their declassification, American historian Mark Walker studied the 400 "secret reports" for his doctoral thesis, from which his first book emerged [4]. These books were the first serious treatments of the German wartime nuclear effort, with the latter two featuring much information on pile research. Walker concluded that German scientists did their best to make a nuclear weapon, but so long as Germany seemed to be winning the war, a new wonder weapon had little priority. When, in early 1942, the war began to turn seriously against their country, the German Army Ordnance Office (Heereswaffenamt; HWA) had to focus on short-term projects. It decided to withdraw from the project, which was subsequently continued without changes by the Reich Research Council. In 1992, soon after the publication of Walker's book, the "Farm Hall" transcripts, records of conversations held by ten leading German scientists during their internment in England, were released. This group included Werner Heisenberg, who was acknowledged by the participants as the intellectual leader of the program and who had paved the way by developing a theory for nuclear reactors. Thanks to the British intelligence officers who made the recordings, we can get a sense of the scientists' reactions to the news of the dropping of the first atomic bomb on Hiroshima. These transcripts reveal an almost unbelievable, yet undeniable, ignorance about nuclear weapons. Walker responded with a second book in which he attempted to explain Heisenberg's ignorance as a "temporary confusion" [5].

Walker became the leading historian on this subject and has remained so to this day, even though his interpretations have been disputed by a historian and several professional physicists [6–9]. Around the year 2000, German historian Rainer Karlsch used newly available documents in Moscow for another book, titled on "Hitler's Bombe", though what he meant were impossible bombs on the basis of inertial fusion [10]. Since 2015, two of us (M.P. and P. de K.) have refuted Walker's interpretation and developed a new explanation for the alleged failure of the German "Uranium Project" [11–13]. The most recent contribution was by Walker with a book that bears the title *Hitler's Atomic Bomb*, with the subtitle "History, Legend, and the twin Legacies of Auschwitz and Hiroshima" [14]. Here, his conclusion is essentially identical to that offered in his second book ([5], p. 206): that whether the German physicists did "try to build atomic bombs depends on the meaning of "try". If trying required making the enormous industrial-scale effort that was obviously going to be necessary, then the National Socialist state did not try; if trying meant working as hard as they could with the materials and resources that were available in order to make as much progress as possible [. . .] then these scientists did try. Readers will have to answer this question for themselves". Walker also concluded that "Hitler's atomic bomb is still influential today, not really because of what happened but instead because of what might have been" ([14], pp. 270–271).

In this article we investigate what "might have been" and whether the German scientists really "tried". While we certainly agree with Walker that the Nazi state did not start a large-scale atomic bomb program, we disagree sharply with his statement that German scientists did work "as hard as they could".

The outline of this paper is as follows. Section 2 reviews some statistics of costs, manpower requirements, and timescales of the Manhattan Project to frame the discussion and assess the prospects for German uranium and plutonium bombs; Section 3 offers details on the facilities of the Manhattan Project. Sections 4 and 5 examine the prospects for German uranium and plutonium bombs, respectively, with the latter including subsections on reactor development, reprocessing, the characteristics of plutonium, and bomb physics. Here, our main conclusion is that a German plutonium-based program would have had only a minor chance of success and that only if it had begun circa mid-1940 might a few bombs have been ready in 1944. Section 6 considers factors that inhibited a timely start to the German program. Section 7 offers a summary, and Section 8 offers some conclusions (After an initial version of this paper was prepared, a helpful reviewer pointed out to us that the assessment of wartime Allied intelligence was also that the best prospect for a German bomb program lay with plutonium. The Manhattan Project's commander, General Leslie Groves, addresses this issue in his memoir; he was also concerned that the Nazis might employ forced labor and circumvent safety precautions to speed up a production program [15]).

2. Assumptions and Statistics

We do not use a fictional German bomb project to assess the possibility of Hitler's atomic bomb. Rather, we use data on costs, personnel, and time requirements from projects that were actually carried out: the Allied Manhattan Project and the German V-2 rocket program, both of which formally started in mid-1942. Where we cite Manhattan Project facts such as starting dates, costs, and personnel numbers, we draw from the books of one of us (B.C.R.) and the official history of the Manhattan Engineer District [16–19].

The total cost of both projects was 2 billion each in the respective currencies (dollars and Marks) [20], and the budget of the wartime German nuclear program has been estimated at 10 million Marks. Based on comparing the Gross Domestic Products and exchange rates, we infer that a 2-billion expenditure had about the same effect on the two economies. The estimated Gross Domestic Products of the USA and Germany in 1940 were about USD 943 and USD 414 billion, respectively, expressed in 1990 dollars. However, the exchange rate in 1940 was 2.5 Marks to the Dollar [21,22]. A link between the V-2 program and a possible German atomic bomb project exists in that the V-2 program was only started by Minister of Munitions Albert Speer once he had been convinced of the futility of developing an atomic bomb in June 1942 [23]. For the V-2 program, some 60,000 concentration camp inmates and forced laborers were employed, a third of whom died due to inhumane conditions. While the development work was performed by a relatively small group of engineers, the huge workforce was engaged in the production of more than 600 rockets per month. We take this as an upper limit for a possible workforce in a German bomb project. It should go without saying that a simple comparison of numbers by no means tells the whole story: Manhattan Project employees were paid for their labor, were motivated by patriotic pride in contributing to the war effort, and included many highly-trained scientists and engineers. Rocket construction was conducted in the "Mittelbau Dora" concentration camp by inmates and forced laborers, of whom 20,000 died as a result of inhumane conditions [24]. This forces the assumption that work on a reactor and plants for reprocessing and radioactive waste storage would also likely have been performed by concentration camp inmates or prisoners of war without adequate protection, as General Groves speculated.

From a technical perspective, the V-2 program was not comparable to the German Uranium Project. The Uranium Project, which started in September 1939, concerned harnessing a completely new form of energy, whereas the V-2 program was a step-by-step improvement of a known technology with comparatively simple solutions. For example, when the rockets, after reaching an altitude of 100 km, repeatedly exploded before impact due to heating upon reentering the atmosphere, it was sufficient to stuff some glass wool insulation between the explosive charge and the outer wall of the rocket to ensure that 70% of them, if not hitting their target (their accuracy was poor), would at least detonate on the ground. In contrast, in the case of an atomic bomb, the problem of possible premature detonation was of an entirely different order of magnitude: such a detonation could render a very expensive weapon essentially useless; addressing this problem required tight control of fissile material purity and development of the high-speed implosion method for triggering plutonium bombs.

The time schedule of a possible German project is framed by the historic development that we now know. To change the course of the war, several German atomic bombs should have been ready for deployment before the Allied invasion of Normandy or, at the latest, before the front shifted onto German territory, that is, in June or by the end of 1944 at the latest. Hence, we surmise that a German project would have had to be started about a year earlier than the Manhattan Project. From the Manhattan Project, we can infer a time frame of approximately three years to produce four bombs from the time that the Project was formally established in August 1942: the Trinity bomb, those dropped on

Hiroshima and Nagasaki, and a fourth one not deployed to the Pacific. We must bear in mind, however, that the formal start of the Manhattan Project was preceded by a roughly three-year period of intensive basic research at universities and industries in both the USA and Great Britain, during which the essential principles and boundary conditions for the construction of atomic bombs were established. Since this was carried out largely through personal initiatives by small groups of scientists, government administrators, and industrial executives, we cannot conclude that the three years from mid-1939 to mid-1942 were necessarily required for that; with a well-organized and well-funded program, it is quite conceivable that this foundational work could have been completed in a much shorter time. Evidence for this is, for example, Frisch and Peierls' memorandum on the physical feasibility of atomic bombs, which was apparently produced over a few days in the spring of 1940 [25].

As elaborated in what follows, our fundamental assumption is that only the smaller part of the Manhattan Project, that for the production of plutonium bombs, may serve for an orientation for the efforts that would have been needed in Germany. The building of a single uranium bomb consumed two thirds of the Manhattan Project's finance and manpower and would have been completely out of reach in Germany for both economic and technical considerations. Plutonium bombs would have been the only remotely feasible choice for a project whose goal was to produce a few bombs for the purpose of preventing defeat.

To appreciate our reasoning, it is helpful to survey the technical, financial, and manpower resources devoted to the Manhattan Project. This is conducted in the following section, after which we consider the prospects from the German side.

3. An Overview of the Manhattan Project

The vast majority of Manhattan Project finances and personnel went into constructing and operating the Project's two fissile-materials production facilities, that for creating pile-bred plutonium at Hanford in the state of Washington and uranium enrichment processing at Oak Ridge, Tennessee. We review both of these, starting with Hanford.

Land acquisition at Hanford began in February 1943. The first step was to to build a camp to house construction workers; by November, this occupied some some 5300 workers. By July 1944, construction of the piles themselves was underway, and the camp was home to 45,000 people. The prime contractor for Hanford, the DuPont Corporation, interviewed over 262,000 applicants and hired over 94,000 to maintain an average workforce of 22,500 over the life of project; the remote location and working conditions caused extensive turnover. The first of three graphite-moderated piles achieved criticality in late September 1944 but was shut down temporarily because of the effects of neutron-capturing xenon poisoning. The other two piles achieved criticality in December 1944 and February 1945, at which time the first lots of separated plutonium were being sent to Los Alamos. The total construction plus operations cost of the Hanford Engineer Works to the end of 1945 was about USD 390 million, equivalent to roughly one half of the total cost of the V-2 program.

By the end of 1945, the Hanford facilities had achieved the capacity to produce a new plutonium bomb about every 10 days. The arithmetic behind this impressive figure is straightforward: In a reactor fueled with natural uranium, plutonium is synthesized at a rate of about three-quarters of a gram per day per megawatt (MW) of operating power. Each of the three Hanford reactors nominally operated at 250 MW, hence yielding a combined output of about 560 g of Pu per day; however, they were often operated at higher power levels to speed production. The Fat Man bomb used about 6.3 kg of Pu or about 11 days worth at the nominal power rating. Of course, this figure would apply once the reactors and reprocessing operations were in a steady state.

The effort to build the uranium bomb was much larger. We describe it here to demonstrate that this could not have been done in Germany during the war. To set the context here, it is helpful to review some of the relevant characteristics of uranium and how it was enriched during the Manhattan Project.

U-235 occurs at an abundance of only 0.7% in natural uranium. High enrichment of uranium-235 is particularly difficult for two reasons: Not only is the 235 isotope very rare, but its mass difference from the dominant 238 isotope is very small, only 1.35%. Any enrichment method is ultimately based on mass differences; so, many consecutive enrichment steps are needed to significantly raise the concentration of U-235: One third of the total separation work is needed to raise the abundance from 0.7% to only 3% [26].

In this section we discuss the Allied enrichment processes; German efforts are described in the following section.

At the beginning of World War II, four main isotope-separation techniques were under consideration: thermal diffusion, gaseous diffusion, centrifuges, and mass spectroscopy. The most advanced process at the time was the "Trennrohr" (thermal-diffusion separation tube) developed in 1938 by Klaus Clusius and Gerhard Dickel. Of these four, General Groves decided to discontinue centrifuge research in late 1943. As to the other three, within two years gigantic plants were built at Oak Ridge, Tennessee, for large-scale uranium enrichment by means of electromagnetism, thermal diffusion, and gaseous diffusion. These operated in a combination series/parallel arrangement, with the processing of feed materials constantly being adjusted as facilities came into operation. The smallest of the three was a Clusius-type thermal diffusion plant code-named S-50. This technique, which worked well for the separation of gases and of isotopes of light elements, was based on thermal diffusion and required no moving parts. To avoid problems encountered with the German effort, as described in the following section, this was designed to achieve only a very slight enrichment, from 0.7% U-235 to 0.86%.

We will touch only briefly on the Oak Ridge gaseous diffusion plant here (large as it was), as it had no German counterpart; our main focus will be on the enormous electromagnetic operation. Ground was broken for the first components of the electromagnetic facility, code-named Y-12, in February 1943. This facility was based on scaling up isotope separation by mass spectroscopy from laboratory to industrial scales using enormous vacuum tanks, an approach apparently not seriously considered in Germany, for reasons we discuss in the following paragraph. The first experimental unit became operational in August 1943, with the first production unit in November of that year, although it was initially extremely inefficient. By September, the construction force hit 10,000 and would later peak at 20,000. This facility required some creative engineering, such the temporary use of over 12,000 US tons of Treasury Department silver for the windings of the magnetic-field coils.

A constraining factor in Y-12's operation was its need for enormous quantities of electrical power. Between November 1943 and the end of September 1945, electricity consumption totaled 1.85 billion kWh at a cost of nearly USD 8 million. This figure is by itself about equal to what was invested in the entire German nuclear program during the war. By the end of the war, Oak Ridge was consuming close to 1% of all the electricity being generated in the United States. From 1943–1945, American electricity production averaged about 270 billion kWh per year [27]. In contrast, a postwar British Intelligence assessment of wartime German electricity supply estimated production of about 85 billion kWh in 1943 [28]. By that time, the German economy was already becoming stressed. The contracting company for Y-12, Stone & Webster, would interview some 400,000 people for construction jobs, and the number of vacuum tank operators alone would grow to 4800. German intelligence apparently had no inkling of these enormous numbers or desire to find out.

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The gaseous diffusion factory, known as K-25, was one of the largest buildings in the world under one roof, eventually housing 2892 processing tanks within which uranium hexafluoride gas was pumped through metallic membranes perforated with millions of tiny holes; molecules containing the lighter isotope of uranium would pass through the membrane slightly more frequently than their heavier counterparts. The construction force for K-25 peaked at just over 19,600 in April 1944, but difficulties in fabricating the membranes delayed the first introduction of process gas until January 1945. Work on Oak Ridge's third and much smaller system, a thermal diffusion plant, did not begin until mid-1944.

In contrast to the prodigious output of plutonium at Hanford, to the end of 1945 Oak Ridge produced enough enriched uranium to supply only three or four bombs: about 70 kg by mid-August (enough for one bomb) and a further 165 kg by the end of the year. Pile production was more efficient, and, with its compressive implosion design, the Fat Man bomb could be fueled with about one-tenth as much fissile material as the uranium-based Little Boy gun-design bomb. In a memorandum to Army Chief of Staff General George Marshall dated 30 July 1945, General Groves estimated that about a dozen bombs should be available by the end of the year, the majority of them being of the plutonium type [29]. By the time of Hiroshima, thinking at Los Alamos was already moving ahead to the idea of an even more efficient "composite core" weapon that would use a combination of U-235 and Pu-239, although General Groves wanted to stick to the proven designs while the war was still on [30].

Overall, the entire Oak Ridge complex cost about USD 1.2 billion, three times the equivalent cost of the V-2 program. Further, while there is no precisely-recorded figure for the cumulative number of people that worked on the Manhattan Project in some capacity or other, a couple of summary statistics can be offered. First, the entire Manhattan Engineer District workforce peaked at about 125,000 in mid-1944, with many of these being in construction. Second, historian Alex Wellerstein has estimated that by August 1945, some 485,000 people had been employed in total, representing about one out of every 250 people in the United States at the time [31,32].

4. What Were the Prospects for German Uranium Bombs?

By late 1939, the concept of an atomic bomb was circulating in the physics community, although the concept of how one would operate was still in a somewhat confused state. The prevailing idea was that an explosive reaction would have to use slow neutrons to take advantage of the large fission cross section of U-235 at thermal energies. The main figure here was Niels Bohr, who also believed, however, that a putative explosion would shut itself down upon reaching a temperature of a few thousand degrees because the protons in any moderating substance would have such high kinetic energies as to render them ineffective at slowing neutrons. In France in May 1939, Frédéric Joliot-Curie and his colleagues Hans von Halban and Lew Kowarski filed a patent titled Perfectionnements aux charges explosives, which outlined basic design concepts for an atomic bomb. While their application made no mention of enrichment, and they referred to using hydrogen compounds to reduce the critical mass (i.e., using a moderator), some of their ideas were entirely valid, such as dividing the fissile material into subcritical parts to be assembled at the moment of detonation, providing a neutron initiator, using a tamper, and shielding against premature triggering by cosmic rays. French researchers' habit of applying for patents on reactors and bombs caused no small amount of concern among Manhattan Project officials [33].

The first clear understanding of a bomb based on unmoderated *fast* neutrons *and* essentially pure U-235 seems to have occurred to Otto Frisch in early 1940, an inspiration which led to the March 1940 Frisch–Peierls memorandum and the formation of the British MAUD committee. In the USA, the notion of fast-neutron bombs took longer to become appreciated. The first report of Arthur Compton's "Committee on Atomic Fission", prepared in May 1941, refers explicitly to bombs utilizing thermal neutrons. This seems a strange oversight in that American scientists had been privy to MAUD meetings in Britain; it was not until the group's second report, prepared in July of that year (about simultaneously with the MAUD report) that the idea of a fast-neutron bomb was raised by Ernest Lawrence in a discussion of the successful synthesis of plutonium. In Germany, Werner Heisenberg conceived of a runaway reactor fueled with highly-enriched U-235, but this would obviously not have been a nuclear weapon as such. Whether and when he understood that one needs fast neutrons for a bomb is not absolutely clear, but in any case, in the German program no work was done at all on U-235 and fast neutrons. At Farm Hall, Heisenberg would claim that he "always knew" that a bomb could be made with 235 and fast neutrons, but he gave no indication of when he had come to this realization [34]. In any event, the need to enrich uranium was raised in the Frisch–Peierls memorandum.

In Germany, Paul Harteck and Wilhelm Groth, with the support of Clusius, Dickel, and Maierhauser, experimented with using the Clusius–Dickel process for uranium enrichment through 1939–1941. However, they found that the separation coefficient of the only practical gaseous compound of uranium, namely uranium hexafluoride (UF_6), was much lower than expected, due to the softness and the large size of the molecules, and this approach was abandoned in the Fall of 1941; this is why the analogous American plant achieved only a small level of enrichment. Some discussion of the German effort along this line is given by Maier [35]. In the autumn of 1941, Harteck and Groth began to study the centrifuge process, which is particularly well-suited for the separation of large masses, because it depends on the mass difference of the isotopes as opposed to their absolute masses. Harteck and Groth choose the centrifuge type developed in the USA by University of Virginia professor Jesse W. Beams [36]. They had it built by the Anschütz company, but the work was hobbled by materials shortages and Allied bombing raids; their work is also described by Irving. After the war, Beams studied the progress Harteck and Groth had made and concluded that the Germans had recognized the potential of the centrifuge process for uranium enrichment but never got beyond the experimental stage, reporting that "at the end of the war they were far behind where we were in this country at the end of 1943 when support of the [American] centrifuge project was effectively cut off" [37]. Today, centrifuges are the most economical technology for uranium enrichment, but this is the result of a British–Dutch–German collaboration that has spanned several deacdes. The key to this success was a materials development program that took many years to perfect. During the war, the time from the start of work on centrifuges in the Fall of 1941 until the end of the war was only a fraction of the time that would have been needed to allow a similar technical breakthrough, not to speak of the time needed to build larger plants and to operate them in order to produce sufficiently large amounts of uranium 235.

Given the immense cost, power, and personnel requirements of the Oak Ridge complex described in the previous section, we conclude that it would not have been practical in the wartime situation in Germany to attempt to reproduce it; and its immense size would have made it terribly vulnerable to Allied bombing raids. With the problems encountered with the thermal and centrifuge methods, Werner Heisenberg's conclusion that a uranium bomb would not be achievable in Germany during the war was entirely correct.

In sum to this point, we conclude that a uranium bomb was out of reach for the Germans during World War II. This leaves only the possibility of plutonium bombs, facilities for which would likely have to have been built underground. Realistically, German scientists likely could not have performed better or faster than their Allied counterparts given their circumstances; so, our four-year timetable optimistically assumes that no major delays would have occurred.

5. What Were the Prospects for German Plutonium Bombs?

Hahn, Meitner, and Straßmann discovered in 1937 that neutron irradiation of uranium produces the radioactive element 93 [38,39]. They could not identify the subsequent product, which, therefore, must have a long half-life. In June 1940, German scientists learned from the a publication by McMillan and Abelson—the last article on nuclear fission appearing in the United States during the war—that the very long-lived element 94 is indeed formed [40]. Carl Friedrich von Weizsäcker, one of Heisenberg's closest collaborators, had thought of the use of element 93 for a bomb, but it is too short-lived, and his thinking was corrected by McMillan and Abelson's publication [41]. This point is important, as any researcher familiar with Bohr and Wheeler's theory of fission would have then inferred that the mass-239 isotope of element 94 could have fissility properties much like those of uranium-235 as they are both "even/odd" isotopes [42]. Thus, it was known to scientists on both sides of the war that, in a reactor, a new element would be produced that would be suitable as material for an atomic bomb and that could be obtained via chemical separation, without having to perfect isotopic separation. With this, a new way to the bomb had opened up.

The road to actually creating the first microscopic sample of Pu was not fast, however. Following up on McMillan and Abelson's work, Glenn Seaborg and his colleagues began the search for the new element in the summer of 1940. By late that year, deuteron bombardment of uranium yielded the first sample of Pu on which chemical analyses could be performed. This reaction, however, gives rise to the short-lived (88 years) isotope Pu-238, but this is now considered to be the discovery reaction. This was written up in a paper dated 28 January 1941, which was withheld from publication until 1946. In late January 1941, they began experiments with the direct neutron bombardment of uranium, which does yield the 239 isotope of Pu. By late March, 0.3 micrograms of Pu-239 had been synthesized, and by late May, tests of its slow-neutron fissility verified that it was more fissile than U-235. Because Pu-239 can be bred from U-238—which is over 100 times as abundant as U-235—this discovery meant that, about a month before the German invasion of Russia, the supply of potential bomb material was potentially increased by a factor of over 100 if the requisite production piles could be built.

Between the discovery of the Pu route to the bomb and the need to have a few bombs to stop the Allied invasion, the time window available for developing bomb theory and potentially building a few plutonium bombs in Germany beginning in June 1940 was only four years. Although it seems unlikely that Germany could have achieved the goal under the increasingly difficult wartime conditions, it cannot be ruled out in principle, in contrast to the case of the uranium bomb. Therefore, in what follows, we will examine the theoretically best possible course of events to determine how the objective could have been reached under very favorable circumstances and whether the requirements for funding, resources, and development would have been feasible. To avoid misunderstandings, we emphasize that here we describe only the most favorable scenario and not a fictional "real" development, in order to show whether success might have been conceivable under the most advantageous conditions.

5.1. Reactor Development

Regarding reactor design, the HWA made the fundamental decision in May 1940 to use heavy water and not carbon (graphite) as a moderator. The German program thus took a different path from that in the United States. Heisenberg had expressed doubts in his reactor theory about the suitability of carbon as a moderator, because of the size of its own capture cross section for neutrons and the inevitable presence of neutron-capturing contaminants, particularly boron. To this end, Bothe and Jensen in Heidelberg measured the capture cross section in a careful experiment using the purest available electrographite [43]. The high value yielded by the experiment meant that reactors with graphite could either not be built at all or only on an enormous scale. On the basis of this measurement, the HWA took the decision in favor of heavy water, an action that has been long disputed in the historiography of this subject, as the first working reactors in the United States used graphite moderation. It was assumed, even by Heisenberg, that Bothe and Jensen must have made a mistake [44]. According to more recent findings, however, their measurement was absolutely correct [45]. The carbon-based graphite in Germany had more impurities than the oil-based American type; so, the decision in favor of heavy water was correct. The decision for heavy water had another advantage: reactors would need to be built inside a cavern for protection; a graphite-moderated system would be large and present difficulties in removing waste heat, whereas a heavy water-moderated system would be more compact, as they require less uranium per unit mass of moderator.

Ordinary water contains heavy water at a ratio of about one part in 6500; the heavy water is isolated by distillation or electrolysis. For the German program, it was convenient that the only large-scale heavy water production facility in the world was located in Norway, which had been occupied by the Wehrmacht. As the Third Reich did not pay for deliveries from occupied countries, economic reasons probably weighed heavily in the decision of the Army Ordnance Office. However, there might have been other motives. The Navy was the only branch of the armed forces to show interest in the uranium project, as it wanted to use reactors for the propulsion of ships, particularly submarines. For that purpose, a compact heavy-water reactor would have been better.

In the Norwegian plant, heavy water was produced by electrolysis as a by-product of the production of hydrogen for ammonia synthesis used for fertilizer production; the heavy water output initially amounted to just 10 kg per month. Paul Harteck began working on a better production process, which ultimately achieved a rate of 180 kg per month. Considerations of building a second stage in Norway were abandoned due to the risk of sabotage, but, with the knowledge gained, several plants could have been constructed at power-plant sites within Germany, although these would have been vulnerable to bombing raids [46].

What scale of heavy water production might have enabled a large-scale project? The Manhattan Project established its own heavy water production facilities, one in Canada and three in the United States. Production in Canada began in June 1943 and totaled just over 10,000 kg by the end of 1945; that in the US began in late 1943 and totaled about 20,500 kg by the end of September, 1945. The Project's first heavy water moderated pile, CP-3, achieved criticality in May 1944, using about 6300 kg of that material as both coolant and moderator, and operated at a power of 300 kW. From the production figures given in Section 2 above, this is too low a power output for efficient plutonium production. Heisenberg's last heavy water pile experiment in the spring of 1945, B-VIII, contained only about 1400 kg of heavy water. Thus, production would have needed to be ramped up dramatically to support a meaningful plutonium production program. Even if the German program had succeeded in developing, say, a 100-MW pile, some 80 days would have been required to synthesize 6 kg of plutonium, about the amount in the Nagasaki Fat Man bomb; to this would have to be added the reprocessing time after the irradiated fuel had been allowed to cool.

To close this subsection, it is illuminating to consider a few more comparative statistics. In one sense, it can be argued that the American and German pile programs ran in rough parallel until about the middle of 1942, in that both programs achieved experiments with positive neutron growth at that time: Heisenberg and Döpel in Leipzig with their heavy water moderated L-IV pile (∼May) and Fermi and his collaborators in Chicago with their graphite-moderated "exponential" pile #9 (∼June/July). However, the amounts of materials involved were quite different. The Leipzig pile involved about 140 kg of heavy water and 570 kg of uranium; Fermi's pile involved some 32,000 kg of graphite. His report on this pile does not state the amount of uranium involved, but his last pile built at Columbia University early that year involved some 3900 kg of uranium oxide. Neither of these piles was self-starting nor self-sustaining, however; they both used neutron sources. By the time Fermi advanced to his first self-sustaining pile in December 1942, the CP-1 pile, he had access to over 350,000 kg of graphite plus some 5600 kg of pure uranium metal and 36,000 kg of metallic uranium oxide. A year later, the X-10 pile at Oak Ridge, which operated at a power level of up to 4 MW, boasted over 600,000 kg of graphite moderator plus 100,000 kg of pure uranium metal fuel. In contrast, the highest amount of fuel in any German pile experiment was about 6800 kg of uranium oxide in Karl Wirtz's "Virus House" piles in Berlin in late 1940. A survey of wartime pile developments in various countries can be found in a recent paper by one of us [47]. From figures given in Irving's *The Virus House*, the total production of metallic uranium in Germany during the war amounted to about 13,700 kg, not enough for even a single loading of the relatively low-power X-10 pile ([3], p. 151). Both heavy water and uranium production would have needed to be significantly ramped up to have supported a meaningful plutonium production program.

5.2. Reprocessing

Although the plutonium route to a bomb has the advantage of avoiding isotope separation, it also involves a dangerous and difficult-to-solve complication: the synthesized plutonium must be chemically isolated from the irradiated fuel. The waste fuel contains highly radioactive fission products. Since only a very small fraction of the parent fuel is converted to plutonium, the spent fuel becomes, after the Pu has been extracted, an enormous waste hazard. In the Manhattan Project, remote handling techniques were developed to carry out the chemical separations behind thick concrete walls and leaded-glass windows. Exhaust gases from reprocessing plants had to be filtered, and the dangerously radioactive liquid wastes were collected into underground tanks. In Germany, destruction by bombing would have caused a regional catastrophe; so, reprocessing would likely have had to have been be carried out in rock caverns, a considerable and expensive construction complication.

5.3. Plutonium

As alluded to above, well before any reprocessing techniques could be credibly contemplated, an entire research field, the study of the properties and production of element 94, would have to have been established. In 1940, this simply did not exist in Germany.

At that time, the only way to produce at least microscopic quantities of the new element was via the use of cyclotrons. The fact that they were still missing in Germany was remarkable in itself, for without this new workhorse of nuclear research, the country was at risk of losing its self-image as the "motherland of nuclear physics". In 1939, 14 cyclotrons were in operation around the world: nine in the U.S., two each in England and Japan, and one in Denmark. A further 27 were under construction. In Germany, apart from a very small accelerator at the University of Bonn, only one cyclotron was being built, by Walther Bothe in Heidelberg. He received no support from the Army and was only able to bring it into operation shortly before the end of the war. Another cyclotron was built at the Reich Postal Research center of Manfred von Ardenne in Miersdorf, but it was not completed by the end of the war. The neglect of cyclotrons by the HWA remains one of the great unresolved riddles of this history. However, even if the construction of cyclotrons had been ordered following a mid-1940 decision to launch a major atomic bomb project, it would likely have been too late to assemble the necessary knowledge for the program from scratch.

The only realistic prospect for a plutonium program in Germany would have been to have made use of two captured cyclotrons in the occupied cities of Paris and Copenhagen. The one already operating in Copenhagen would have been suitable for the production and study of plutonium, but Heisenberg blocked plans to bring it to Germany with the help of Carl-Friedrich von Weizsäcker, whose father was state secretary of the Foreign Office and previously Ambassador to Denmark [48]. The Paris cyclotron was still under construction when it was captured and was completed by Frédéric Joliot-Curie with the support of Wolfgang Gentner from Heidelberg. Gentner had returned from a post-doctoral stay at Berkeley in 1939, where he had become a cyclotron expert. Gentner also prevented the use of the accelerator by members of the Uranium Club [49].

Without a cyclotron and before the development of reactors, there was no other way of producing any appreciable amount of plutonium. Walker's assertion that "No one tried harder than Otto Hahn, or wanted more, to produce small samples of plutonium and analyze them chemically, and it was exactly this crucial first step, taken successfully by Philip Abelson, Edwin McMillan, Glenn Seaborg and others in a joint effort at the University of California, that allowed the United States government to commit itself early on to large scale plutonium production" is mistaken ([4], p. 231). In his irradiation experiments, Hahn could produce only picogram-level amounts of fission products, not enough to detect chemically or spectroscopically. He could potentially establish their presence through measurements of their radioactive decay, but the half-life of plutonium, over 24,000 years, is so large as to render this impractical. At the time, McMillan and Abelson estimated the half-life to be a million years or more. Hahn would of course have loved to be the first to hold a man-made element in his hands, but that was impossible. At best, he could try to determine the production rate by determining the half-life of the precursor product, neptunium [50].

Plutonium proved to be a very complex and potentially dangerous element. Between room temperature and its melting point, Pu has six different structural phases, and pulverization of plutonium into a powder by phase changes during heating may cause spontaneous combustion. It is also toxic if inhaled and so needs to be handled in glove boxes. Once it has been isolated, to form Pu into a desired shape requires alloying with a stabilizing binding material. The only suitable alloying material is gallium, a matter which involved significant metallurgical research at Los Alamos.

A further issue with plutonium is that of plutonium-240. In an operating reactor, Pu-240 is formed when already-synthesized nuclei of Pu-239 capture neutrons. This isotope tends to be spontaneously fissile, thus introducing a highly unwelcome source of neutrons within the plutonium. To prevent a resulting premature detonation, the proportion of Pu-240 had to be kept as small as possible by both irradiating uranium in a reactor for relatively short periods (about 100 days at Hanford) and by achieving detonation with extraordinary speed. For this, the HWA could have been well prepared, as implosion technology with shaped charges had been highly developed. The starting point for this had been the Navy's wish to develop mines capable of destroying ships from the seabed of of the North Sea at a depth of 40 m [51]. This is one instance where the Germans might have had an important advantage over the Allies had their program progressed to that stage. However, it has to be emphasized that in the implosion process, all detonators have to be synchronized to on the order of a microsecond; ignition of the plutonium bomb was certainly the most difficult problem that was solved at Los Alamos [52].

5.4. Bomb Physics

Perhaps the largest deficit for the German nuclear program in mid 1940 was that a realistic concept for a bomb did not exist. While plutonium studies could have been made in parallel to the reactor experiments, a clear understanding of the materials and technologies needed to build an atomic bomb would have been prerequisite to launching a large project. Heisenberg's description of a nuclear explosive made from almost pure uranium 235 was a vague and imprecise description of an exploding reactor amounting to but half a page in the midst of a 42-page report on reactors [53]. Before starting a large project, a group of good theoretical physicists would have had to have been formed to reproduce what Frisch and Peierls did in Birmingham in a few days [54]. While their famous memorandum was not perfect in that they seriously underestimated the critical mass of uranium 235, its essential physics was correct, and it provided actionable orientation for government decision-makers. A similar concept for a bomb was never established in Germany, either by Heisenberg or other physicists. This is not by any means to say that they were not more than capable of doing so, but they apparently never did.

It can also be mentioned here that turning physics into the engineering and assembly of actual bombs ready for combat deployment is far from trivial. At its peak, the Los Alamos laboratory employed some 2500 physicists, chemists, mathematicians, machinists, engineers, and ordnance experts. By the end of 1945, the cost of construction and operations at Los Alamos had accumulated to about USD 74 million.

6. What Inhibited a Timely Start of a Bomb Development Project in Germany in 1940?

Having surveyed the requirements and possibilities for a German program, we turn to the question of what factors inhibited the emergence of such a program.

A program to develop and build a few plutonium bombs would have incurred high costs and required a very capable workforce in science and industry. The scarcest resource, however, was time. Obviously, any participants could not have known this in advance. With every month that passed, the chances of success for a large-scale project dwindled. What happened in the period immediately after the discovery of plutonium (in principle, at least) in the summer of 1940?

The answer can be found in an official report by the HWA for a review conference in February 1942 [55]. Some context for this is relevant. In December 1941, given the deteriorating situation of the Russian front, the order was given to stop research unless it would produce results in time for use in the war. Hence, the Army decided to return the uranium program to the Reich Research Council. Work on the relevance of the plutonium route to a bomb should have started immediately after its discovery in 1940. While the February 1942 report speaks at length in its introduction and conclusion about the prospects of the new fissile material, the technical section shows that the discovery had no consequences at all for the Uranium Project. Only in an appendix is "Element 94" mentioned, with a reference to von Weizsäcker's recollection of McMillan and Abelson's publication. However, no working report is cited; a striking opportunity was recognized but not seized. Another surprising deficit is the total absence of any work on the physics of an explosive; all that is quoted is Heisenberg's and Müller's early work on an exploding reactor. Walker essentially ignores this inactivity. A chapter in the report on future planning emphasizes just how far the German project was from any consideration of a meaningful bomb project. Three future areas of work were anticipated. If a self-sustaining pile could be constructed—a development predicated on having available enough uranium and heavy water—two avenues were anticipated: first to develop the machine into a technically usable apparatus and, then, to consider possible military use, particularly as a source of power for ship propulsion and as a stationary energy source. The third area was the production of a uranium or element 94 explosive, but prospects along this line could not yet be reliably assessed.

In asking who bears responsibility for this situation, two rarely-mentioned figures come into the spotlight: Karl Becker and Emil Leeb, who shared the leadership of the Army Ordnance Office in the decisive years. A career officer, Becker was also a trained chemist and in 1933 had been appointed professor at the Technical University of Berlin. From 1937, he had also served as President of the Reich Research Council. The head of the Council's physics division, Abraham Esau, had already convened a group of scientists in April 1939 to explore the possibilities of using the newly discovered energy source; this was the first "Uranium Club". Immediately after the outbreak of war, Becker decided to put the Uranium Club under the auspices of the Army Ordnance Office, and he and his head of the research department, Erich Schumann, appointed Kurt Diebner to be responsible for the new club. Diebner was a physicist and a civilian employee with the lowest service rank (Regierungsbaurat) allotted to academics.

Becker's career came to an abrupt end in 1940 in the so-called "ammunition crisis", during which accusations arose from the Wehrmacht High Command against the HWA of inadequate production and procurement of the ammunition required for the French campaign. The situation resulted in Becker's suicide in April 1940.

Following Becker's death, General Leeb took over as head the Army Ordnance Office. Leeb was a career soldier with no ties to science, and he later (1944) reversed Becker's decision to place the research department directly under the HWA's executive staff and subordinated it to the Department of Development and Testing [56]. Leeb's main concern was to protect the Office's work from interference by politicians, and under him nothing changed after the discovery of the more promising path to the atomic bomb via plutonium. We know this because of inconsistencies in the February 1942 report. The "introductory overview" (pages 8–17) and "concluding remarks" (pages 132–134) praise the possibility of producing explosives from "element 94", but the actual technical report (pages 18–131) based on 140 secret reports shows that nothing had been undertaken in this direction up to the beginning of 1942 ([13], p. 649). In the second chapter, "Mode of Action of Energy-Producing Devices", only two important neutron-generating processes are mentioned: (1) the fission of U-235 by thermal neutrons and (2) the fission of U-238 by fast neutrons. The essential concept that is missing here is fission of U-235 by fast neutrons, which is how a bomb operates.

We will never know Becker's intentions for the uranium project, but the effective result was that Diebner's superiors, Schumann and Leeb, gave no real support to the uranium project.

In comparing the situation in Germany to that of the Allies, it becomes apparent that the greatest obstacle to a bomb program was the lack of an equivalent to the Frisch–Peierls memorandum. There was no scientifically-grounded assessment of the construction, functioning, and effects of an atomic bomb. In the beginning, Frisch and Peierls had no official mandate for their work; their motivation was the pure scientific curiosity typical of researchers. Without such a foundation, the responsible authorities in Germany could not make a decision to commit large resources to a speculative project.

Returning to the work of scientists, why was it that in Germany some spoke repeatedly about the possibility of an atomic bomb throughout the war, yet evidently no one made any attempt to determine how it would actually function or what its effects would be? Such an investigation involving extreme conditions of matter and energy should have been inherently fascinating to physicists. However, no one showed any initiative; the matter was left to Heisenberg, who limited himself to a few superficial and partly incorrect lines

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devoted to the “explosive” in his reactor theory. However, this is not really the relevant question: Heisenberg’s task was to devise a heat engine and not a bomb; so, it is not surprising that the Farm Hall transcripts reveal he had not attempted to calculate a critical mass, even if he may have understood that a bomb would have needed fast neutrons and essentially pure U-235. Bomb physics and plutonium never played a role in the work of the Uranium Club, even though Fritz Houtermans, who was not working within the Uranium Club, outlined a plutonium production reactor in August 1941 [57].

To address why no physicists took an interest in these matters necessarily enters the realm of speculation; so, we restrict ourselves to a brief comment. Frisch and Peierls had been trained in the scientific traditions of Germany by many of the same teachers as the members of the Uranium Club. In undertaking their work, were they driven by a desire to make themselves useful in their safe new homeland? Conversely, did the restraint shown by physicists in Germany stem from a precaution to keep their distance from a dangerous and brutal totalitarian regime? We will never know.

7. Discussion

In hindsight, the answer to the question of how realistic the threat of “Hitler’s atomic bomb” was is an unequivocal “not at all” in the case of a uranium bomb. For a few plutonium bombs, the situation is less clear. In terms of finances and personnel, the construction of a few plutonium bombs would have been difficult but possibly within the capacity of the Third Reich. However, the time available between the discovery of the plutonium possibility in mid-1940 and the Allied invasion of mid-1944 would have been a tight window. On the Allied side, over five years elapsed between the Frisch–Peierls memorandum and the Trinity test. In Germany, a tightly organized project might have had a chance of success if it had begun about the same time, before the economic strains of the war became overwhelming. However, at that time, Germany had achieved a fast victory over France. An atomic bomb appeared to be unnecessary for the prosecution of the war, and nobody thought of the potential to increase Germany‘s military power by possession of atomic bombs. Everything that happened afterward was irrelevant to the danger of Hitler’s atomic bomb. The low probability of success was a consequence of the decisions made by Esau, Becker, and Leeb in favor of a small purely academic Uranium Project by the RRC and the HWA and the relative lack of interest in cyclotrons. The most important factor, however, was that neither Heisenberg nor anyone else volunteered or was forced to develop the theoretical foundations of the atomic bomb. This answers also Walker’s analysis: “Hitler’s atomic bomb” in the form of a few plutonium bombs “might have been”, albeit with a very low probability of success, but the threat was not real, because the German scientists did not “try”, nor did they provide a basis for a responsible decision about a bomb project.

In assessing the question of fear of a Nazi bomb, we must also ask what facts could have been known to leaders and scientists of the Manhattan Project.

All previous authors on the uranium project have studied the German secret reports gathered by the ALSOS mission. However, what seems to have been left unaddressed is that some 500 publications on nuclear physics and cosmic radiation appeared in German scientific journals during the war, notably in *Die Naturwissenschaften* and *Zeitschrift für Physik*. Among the authors were many prominent physicists and chemists, including Heisenberg, Hahn, Bothe, Harteck, Siegfried Flügge, Walter Mattauch, Hans Jensen, Fritz Straßmann, Friedrich Houtermans, Erich Bagge, and Wolfgang Riezler. Anyone familiar with German physics must have realized that a development project for Hitler’s atomic bomb could not have been carried out without the involvement of at least some of these individuals, who apparently had time to devote to research beyond energy production from nuclear fission. Heisenberg himself found time to publish a book on cosmic radiation

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that presented the results of a 1942 symposium featuring 15 lectures, an indication that his interest was no longer exclusively focused on neutron-induced fission but mostly on nuclear reactions involving high-energy particles, which, without access to particle accelerators, could only be found in cosmic rays [58]. It is known that Soviet scientists concluded from this book that no work on an atomic bomb was being carried out in Germany; see [13], p. 646; see also [59]. Further, Heisenberg wrote a series of articles that prepared the ground for the future orientation of nuclear physics towards elementary particles that appeared in *Zeitschrift für Physik* [60].

Corroborating evidence of the German situation was turned up recently by one of us (P. de K.): a letter by Robert Oppenheimer to Manhattan Project security officer Major Richard Furman (Oppenheimer 1944) [61]. Dated 4 March 1944, the letter concerns a publication in *Zeitschrift für Physik* 121, p. 285 by Heisenberg's co-workers Maurer and Pose [62]. The paper was originally a secret report from January 1942, which was apparently declassified and published in 1944 without changes. The paper concerned measurements of the half-life of U-238. While Oppenheimer cautioned that the paper could be "a deliberate or a feigned or an enforced ignorance on the point which is decisive for our whole program" (that is, the paper could have been a deliberate deception), when taken at face value, such an open publication hinted that the Germans were very far behind in the race. Together with the vast number of non-fission publications, this reinforced the conclusion that German nuclear physicists had plenty of time to work on other fields of nuclear physics. The Americans probably never made a systematic study of all German open publications. In the United Kingdom, Rudolf Peierls did so for the first few years of the war and concluded that "The picture emerged that Germany had no crash program, no large-scale project that required a major participation by scientists. There did seem to be some atomic research going on, and Heisenberg and a few others were probably connected with it. On the whole, my findings were reassuring" [63]. Other examples along this line have recently been found among the papers of James Chadwick and Egon Bretscher in Britain. In the Chadwick papers is a report by Klaus Fuchs, probably dating from late 1941, examining a paper published by Fritz Houtermans in the November 1941 *Annalen der Physik* on the energy requirements of isotope separation [64]. While Houtermans remarks that his calculation was made with a view to "possible future isotope separation for technical purposes", Fuchs concludes that no attempt had been to apply the calculations to a large-scale plant and that they appeared to be of little practical value. He advises that the paper could be a "blind", but he is overall rather dismissive of the effort. Similarly, an August 1942 report by Fuchs and Rudolf Peierls found in Bretscher's papers surveys the German literature over about the preceding six months. They note that there are some papers pertinent to the "Tube Alloys" work (the British term for the Allied nuclear program) and slow-neutron research, but that they largely concern matters of minor importance; Fuchs and Peierls' tone indicates that they are not overly alarmed, consistent with his assessment related above.

The message of these examples is that experienced scientists could deduce a fair amount from the open literature. Of course, no prudent military intelligence officer would take these examples as conclusive proof that there was no meaningful German program. By 1944, the cost and complexity of the Manhattan Project had become so high that there could be no question but to continue the work; the momentum of the program was immense. After the capitulation of the German Reich, any fear of a "Hitler's atomic bomb" was irrelevant, but the war in the Pacific was still raging.

8. Conclusions

To close, we turn our attention back to the German scientists. They may well have suspected that their former friends and colleagues in the United States and Britain were working on a secret project. Conversely, those colleagues could have interpreted the continued activity of normal publications in Germany as an indication that this was no such project there. Of course, the former colleagues did not know that Germany lacked anything comparable to the Frisch–Peierls memorandum until the ALSOS mission carried out is work, but by that time, the war was long over.

Regarding the threat of "Hitler's atomic bomb", it is not totally impossible but very unlikely that a German project to build a few plutonium bombs could have been successful within only four years. However, this would have required an enormous effort during a time of the danger of destruction of facilities by air raids or the demands of building and operating highly-radioactive facilities underground. Ultimately, German scientists neither tried nor failed to produce a bomb; the Uranium Project remained a scientific exploratory program, whose mission was not one of design and production. With no understanding equivalent to that of the Frisch–Peierls memorandum, there was never a basis for a decision to enlarge the program in terms of finance, manpower, and industrial capacity to the extent needed to produce a few bombs. As the effort would have been very demanding and the prospects of success of such a program within the given time window very low, it was reasonable that the HWA never thought seriously about an atomic weapons program. We conclude that there is absolutely no credibility to the concept of "Hitler's Atomic Bomb".

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