Uranverein: A Physical Discussion

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Abstract: The aim of this study is to examine the German nuclear project, the Uranverein, from a technical standpoint in order to assess the plausibility of the two contrasting narratives -apologetic or polemic- regarding their failure to achieve the atomic bomb. From a scientific perspective, it can be argued that they possessed the necessary knowledge to pursue its development; however, they encountered significant contextual obstacles.

I. INTRODUCTION

This historical project focuses on the investigation of nuclear physics conducted in Germany during the Second World War as part of the project commonly referred to as the Uranverein. Its aim is to examine the technical and scientific aspects behind Germany's failure to develop an atomic bomb. In the literature, two opposing perspectives emerge regarding the reasons behind this failure: the portrayal of the Germans as either heroes or incompetents. In between, there is a whole spectrum of gray. The primary objective of this project is to evaluate the plausibility of these extreme versions in the context of physics. In order to analyze the progress of the Uranverein -what the Germans did and did not achieve, as well as their advances in knowledge and technical developments-, it is necessary to examine the physics behind the actual atomic bombs developed by the Americans. This will provide an overview of the knowledge needed to develop an atomic bomb, which can be compared with the accomplishments of the Germans.

For this purpose, extensive research has been conducted, including consultation of primary sources such as Werner Heisenberg's autobiography [3], and Samuel Goudsmit's *Alsos* [4], as well as a thorough review of relevant secondary literature, including the publications and articles listed in the References section. Worth mentioning, *Nazi Science. Myth, Truth and the German Atomic Bomb* by Mark Walker [2], “The Theory of Nuclear Explosives That Heisenberg Did not Present to the German Military” by Carl H. Meyer and Günter Schwarz [7], and “Laboratory Life Instead of Nuclear Weapons: A New Perspective on the German Uranium Club” by Christian Forstner [8].

Section II presents the aforementioned contrasting versions. Section III discusses the fundamental physics required for the development of an atomic bomb. Section IV highlights the advancements made by the Germans in key realms of physics research. Lastly, Section V presents our final conclusions.

II. TWO PERSPECTIVES: A CALL FOR BOYCOTT OR AN ACT OF NEGLIGENCE

The question of why Germany did not succeed in developing the atomic bomb is a matter of great interest and lacks a single, straightforward answer. The Uranverein has been extensively studied by historians, scientists and philosophers. Their collective findings reveal that the project was profoundly affected by disorganization, a lack of interest from part of key scientists, and undoubtedly by the interference of fascist politics in scientific and industrial affairs.

Werner Heisenberg's role within the Uranverein has been the subject of continuing controversy. Mark Walker distinguishes between two theses [2]: the apologetic thesis, in which Heisenberg explicitly refused to participate in the construction of an atomic bomb for moral reasons, as he would never provide such a weapon to Adolf Hitler; and the polemic thesis, which argues that German scientists were actual incompetent Nazis that lacked the necessary knowledge to successfully develop an atomic bomb ([2], p. 207).

According to Heisenberg's account [3], he and his team were well aware of the physics behind a nuclear explosive, but made a conscious decision not to build one. They struck a balance and chose to inform their army superiors that the development of an atomic bomb was feasible, thus ensuring the continuity of the project, while emphasizing that it would take considerable time to achieve, thus reducing the immediate pressure ([1], pp. 65-66). Furthermore, Heisenberg asserted that they believed that the exorbitant technical costs involved would provide physicists with a compelling argument to persuade their governments that atomic bombs would not be used in the course of the war ([6], p. 3).

The polemic thesis relies on *Alsos*, an American scientific intelligence mission, headed by the atomic physicist Samuel Goudsmit. The aim was to investigate German’s knowledge and progress on the uranium problem and the atomic bomb, concluding they did not possess an atomic bomb nor were

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likely to develop one in the near future. Goudsmit states that their work was small scaled, limited to an uranium pile in its early stages and that a selfsustained chain reaction had not been achieved [4]. *Alsos* was completed with *Operation Epsilon*, which consisted in the arrest at *Farm Hall* of German physicists and personalities like Werner Heisenberg, Otto Hahn, Paul Harteck and Carl Friederich von Weizsäcker, among others.

Goudsmit's basis for claiming that the Germans had a limited understanding of the atomic bomb can be divided into three parts. According to his claims, the Germans lacked comprehension regarding the fissionable material plutonium, the necessity of fast neutrons in such weapons, and the requirement for a small quantity of material. These three combined created the argument that Germans believed the reactor would be the bomb itself ([2], pp. 215-216). The plausibility of these assertions that would prove that Germans actually did not have the necessary knowledge on how to build an atomic bomb will be discussed in Section IV.

III. THE PHYSICS OF THE BOMB[1]

The development of the atomic bomb by the Manhattan Project in the United States (US) followed the discovery of fission in 1938 by Otto Hahn and Fritz Strassmann, German scientists, who investigated the outcomes of bombarding uranium with neutrons. Lise Meitner and Otto Frisch analyzed the results using Niels Bohr's liquid drop model, determining that these products resulted from this new form of nuclear reaction. Fission involved the division of a heavy nucleus which, upon absorbing a neutron, resembling a liquid drop, began to oscillate intensely, becoming unstable and ultimately splitting into two smaller nuclei. This process released multiple neutrons and a substantial amount of energy. Subsequently, the focus shifted towards the pursuit of a self-sustained nuclear chain reaction, which entails a reaction in which the neutrons liberated by fission are utilized to initiate the fission of neighboring nuclei, and so forth ([5], p. 297).

Bohr learned that it was the rare isotope U-235 (consisting on 0.71% of the natural uranium), and not U-238, whose fission by thermal neutrons was observed ([8], p.186). U-238 is then considered to be an obstacle to achieving a chain reaction as it absorbs neutrons without undergoing fission since its fission cross section -effective size of the atom as perceived by the fast neutron- is significantly lower than that of the U-235. Thus, in natural uranium the probabilities of fission are low, but can be increased in two ways ([8], p. 187). One method is to use a moderator, a substance that deaccelerates neutrons, but this makes the process too slow for an explosion. The second is to enrich the U-235 content on natural uranium. Note that a sample of almost pure U-235 can fission at low and high neutron energy levels with slow and fast neutrons ([7], p. 6), making a controlled or uncontrolled chain reaction, respectively. Thus, the explosive transformation can solely take place in almost pure U-235.

The subsequent stage in obtaining significant quantities of energy required the construction of the so-called nuclear reactor or pile, an structure where nuclear chain reaction takes place. There are two requirements to achieve the nuclear chain reaction. First, the neutron multiplication factor $k > 1$. This is, the number of neutrons from a generation to another has to grow. Second, it must achieve a minimum size of fissionable material, known as critical, to prevent neutron leakage. The critical size indicates the point at which the losses and the production of neutrons are at balance. This leads to a critical mass, the amount of uranium needed to construct a nuclear weapon ([7], p. 2). The critical radius is obtained from the diffusion equation[2],

$$\frac{\partial}{\partial t}N(\vec{r},t) = D\,\nabla^2 N(\vec{r},t) + \frac{\nu-1}{\tau}N(\vec{r},t)\,, \tag{1}$$

where N is the number of neutrons per $\mathrm{cm}^3/\mathrm{sec}$, ν is the average number of neutrons produced per fission, τ is the average time interval between fissions and D is the diffusion coefficient, how rapidly neutrons spread out throughout space, an uranium sphere of radius R. The non-stationary solution yields a critical radius of

$$R_c = \frac{\pi}{2}l\,, \tag{2}$$

where l, the diffusion length, is

$$l = \sqrt{\frac{D\,\tau}{\nu-1}}\,. \tag{3}$$

In 1940, it was discovered that the U-238 that absorbed a neutron became U-239, which decayed in the element 93, neptunium Np-239, in 23 minutes, and that this, in turn, decayed in the element 94, plutonium Pu-239, in 2.3 days. This element had the potential to be a nuclear explosive, and had the advantage, over U-235, that its isolation depended on the separation of two different elements, much simpler than the separation of two isotopes ([5], p. 302).

On May 1942, there were six possible paths to nuclear explosives in the US: four ways of isotope separation (to obtain U-235) and two ways to build a reactor (to obtain Pu-239). It was chosen to pursue them all.

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[1] Unless otherwise stated, the content of this section has been sourced from reference [1].

[2] The comprehensive deduction can be found in reference [7].

The ways of isotope separation used on Manhattan's Project were:

- Gaseous diffusion.
- Electromagnetic separation.
- Liquid thermal diffusion.
- Centrifugation.

Centrifugation was abandoned because of the need for excessive technical precision. The remaining three were combined to ensure the optimization of the separation of uranium isotopes. U-235 was the nuclear explosive utilized in the construction of the Hiroshima bomb.

The two ways to build a reactor were using either graphite or heavy water as moderator. Enrico Fermi's pile reached critical size for the first time in December 1942, using a high-purity graphite moderator. This achievement provided the fundamental basis for the alternative use of Pu-239, which ultimately led to the creation of the Nagasaki bomb.

The techniques used to detonate the Hiroshima and Nagasaki bombs were the shooting method and the implosion method, respectively, but this will not be detailed due to its inherent divergence from the primary objective of this project.

IV. URANVEREIN

The German nuclear fission project began in September 1939 under the auspices of the German Army, establishing Germany as the sole nation worldwide with a nuclear program at that time. The project was conducted at prestigious institutions such as the Kaiser Wilhelm Physics Institute and the University of Leipzig, among others, and involved the expertise of prominent physicists and other eminent scientists. However, it is worth noting that these individuals worked in separate factions that often refrained from exchanging information. A detailed account of the progress of the project can be found [1] and [2].

The analysis of German developments can be divided into the following subsections. Subsection A focuses on isotope separation, required for an uranium bomb. Subsections B and C delve into the moderator required for a reactor that produces plutonium, as well as the discovery of plutonium itself. Subsection D examines the German knowledge regarding the attainment of critical mass, which is essential for both U-235 or Pu-239 atomic bombs. Lastly, Subsection E discusses whether the Germans understood the distinction between a reactor or an explosive, which Goudsmit denied.

A. Isotope Separation

In Germany, the efforts on uranium separation did not yield significant progress or encouraging results ([1], p. 134). When the physicists at *Farm Hall* learned about the Hiroshima bomb, they remained highly skeptical that the Americans had actually achieved isotope separation ([2], p. 222).

Gustav Hertz was involved in research into the gaseous diffusion method, but faced credibility problems because of his Jewish heritage ([5], p. 301). Harteck also contributed to this field of study ([1], p. 60), but eventually shifted his focus to centrifugation ([1], p. 180.), which provided small scaled results ([1], p. 133).

Manfred von Ardenne proposed electromagnetic separation in 1940, but Weizsäcker contacted him and expressed his opinion on the unviability of a U-235 bomb due to technical reasons, which Ardenne took since Weizsäcker's scientific superiority ([1], p. 133).

Erich Bagge worked on a method called channel of isotopes, and in 1944 got some grams of separated isotopes ([1], p. 133).

B. Moderator

Both heavy water and graphite are good moderators for a nuclear reactor, but the latter has the cost advantage ([1], p.57). In Germany, the cross section of graphite -again, effective size of a carbon atom as perceived by the fast neutron that would slow the neutron by collision- was underestimated by Weizsäcker's assistants ([5], p. 301) and Walther Bothe wrongly confirmed experimentally those assumptions -it is assumed to be because their material was impure. Harteck also tried to observe a nuclear chain reaction in a mixture of uranium oxide and solid carbon dioxide, but did not detect neutron multiplication in account of having lack of uranium. If those experiments had had support, failure may have been avoided ([1], p. 63).

In 1940, Germans conceived a reactor of uranium and heavy water to form a new fissionable element. Even though they rejected graphite, they had possible ways to obtain nuclear explosives and were in a good position to develop their nuclear project due to the war situation ([1], p. 64).

During the war, a total of 22 experiments with uranium and different moderators were performed. They obtained a neutron multiplication factor over the unity, but they never reached the critical mass in account of they were lacked of heavy water. When they reconsidered graphite, they still hoped to reach the critical point before the end of the war, but soon after the Allies occupied the zone and destroyed their laboratories ([1], pp. 135-143).

C. Plutonium

In 1940, Hahn's group learned about plutonium ([5], p. 302). The same year, Weizsäcker reported to the Army Ordnance about the potential of this element as a nuclear explosive ([2], p. 220), and in 1942 Heisenberg alluded to this in a meeting in Berlin ([7], p. 15).

However, in *Farm Hall*, Harteck mentioned that the element 93 was a nuclear explosive that could be produced in a nuclear reactor. As has been said, Germans knew that indeed was plutonium that could potentially be an explosive for the bomb, but as a matter of habit they referred to it as “93”. Goudsmit takes it in favor by denying that Germans knew about the existence of plutonium ([2], p. 217), but evidence, supported by the *Farm Hall* transcripts, suggests that Heisenberg acknowledged during the war that both U-235 and Pu-239 were fissionable materials capable of being used in nuclear explosives.

D. Critical Mass[3]

This is probably one of the most controversial points. Goudsmit suggests that the Germans believed that tons of uranium were needed to make an atomic bomb [4], despite the fact that the bomb dropped on Hiroshima contained only about 60 kg of this element ([1], p. 102). Indeed, when the physicists at *Farm Hall* first learned of the Hiroshima bomb, Heisenberg used the Random Walk method to explain to Hahn how the bomb worked, which gave an estimate of the critical radius of 54 cm ([7], p. 2). However, he stressed that this value could be significantly reduced by incorporating a fast neutron reflector ([2], p. 222).

It is imperative to highlight Heisenberg's 1939 report to the German Army Ordnance, in which he formulated the theory for the construction of a nuclear reactor. He solved the diffusion equation using the stationary approach -since in the case of the reactor the equilibrium situation has to be studied- without delving into detailed quantitative analysis of explosives ([7], p. 14). This approach also yields Eq. (2) as a solution for the critical radius.

In 1942, a report to the German Army Ordnance mentioned a critical mass estimate of between 10 and 100 kg, although the calculations on which the estimate was based were not shown. Heisenberg probably supervised the project, although he was not its author ([2], p. 216).

A week after Hiroshima, Heisenberg gave his colleagues a lecture in which he explained how the Allies built the bomb, and arrived at a range of 6.2 to 13.7 cm for the critical radius, corresponding to a critical mass of 19 to 205 kg ([7], p. 26). He used an unexplained equation for the diffusion length, but if he had used Eq. (3), that could be extrapolated of his 1939 report, he would had obtained 3.02 to 10.68 cm for the critical radius, corresponding to 2.20 to 96.95 kg for the critical mass ([7], pp. 25-28).

E. Nuclear Reactor and Nuclear Explosives

Heisenberg’s 1939 report constituted the best recompilation of the subject that existed at the time. It actually provided a clear understanding about the distinction between nuclear weapons -isolating U-235 and achieving a chain reaction with fast neutrons- and nuclear reactors -with mixtures of natural uranium and a moderator ([1], pp. 58-59). He concluded that a controlled fission in an uranium reactor was possible and that enriched U-235 constituted an enormous nuclear explosive, in which only fast neutrons get involved. He also warned about the difficult engineering ([5], p. 299). Statements from the report, which demonstrate a clear comprehension of the physics, are quoted below ([7], p. 5):

1. This explosive transformation of uranium atoms can only take place in almost pure U-235, because neutrons will be absorbed at resonance points of U-238 even if only small amounts of impurities of U-238 are present.

2. Enrichment of U-235 is the only method to make the volume of the machine small in comparison to 1 cubic meter. Moreover, it is the only method to produce explosives which exceed the explosive power of the strongest available ones by several powers of ten.

Also in *Farm Hall* Heisenberg recognized that such explosives relied on fast-neutron chain reactions ([2], p. 216). Heisenberg said ([7], p. 13):

In the case of a bomb it can only be done with the very fast neutrons. The fast neutrons in “235” immediately produce other neutrons so that the very fast neutrons which have a speed of -say- 1/30th that of light make the whole reaction. Then of course the reaction takes place much quicker so that in practice one can release these great energies. In ordinary uranium a fast neutron nearly always hits “238” and then gives no fission.

Consequently, although it is true that some German reports included the idea of the reactor itself as a bomb, this should not be interpreted as Heisenberg's thinking, but rather that of his researchers ([7], p. 8).

V. CONCLUSIONS

The Uranverein failed to obtain the atomic bomb before the end of the war, and an examination of various disciplines can shed light on the underlying reasons.

In the realm of theoretical research, Heisenberg had the ability to easily extrapolate his findings from the 1939 report on nuclear reactors to nuclear explosives. It is fair to assert that

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[3] Unless otherwise stated, the content of this subsection has been sourced from reference [7].

at a certain juncture the Germans did make calculations, as evidenced by the 1942 report containing a reasonable estimate of critical mass. It seems credible to assume that the Germans possessed a comprehensive understanding of the physics underlying nuclear explosives.

Numerous sources indicate that the Germans held the belief that nuclear weapons were unattainable before the end of the war. Some attribute this to a sense of complacency: German Army was confident in its ability to emerge victorious from the war. In fact, this perception persisted until 1942, which stands out as a crucial turning point. In that year, the Army Ordnance decided not to devote resources to the development of long-term weapons, but rather to focus on achieving immediate results. It was decided that nuclear weapons would not be a priority in the war effort. Walker associates this decision with various factors such as the prevailing mindset among the Germans that the war would be brief, considerations regarding the availability of raw materials and manpower, and the impact of the war on the economy [2].

At that time, Germans had not yet achieved U-235 separation or a self-sustained chain reaction in a nuclear reactor. After the decision of the Army Ordnance, the Uranverein redirected its focus towards these two key aspects. When it comes to the technical dimension, it can be argued that they did not invest significant efforts in developing new methods for isotope separation. The rejection of graphite as a viable option was an error that hindered the potential successes that the Germans could have attained. However, when they reconsidered graphite, they managed to achieve a k>1 value and held expectations of reaching the critical size required for a self-sustained chain reaction.

There was a lack of cohesion among the various areas of work, with independent efforts yielding only modest results on a small scale [8]. Nevertheless, Goudsmit's claims that the Germans failed in isotope separation because they relied exclusively on centrifugation [4] have been shown to be unfounded. Similarly, the claims that the Germans were unaware of the connection between heavy water and an atomic bomb and had limited knowledge of plutonium are also false. In addition, Goudsmit's assertion about their misunderstanding of critical size, which he presents as a long-standing misconception, is contradicted by the *Farm Hall* transcripts, which demonstrate its falsity.

In summary, it can be stated that the Germans had the ability to develop the scientific theory of the atomic bomb, but the engineering difficulties posed by being in the middle of a war prevented them from making progress in that direction. In 1941, they decided to focus their efforts and manpower on short-term results, and the focus of the Uranverein shifted to the reactor. It is worth noting that this was the same year that the United States entered the war.

Nevertheless, the inquiry into why Germany did not succeed in developing an atomic bomb, as has been said, lacks a straightforward and singular explanation. This study has focused on exploring the technical and scientific contributions made by Germany. However, a more comprehensive and in-depth investigation would entail considering the international context, the resources and logistics of the country, as well as the scientific landscape within a totalitarian regime under Hitler's leadership. Moreover, it could delve into a philosophical and humanistic perspective on the consequences associated with living in a state of fear and uncertainty under the regime of fascism.

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