Physics in Perspective

Laboratory Life Instead of Nuclear Weapons: A New Perspective on the German Uranium Club

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Why did German physicists not build an atomic bomb during the Second World War? This question has long been controversial. This essay provides a new perspective through a focus on the everyday practice of the physicists in their laboratories. The study of everyday research work has long been obscured by the question of the bomb. To this end, the research of the Viennese group in the German *Uranverein*, or "Uranium Club," will be analyzed in detail. What breaks and continuities were there in everyday laboratory practice? Were the physicists able to acquire new resources? Did they at least come close to the scale of Big Science or did their research remain tied to the academic laboratory?

Key words: Nuclear physics; World War II; Uranium Club; German atomic bomb; Laboratory practice.

Introduction

Since the end of the Second World War, the German *Uranverein*, or "Uranium Club," has been a source of much controversy. It has sparked disputes among contemporary witnesses,[1] among historians,[2] and has caused quarrels between historians and physicists.[3] Central to these controversies has been the question of the atomic bomb and why German physicists who were part of the *Uranverein* did not build a nuclear weapon during the war. Was it the incompetence of the German physicists? Was it a moral refusal? Or did they perhaps indeed detonate a subcritical bomb after all?

With his foundational work on the German *Uranverein*, Mark Walker has shown that the question of an atomic bomb never arose for the club's physicists during the war.[4] Be it through speculative interpretations or crude misinterpretations of historical sources, several attempts have been made to shake this fundamental observation. In contrast to many other approaches, this essay will not focus on the question of nuclear weapons. The analysis instead concentrates on the

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physicists' everyday practices, exploring what the daily work of the laboratory entailed. The focus rests on the Viennese branch of the *Uranverein*, whose work has been relatively neglected and is easy to access through the available archives. Two archives are of particular importance: first, the Deutsches Museum in Munich, which contains the central inventory of the secret reports of the *Uranverein*; second, the excellently indexed holdings of the Institute for Radium Research in the Austrian Academy of Sciences archives in Vienna. This inventory makes it possible to contextualize the secret reports in another area, namely the work carried out before and after the *Uranverein*.

By way of introduction, this essay will briefly outline the path from early radioactivity research to nuclear fission and thereby highlight the importance of the Viennese researchers in the European network. This role is presented in the context of the period that culminated in Austria's annexation by Nazi Germany in 1938, which was followed by the integration of some of the Viennese researchers into the newly founded German *Uranverein*. Werner Heisenberg's research report *Die Möglichkeit der technischen Energiegewinnung aus der Uranspaltung* (The possibility of technicalenergy production from uranium fission),[5] written in autumn/winter 1939, is of particular importance. The report was fundamental and programmatic for the further direction of the German nuclear project. Isolating individual aspects of the report has already led to considerable misinterpretations.[6]

What impact did the report have on the work of the physicists? Scientists who were part of the *Uranverein*, which was small compared with the Manhattan Project, were not assigned to a central project. Instead, they were assigned to research groups established on top of existing university groups. Newly created groups, such as those of the German Army Ordnance Office, competed with the existing groups. To illustrate these relationships, the work of the Viennese group of the *Uranverein* will be analyzed. It consisted of staff from the University of Vienna and the Vienna Institute for Radium Research. The Vienna Group investigated scattering cross sections of neutrons and determined the range and mass of nuclear fragments. What methods and instruments did the university have at its disposal? To what extent did the work in the *Uranverein* bring new methods or resources for the Vienna group? Finally, the consequences of the analysis for the further consideration of the *Uranverein* will be explored.

Vienna in the Context of International Radium Research and Nuclear Physics

Radioactivity research had attracted the interest of Viennese physicists and chemists by the end of the nineteenth century. They had exclusive access to the uraninite mines in the Bohemian town of St. Joachimsthal, now Jáchymov in the Czech Republic, and thus became a focal point for the Europe-wide distribution of the coveted raw material. For example, after a request to the Imperial Academy of Sciences in Vienna, Pierre and Marie Curie received a shipment of uraninite free

of charge and returned a sample of the radium they had just discovered to the academy.[7] By 1901, the academy had established a commission for the investigation of radioactive substances, led by Franz Serafin Exner, the head of the University of Vienna's Physics Institute II.[8] The Institute for Radium Research, however, was not established until 1910 thanks to a contribution by the industrialist Karl Kupelwieser. Franz Exner was appointed director. Stefan Meyer, as managing director, took over the coordination of the daily research practice and, from 1920, the management of the institute. Along with Paris, Vienna became a repository of a second radium standard. As such, the institute found itself in the difficult position of balancing national research interests and international academic cooperation from the very beginning. This has been intensively studied by Maria Rentetzi, Silke Fengler, Carola Sachse, and Wolfgang Reiter,[9] as well as Roger Stuewer who has analyzed Viennese research in a broader context of nuclear research between the two world wars.[10]

In the 1920s and 1930s, radioactivity research began to split into the subfields of radiochemistry, pursued in particular in the *Laboratoire Curie* in Paris, and nuclear physics, which Ernest Rutherford's laboratory studied in Cambridge. The first historical analyses with a focus on Vienna examined the work of the physicist Marietta Blau and the controversy over artificial nuclear disintegration between Vienna and Cambridge.[11] The Viennese physicists had bombarded nitrogen with α-rays, but their methodology when observing the reactions with scintillation screens was flawed. In the course of the controversy surrounding the method of evaluating scintillation screens, Blau developed her work with film emulsions. By the 1930s, she had refined this method to such an extent that individual protons could be detected, and Blau used it to discover the "disintegration stars" of cosmic rays.[12]

The physicist Georg Stetter, who was later to play a central role in Viennese nuclear research, took a different path. Stetter had studied physics at the University of Vienna and received his doctorate in 1922. That same year, he became an assistant at the University of Vienna's Physics Institute II, qualifying as a professor in 1928.[13] He made quantitative measurements on nuclear fragments with the use of tube amplifiers. Together with Josef Schintlmeister, Gustav Ortner, and Ewald Schmidt, he further developed the tube electrometer into an instrument for measuring nuclear reactions.[14] This was pioneering work in nuclear physics that later shaped one of the Viennese research fields in the *Uranverein*.[15]

James Chadwick's discovery of the neutron in 1932 at the Cavendish Laboratory marked a turning point for radioactivity research. An elementary particle was now available with which one could easily penetrate the atomic nucleus.[16] Chadwick used the α-emitter radium and mixed it with beryllium. To his credit, he succeeded in identifying the released radiation as a chargeless particle and in ruling out the possibility that it was high-energy γ-radiation, as had previously been suspected.

Similar experiments had been carried out before at the other centers of radioactivity research and nuclear physics, but none had succeeded in this final step. In 1930 at the Imperial Physical Technical Institute in Berlin, Walther Bothe and Herbert Becker observed a secondary radiation in addition to ordinary γ-rays when bombarding beryllium with the α-rays of a polonium preparation. They considered these to be the hardest (most energetic) γ-rays so far due to their charge neutrality.[17] Irène and Frédéric Joliot-Curie in Paris, as well as Stefan Meyer's working group at the Institute for Radium Research in Vienna, conducted similar experiments.[18] Chadwick's results became clear in 1932 and were quickly replicated at the other centers. The (α,n) nuclear reaction was therefore available to the nuclear physics community as a way to produce neutrons, referred to as a neutron source.[19]

The newly discovered neutron was employed as the other forms of radiation had been: the known elements were bombarded with neutrons and an attempt was made to extrapolate the nuclear reaction that had taken place by analyzing the end products. By January 1934, the Joliot-Curies in Paris had observed the artificial activation of aluminum by α-rays, and in March the Italian physicist Enrico Fermi in Rome succeeded in artificially activating various elements with neutrons. Fermi's laboratory developed into a major European center for neutron physics until his emigration to the United States in 1938. His neutron sources consisted of 30–80 cm–long glass tubes into which beryllium powder and radon, then also called radium emanation, were melted. The cylindrical samples were then arranged around a center of the neutron source.[20] Fermi also irradiated uranium with neutrons; however, he did not succeed in discovering nuclear fission. The fission of a heavy nucleus by neutrons was outside the expectation of physicists at the time; instead they assumed that the neutrons would latch on to the nucleus and lead either to the formation of heavy isotopes or to the creation of a new element when the captured neutron transformed into a proton by emitting a β-particle.

At the Kaiser Wilhelm Institute for Chemistry in Berlin, Otto Hahn, Lise Meitner, and Fritz Straßmann also attempted to produce transuranic elements by bombarding uranium salts with neutrons. With the annexation of Austria by Nazi Germany in March 1938, Lise Meitner suddenly became a German citizen and her only option was to flee into exile in Sweden to escape Nazi Germany's grasp.[21] At the end of 1938, Hahn and Straßmann, who both remained in Berlin, succeeded in chemically detecting barium as the end product of nuclear fission.[22] The only possible explanation was a bursting of the uranium nucleus. From exile, Lise Meitner and her nephew Otto Frisch made a physical interpretation of nuclear fission on the basis of what was known as the liquid-drop model.[23]

The annexation of Austria also led to rifts within Viennese institutes. The Radium Institute had already suffered through financial and personnel cuts due to the loss of funding from private foundations during the world economic crisis.[24] From 1934 to 1938, the Austrofascist governments abolished parliament and replaced it with one-party rule. During this period of the so-called corporative

state in Austria, political purges took place partly openly and partly under the guise of austerity measures. Mitchel Ash estimates that about 25% of the university staff in the corporative state lost their jobs by 1938.[25] Following annexation, Nazi Germany's racist and anti-Semitic legislation was suddenly enforced in Austria as well. This resulted in further job losses.

Until the annexation, two centers of radioactivity and nuclear research existed: one within the University of Vienna's Physics Institute II, the other at the Institute for Radium Research. About one third of Viennese physicists lost their positions following annexation, largely due to the anti-Semitic measures implemented under Nazi leadership. The physics chairs at the University of Vienna were subsequently occupied by supporters or followers of the Nazi regime. Georg Stetter, who had been a member of the illegal NSDAP before the annexation, was appointed Head of the Physics Institute II. The position had been vacant for several years. After the retirement of the former director, Gustav Jäger, in 1934, the position remained empty due to the austerity measures under the corporative state. It was managed jointly with the Physics Institute I. Not until Austria's annexation by Nazi Germany was Jäger's position reactivated and filled by Stetter.[26]

Gustav Ortner replaced Stefan Meyer as director of the Institute for Radium Research. Stefan Meyer and his deputy Karl Przibram were dismissed because of anti-Semitic Nazi policies. Both were able to stay at the institute for a short time as guests until they had to leave after a smear campaign. Przibram emigrated to Belgium, and Meyer was able to survive the Nazi dictatorship in Bad Ischl in Austria.[27] In 1943, parts of the institutes were merged to form the Four-Year-Plan Institute for Neutron Research under Stetter's direction.[28]

The Beginnings of the Uranium Club

The Uranium Club formed the organizational framework for the scientists and researchers in the German nuclear project. The frequently cited competition between different institutions characteristic of science in the Nazi state is evident in the *Uranverein*'s founding. In April 1939, the physicist Wilhelm Hanle gave a lecture in Göttingen on the use of nuclear fission and the possibility of a uranium machine. Hanle had completed his doctorate in Göttingen in 1924 under James Franck, who had been expelled by the National Socialists. Hanle, after stopovers in Jena and Leipzig, had been transferred back to Göttingen by the Reich Ministry of Education in 1937. Subsequently, Hanle and Georg Joos, Franck's successor, wrote a letter to the Reich Ministry of Education pointing out the possibilities of a uranium burner, as well as those of a highly efficient explosive. Under the leadership of the Jena physicist Abraham Esau, who led the physics division in the Reich Research Council, a founding workshop—in today's terms—for a uranium club took place in Berlin on April 29, 1939.

In parallel, the Hamburg physical chemist Paul Harteck and his assistant Wilhelm Groth wrote to Erich Schumann, the head of the research department of the

German Army Ordnance Office (HWA), on April 24, 1939, clearly indicating the possibility of a new explosive. Yet the significance of fission for the war plans of the German Reich was unclear at first: should the potential be low, it was also low for Germany's opponents. However, should nuclear research prove relevant to war, the danger of missing out would be too great if nuclear fission were not investigated further. The HWA commissioned Kurt Diebner to lead the project. Diebner had completed his physics studies in Halle with a doctorate in 1931 and moved from the Imperial Physical Technical Institute to the research department of the HWA in 1934, where he worked as a nuclear physicist and explosives expert. Under his leadership, the HWA took over the organization of the *Uranverein* in October 1939, and the Kaiser Wilhelm Institute (KWI) for Physics became a central interface in the German nuclear project, in which numerous groups collaborated: at the University of Leipzig, a research center of the HWA in Gottow near Berlin, the KWI for Medical Research in Heidelberg, the universities of Hamburg and Munich and, last but not least, at the University of Vienna.[29]

Werner Heisenberg's Programmatic Expert Report

After the HWA had taken over the management of the project, it organized a central conference in Berlin in September 1939. One of the participants was Werner Heisenberg. At that time, he held a professorship in theoretical physics at the University of Leipzig. In the following two and a half months, Heisenberg produced a feasibility study that was to make him one of the central figures of the *Uranverein*. The importance of Heisenberg's study lies in the program it set for the further work of the *Uranverein*.

Heisenberg assumed that the interpretation of the fission process by Niels Bohr and the American physicist John A. Wheeler based on the liquid drop model of June 1939 was correct, and that in particular the uranium isotope 235 was responsible for the fission processes with thermal neutrons.[30] For his feasibility study he drew on a paper by Herbert L. Anderson, Enrico Fermi, and Leo Szílard on the production and absorption of neutrons in uranium, published in *Physical Review* in early July 1939.[31]

The three physicists from Columbia University, New York, gave an estimate of the neutrons released during the fission process. They had placed 52 cylinders, 5 cm in diameter and 60 cm long, filled with uranium oxide in a cylindrical tank with a volume of 540 L. In the center was a Ra+Be neutron source and the cylinders were surrounded by a 10% $MnSO_4$ solution. This involved an estimate of neutron propagation, the capture of thermal neutrons in hydrogen and uranium 238, and the resonance capture of neutrons in uranium 238.

Based on this, Heisenberg estimated the number of neutrons produced per absorbed thermal neutron. First, the probability of resonance capture before a fast neutron reaches the thermal range had to be determined. The experimental arrangement had to be designed to minimize loss of neutrons through resonance

capture. Heisenberg distinguished between two cases: uranium or a uranium compound in a solution with another substance (homogeneous) or spatially separated in larger pieces from the surrounding substance (heterogeneous). From the general theoretical considerations, he was able to show that a homogeneous solution was more favorable than the geometry chosen by Anderson, Fermi, and Szílard.

At the same time, he pointed out a suggestion by Paul Harteck that the resonance capture can be further reduced by a favorably chosen geometry. He then looked at solutions in water and in heavy water, D_2O. He calculated that a solution in water must always lead to a reduction in neutrons and that a uranium–water mixture is unsuitable for nuclear fission. Enrichment of uranium 235 seemed to him to be the safest method. With an enrichment level of 30%, a self-sustaining chain reaction would be extremely probable; at 50% enrichment, it would be certain. Because of the expected cost of enrichment, he proposed using a neutron moderator with similar braking properties to H_2O that absorbs fewer neutrons.

Heisenberg compiled a table of experimentally determined or theoretically estimated cross sections for hydrogen, deuterium, carbon, oxygen, and uranium. This showed that a mixture of heavy water and water as a moderator would lead to a neutron increase. Due to the long free-path lengths before an event occurred, he noted the necessarily large dimensions of a uranium machine and the associated costs and ruled out a chain reaction in uranium 238 with fast neutrons. With the change in neutron number, he also had to consider propagation by diffusion. Due to the temperature dependence of the quantities in the diffusion process, he determined that uranium 238 was not a suitable explosive. He instead noted that a sphere of enriched uranium 235 of a sufficient radius would lead to an abrupt increase in temperature to about 10^{12}°C. He stressed that "this explosive transformation of the uranium atoms can only occur in almost pure U_{92}^{235}, because even with small additions of U_{92}^{238} the neutrons in the resonance site are snatched away from U_{92}^{238}."[32] The discussion of uranium as an explosive consumed only about half a page of Heisenberg's twenty-five-page report. It inevitably leads to a misinterpretation of the sources when this is singled out as the report's central aspect. Central to Heisenberg's work was the question of the feasibility of a uranium machine.[33]

He showed in his analysis that a reflective layer, made of a neutron moderator, would lead to a significant increase in the efficiency of a uranium machine. Even ordinary water would have clear advantages over air. For a homogeneous reactor of natural uranium and D_2O, Heisenberg estimated a minimum radius of 60 cm for a sphere surrounded by water to keep a chain reaction operating stably at 800 °C.

Next, Heisenberg investigated a spatially separated arrangement of uranium and moderator in the most general form. He found that here, too, pure H_2O is unsuitable as a neutron moderator and leads only to a slight reduction in neutrons. He then gave an estimate for D_2O as a moderator and the dimensions of an expected reactor: the most favorable plate thicknesses were found to be 4 cm with

gaps of 11.5 cm filled with D_2O, with an overall size of 1.2 m^3. Heisenberg hoped to reduce the size by a factor of two to three by finding an even more geometrically practical solution. For graphite as moderator, the plate spacing increased to 33 cm with a necessary volume of 3 m^3 to achieve a self-sustaining chain reaction. This then would require about 30 tons of graphite and 25 tons of uranium oxide. Finally, he looked at a mixture of heavy water and graphite as a moderator, where the volume and material requirements were significantly lower.

In his summary, Heisenberg reviewed the points that seemed most important to him:

- The enrichment of uranium 235 was the safest path towards a functional uranium machine. The higher uranium 235 was enriched, the smaller the machine.
- The enrichment of uranium 235 represented the only path toward new explosives "that exceed the explosive power of the most powerful explosives to date by several powers of ten."
- Uranium 238 in combination with heavy water or graphite could also be used as a moderator for energy generation.
- It was indispensable for a successful design that all scattering, effective, and capture cross sections be precisely verified experimentally.

Heisenberg's report was of central importance because it guided the next fundamental steps in the work, as well as the first concrete estimates for the construction of a uranium machine. The experimental results published in the *Physical Review* in March and April 1940 clearly proved that uranium 235 was responsible for fission with thermal neutrons. The US group had separated uranium 238 and 235 in a mass spectrograph and bombarded the samples with neutrons of different speeds.[34]

As mentioned in Heisenberg's report, this theory now had to be verified by experimentally determining and refining the nuclear constants, as well as by testing various geometric arrangements. This was followed by work on isotope separation. Various moderators were also tested for their suitability. A micro-study of the Vienna group's work will now shed light on everyday research in the *Uranverein*.

Everyday Research in the Vienna Group of the *Uranverein*

Of the Viennese researchers, the group around Georg Stetter, using the methods he had developed, including the use of tube amplifiers for nuclear physics measurements, was the *Uranverein*'s most active. For Stetter, the annexation of Austria had paid off: he was able to take up the vacant professorship of the Physics Institute II and received funding from the German Research Foundation for his research. The Reich Office for Economic Expansion also amply supported its projects in 1939 with 76,590.04 Reichsmark.[35] The Vienna group had grown over many years: it included, among others, the physicists Josef Schintlmeister, Gustav

Ortner, Friedrich Prankl, and Willibald Jentschke, some of whom had worked with Stetter since the late 1920s. A new addition was the physicist Karl Lintner, who received his doctorate on April 29, 1940 with a thesis on "A Coincidence Method for Determining the Range of Heavy Nuclear Fragments from Uranium" and worked as a research assistant and later as an assistant in the University of Vienna's physics department.

In the following section, the three central research fields of the Vienna Group in the *Uranverein* will be outlined:

- The identification of plutonium by the physicist Josef Schintlmeister from 1940 to early 1942.
- The investigation of fast neutrons in uranium by Georg Stetter and assistant Karl Lintner from around 1941–42, and in other elements by Friedrich Prankl.
- The investigation of the energies and ranges of uranium core fragments by Willibald Jentschke, Friedrich Prankl, and Karl Lintner.

Finally, this section will discuss the neutron sources used, and those that were sought.

Did the *Uranverein* bring new methods, new forms of cooperation, or new research subjects to the everyday life of Viennese physicists? To answer this question, the preliminary work by nuclear physicists must be examined. This makes it clear what methods were available in 1939. This also makes it possible to delineate which methods were newly added.

Schintlmeister used chemical methods to identify new elements in his investigations of the 1.8 cm α-emitter. Radiochemistry had developed as a discipline since the turn of the twentieth century. Using an increasingly finely differentiated methodological apparatus, chemists succeeded in detecting quantities of substances that could hardly be weighed.[36] With these methods, Otto Hahn and Fritz Strassmann managed to detect barium as a fission product of uranium.[37] The next section will show how Schintlmeister used these methods.

The scattering experiments by Stetter and Lintner on fast neutrons in uranium, designed to measure uranium's neutron cross-section, were also based on a methodologically traditional approach. In the center of the set-up was the neutron source, surrounded by the substance to be investigated.

One of the central achievements of the Viennese physicists was the modification of tube electrometers that made detailed quantitative measurements possible. The aim was to create a counting method that simultaneously allowed differentiation of the counted corpuscles. Until then, Stetter had used mass spectroscopy to determine the charge-to-mass ratio. The corpuscles were counted on a scintillating screen with the aid of a microscope.[38] Georg Stetter carried out the initial work on tube electrometers with his co-workers Gustav Ortner and Ewald Schmidt at the end of the 1920s and refined them over the following years.[39] The first publications already show the efforts to replace scintillation experiments with the new method.[40] Later, with Schintlmeister, Stetter expanded the experimental

set-up to a double-tube electrometer with two ionization chambers. This made it possible to clearly determine the ionization capacity and the range of the radiation.[41]

Stetter's student Willibald Jentschke also worked on the double-tube electrometer.[42] In 1935, he received a doctorate with his dissertation "Ionization Measurements of Single α-rays with the Double-Tube Electrometer." Immediately after the discovery of uranium fission with neutrons, he and Prankl succeeded in determining the range of uranium core fragments, that is after Hahn and Strassmann's chemical proof of a fission product and Meitner and Frisch's physical interpretation, Jentschke and Prankl also proved the fission products physically, after Frisch had done so.[43] These measurements were made before the *Uranverein* was founded. For measurements carried out at the *Uranverein*, the ionization chambers were adapted; no fundamental changes were necessary. The work described below resulted in Jentschke qualifying as a professor in 1943 with the thesis "Energies and Masses of Uranium Core Fragments upon Irradiation with Neutrons." This work will be revisited later.

In passing, it should be mentioned that the tube electrometer also played a decisive role in the discovery of the natural isotopes of astatine in 1944 by Berta Karlik and her assistant Traude Bernert. The two physicists worked independently of the *Uranverein*, but were funded by the *Reichsforschungsrat* and the *Deutschen Forschungsgemainschaft*. This shows that the tube electrometer had established itself as a standard instrument of Viennese nuclear physicists by the end of the 1920s.[44]

The Identification of Plutonium

As early as 1934, Enrico Fermi in Rome had observed the transformation of elements into those of the next higher atomic number. In this process, an element with atomic number Z captures a neutron and transforms into a new element with atomic number Z + 1 by emitting a β-particle. In the case of uranium 238, it captures a neutron. Plutonium 239 is produced from the excited uranium 239 nucleus after two β-decays.

Element 93, later named neptunium, was discovered by Edwin McMillian and Philip Abelson and their discovery published in *Physical Review*. Kurt Starke, working at the KWI for Chemistry, subsequently independently found neptunium as well.[45] The exact detection of plutonium was first achieved by the American chemists Glenn T. Seaborg, Arthur C. Wahl, and Joseph W. Kennedy. Their paper, submitted in January 1941, was not published in *Physical Review* until 1946 with the addition "This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war."[46]

The *Uranverein* also focused on the possibility of a new element. Schintlmeister in Vienna observed an α-emitter with a range of 1.8 cm. His experiments allowed the reasonable assumption that it was the new element 94. The chemical

properties, combined with theoretical nuclear-physical estimates, did not lead to an exact determination of the element. However, it was clear that it was fissionable by neutron bombardment—either by fast or thermal neutrons, depending on its mass number. At the end of his last report on element 94, Schintlmeister emphasised the possibilities that the new fissile element would offer: "What practical significance it would have to possess several kilograms of a pure substance, which splits with thermal neutrons, I do not need to elaborate. I believe it is justified, for the sake of this prospect alone, to continue the trials intensively."[47]

How did Schintlmeister arrive at this assessment? First, he discussed the chemical properties of the new element in his reports. Based on previous research, he ruled out elements with atomic numbers lower than uranium, although there were still gaps in the periodic table for atomic numbers 43, 61, 85, and 87. Thus, the new element had to be a transuranic element, with an atomic number greater than 92. Using analogies with the possible electron configurations of the outer shells in other elements and chemical experiments, especially precipitation reactions with hydrogen sulphide (H_2S), and the volatile properties of compounds formed in nitric and sulphuric acid (HNO_3 and H_2SO_4), he determined that the new element must have atomic number 93 or 94. From the α-decay properties, the energy of the α-particles, and a missing β-decay, he concluded that the new element must have the atomic number 94. The most likely mass number he estimated was 244, but 242 could also be possible. His report emphasized that, according to the theory of Bohr and Wheeler, at a mass number of 244 or 242, fission with thermal neutrons is possible; at a mass number of 246, fission only occurs under the action of fast neutrons.[48]

In his February 1942 report, Schintlmeister turned to the question of generating energy through nuclear fission of the 1.8 cm α-emitter. The report was prepared for the February 26 *Uranverein* conference, where Schintlmeister presented his results in Berlin.[49] He first discussed the extraction of plutonium from sphalerite. Considering the chemical processes involved in smelting, a rough estimate of the half-life, and an assumed atomic weight of 244 for the new element, Schintlmeister estimated that one ton of ironstone (a smelting by-product) would contain about 0.1 g of plutonium. This seemed low at first, but Schintlmeister pointed out that 40% of the world's production of platinum is produced as a by-product of processing sulphide ores in Canada and that technical chemistry should not be underestimated. From nuclear physics estimates of known decay and fission reactions, Schintlmeister concluded that the new element could be fissioned by thermal neutrons.[50]

In short, Schintlmeister tried to identify the properties of the new element with the help of chemical laboratory analyses. His work thus lay within the classical framework of the activities of a radiochemist of the time, supplemented by the use of the ionization chamber and the tube electrometer to determine the range of the α-radiation of the new element.

Scattering Experiments with Neutrons

Friedrich Prankl, an assistant at the Institute for Radium Research in Vienna during the war, summarized the investigations of cross sections of fast neutrons in various elements after the war. The aim was to obtain more precise information on both the size of the absorption and the size of the increase in neutrons due to (n,2n) processes. The experimental set-up is shown in figure 1.

In this experiment, two different neutron sources were used to cover different energy spectra of the neutrons. One is an Rn+CaF neutron source with a maximum energy of the neutrons produced of 2–3 MeV and the other is an Rn+Be neutron source with a maximum neutron energy of about 14 MeV. The neutron source, which was fused into a thin-walled glass sphere 8 mm in diameter, was located in the center of a hollow sphere, with a 2–3 cm thick wall, of the substance to be investigated. These substances were examined in solid, molten, or powdered form. Fast neutrons emitted by the neutron source passed through the test substance and were slowed in a water tank, where they were detected as thermal neutrons with the help of a boron ionization chamber. To prevent the effects of backscattered thermal neutrons from the water vat, the hollow sphere of the test substance was surrounded by another thin-walled hollow sphere containing absorbers with large capture cross-sections for thermal neutrons, such as cadmium and mercury. Carbon, aluminum, sulphur, iron, copper, zinc, cadmium, antimony, tungsten, mercury, thallium, lead, and bismuth were examined in the experiments. This was a standard method for investigating nuclear properties, carried out before and after the war. But, of course, precise knowledge of the effect and scattering cross sections was also a prerequisite for successful construction of a uranium machine.[51]
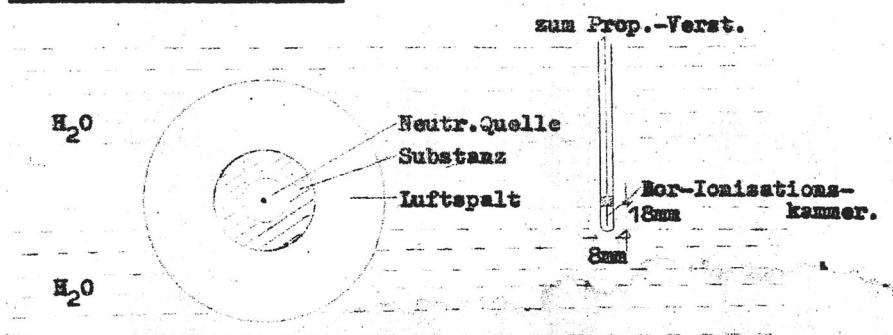

Fig. 1.   Experimental set-up for determining the cross sections of fast neutrons. The diameter of the sphere was less than 20 cm. *Source*: Prankl, Archive of the *Deutsches Museum München* (ADMM), FA 002 / Vorl. No. 0702

In 1941, Stetter and Karl Lintner began studying fast neutrons in uranium. Although a uranium machine initiated by fast neutrons was no longer used in the calculations, the influence of fast neutrons for a uranium machine with thermal neutrons (that is, with heavy water as a moderator) could not be neglected because the fission neutrons are fast neutrons to begin with. In an initial paper, Stetter and Lintner investigated the increase in fast neutrons due to the fission process and the decrease due to inelastic scattering. They chose the arrangement shown in figure 2.

This arrangement consisted of a system of concentric spheres. In their center was either a Rn+Be neutron source or a Ra+Be neutron source. Three spherical shells followed toward the outside: an inner spherical shell K_1 with a diameter of 5 cm, a middle spherical shell K_2 with 14.8 cm, and an outer spherical shell with a diameter of 28 cm. The spheres K_1 and K_2 were either alternately or simultaneously filled with uranium.

An ionization chamber with four large-area uranium layers and a diameter of 13.4 cm was used to detect the neutrons. They were applied by electrolysis of uranyl nitrate in water "homogeneously by interrupting and stirring." Their thickness corresponded to an air equivalent of 0.5 mm. A thermal neutron entering the ionization chamber passes through the uranium layer and carries out a fission process. Due to the thinness of the layer, the fission products ionize the gas in the ionization chamber, resulting in a deflection that is clearly visible on the amplifier. In this way, even individual processes could be detected.[52]

Initially, the experiments were carried out without cadmium and paraffin. Different filling combinations were then tested. First, an empty measurement was carried out with the neutron source, then once only K_1 filled with uranium, once K_2, and once K_1 and K_2. This is, however, how all the neutrons in the arrangement hit the ionization chamber. In a second series, K_2 was surrounded with cadmium and paraffin. This filtered out the neutrons that had lost energy through scattering. Subsequently, the escaping fast neutrons were decelerated to thermal levels and thus detected in their entirety in the ionization chamber. From the different numbers of events, Stetter and Lintner calculated the scattering cross section for inelastic scattering of fast neutrons in uranium and the number of neutrons released in a fission process with one fast neutron. A total of 4–5 neutrons are released in such a fission process, but the fission cross section is only 1/10 of the scattering cross section. This means that only one in ten fast neutrons provokes fission; the rest are lost through inelastic collisions. This meant that no self-sustaining chain reaction was possible.[53]

The second report in the series by Stetter and Lintner is subtitled: "Accurate Determination of the Inelastic Scattering Cross Section of the Neutron Number in 'Fast' Fission." Increased accuracy was achieved by a modified experimental geometry, shown in figure 3, and by a modified measurement procedure. The new experimental set-up differs from the old one in particular through the thinner uranium layer that surrounds the radiation source at a greater distance. With the help of a uranium ionization chamber, Stetter and Lintner again determined the
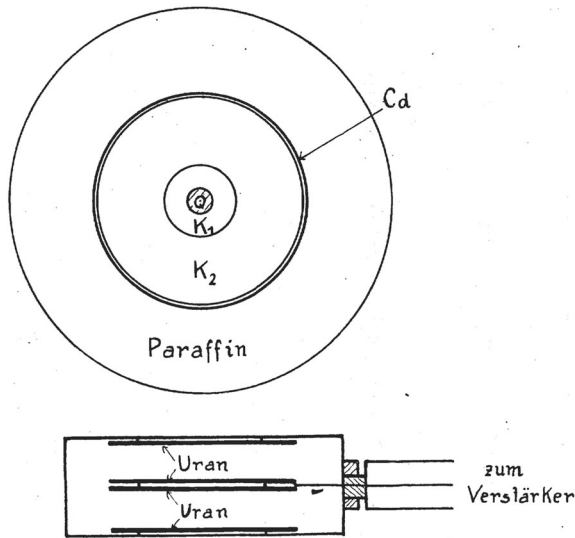
Fig. 2. Experimental set-up by Stetter and Lintner for the investigation of fast neutrons in uranium, as well as a uranium ionization chamber for the detection of neutrons. *Source*: ADMM, FA 002 / Vorl. No. 0240

number of fissionable neutrons. This time, they measured the number of neutrons produced by the fissions using dysprosium oxide indicators in a tub of water. They then determined the β-activity of the indicators using a counting tube with an amplifier.[54]

The experiment resulted in a more precise determination of the inelastic scattering cross section for Ra+Be neutrons in uranium and a rapid drop in the number of neutrons capable of fission with increasing uranium thickness, while the total number of neutrons increased rapidly at first with increasing uranium thickness, but then only very slowly. The authors could not then clarify the details of the course of this growth curve.[55]

In further scattering experiments, Stetter and Lintner investigated the elastic scattering cross section and the total effective cross section, interpolating from an investigation of the (n,2n) process in lead to the analogous process in uranium and inferring the number of fission neutrons.[56] All these experiments were carried out in the laboratories of the University of Vienna's Physics Institute II in Boltzmanngasse. The spatial dimensions, use of materials, and personnel clearly show the character of academic laboratory science. These experiments also remained within the traditional methods of nuclear physics.
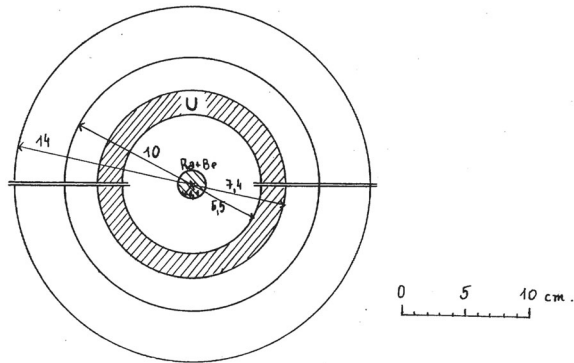
Fig. 3. Improved experimental set-up by Stetter and Lintner for the investigation of fast neutrons in uranium. From: ADMM, FA 002 / Vorl. No. 0243

Nuclear Fragments of Uranium

In a series of experiments, Willibald Jentschke, with varying participation from Prankl and Lintner, investigated the energies and masses of uranium's nuclear fragments with the aid of the double ionization chamber shown in figure 4. Uranium foil is stretched between the two ionization chambers such that, after fission, one fragment flies into the left-hand chamber and the other into the right-hand chamber. There, the fragments ionize the filling argon gas, and a very high applied voltage causes these electrons to release further electrons. These torrents only occur close to the anodes within a range where the current pulse measured at the amplifier is proportional to the energy of the collapsed nuclear fragments. The γ-radiation emitted by the Ra+Be neutron source was shielded by a lead jacket. The neutron source and the entire arrangement were surrounded by a paraffin jacket so that mainly thermal neutrons hit the uranium foil. A coincidence counter registered only simultaneous events.[57]

The Viennese physicists already had experience with the ionization chamber. The problem with this experiment consisted of the production of a uranium layer so thin that deceleration of nuclear fragments in the layer was negligible. The simplest way to produce such a layer was similar to the production of the dysprosium oxide indicators. Metallic powdered uranium was mixed with alcohol, evaporated, and fixed with Zapon varnish. Thin foils were made from this mixture and made conductive by cathodic pollination. However, the grains of uranium powder were too coarse and therefore caused the emerging nuclear fragments to scatter, making it impossible to measure their energy accurately.

The second method was an electrolytic process. A gold layer with an air equivalent of 0.2 mm was vapor-deposited onto an acetyl cellulose base. Subsequently, uranium from an aqueous uranyl nitrate solution was electrolytically applied to the gold layer. The acetyl cellulose base was dissolved in several
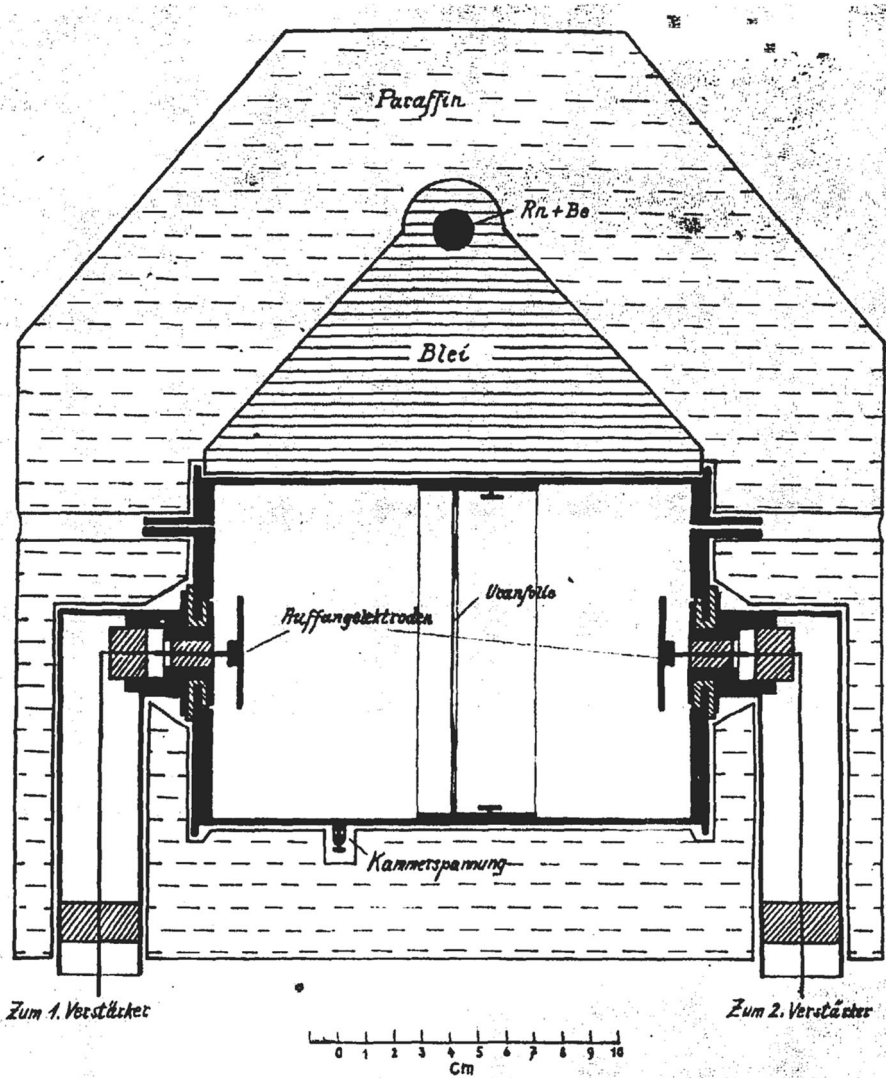
Fig. 4. Double ionization chamber for determining the energies and mass of the nuclear fragments. From: ADMM, FA 002 / Vorl. No. 0044, p. 5

acetone baths and the uranium–gold foil was attached to an aluminum foil with a round opening 3 cm in diameter. This resulted in thin and homogeneous uranium–gold foil, which had the disadvantage that some of the nuclear fragments first had to pass through the gold foil and could thus suffer inelastic scattering. Therefore, another process was sought.[58]
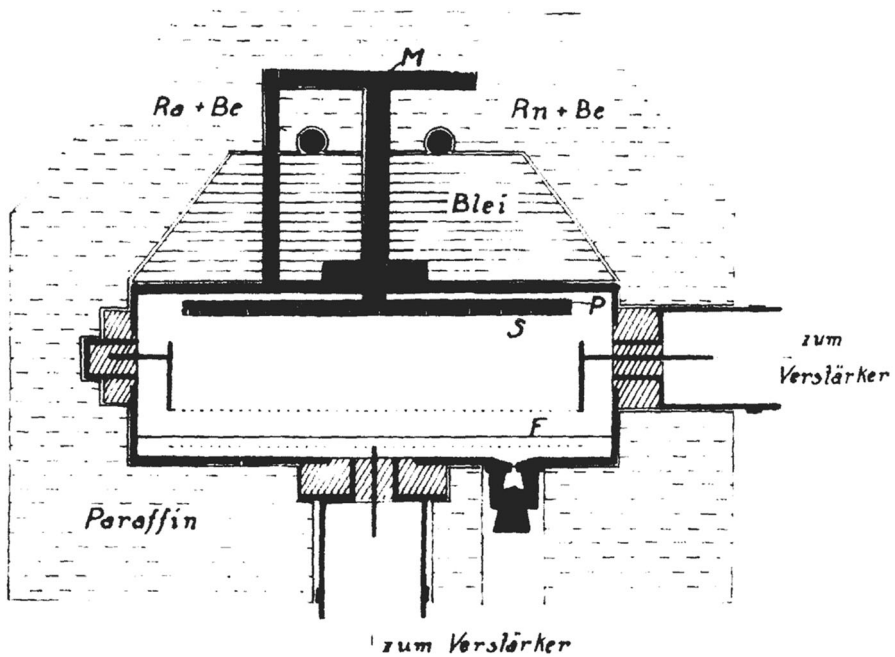
Fig. 5. Double ionization chamber for determining the range of the nuclear fragments. From: ADMM, FA 002 / Vorl. No. 0096, p. 4

First, a comparatively thick layer of uranium was electrolytically applied to a platinum disc. This was then cathodically vapor-deposited onto an acetyl cellulose base. The finished uranium layer was then reattached to an aluminum foil and the acetyl cellulose base dissolved in acetone baths. Despite a thickness of only 6 µm and an air equivalent of only 0.03 mm, the finished uranium layer proved to be more than stable and could thus be used for the experiment. This made it possible to determine the masses of the resulting fragments. Fragments of equal weight hardly ever occurred; the heavy fragments varied between an atomic weight of 127 and 162, with the masses of the light ones between 109 and 174, according to Jentschke and Prankl.[59]

In addition, Jentschke and Lintner determined the range of the nuclear fragments using the arrangement shown in figure 5. A method had to be chosen in which the ionization of the α-rays of uranium and other random radioactive substances did not interfere. The nuclear fragments therefore passed through two ionization chambers separated by a thin foil (F). The double ionization chamber used had a diameter of about 10 cm. The particles that occurred in each chamber were registered separately after suitable amplification using mechanical counters.

A third counter ensured that only nuclear fragments occurring in both chambers were counted.[60]

The effective depth of the large ionization chamber could be varied with a micrometer screw (M). The maximum depth of the large chamber was 26 mm, 6 mm for the small one. Attached to the micrometer screw is the preparation carrier (P), with a uranium layer with an air equivalent of 1 mm applied by electrolysis. Each of the two chambers contained net electrodes consisting of brass rings across which a fine brass wire with a diameter of 0.2 mm was stretched. These were connected to an amplifier and a counter. The counter of the large chamber was set so that it only responded to heavy nuclear fragments. The particle counter in the small chamber was set as sensitively as possible. A third counter ensured that only those pulses were counted that occurred simultaneously in the large and small chambers. This ensured that the counted coincidences were only triggered by heavy particles.[61]

The irradiation of the uranium was again carried out with Ra+Be neutron sources, whose escaping gamma radiation was shielded from the uranium layer with lead. The complete arrangement was surrounded by paraffin so that the slow neutrons hit the uranium layer. In total, two substantial series were measured in over 905 h, once with an argon filling, once with a nitrogen filling of the chamber. In each series, the sensitivity of the counter of the small chamber was also varied. The results were then converted to air and compared with each other.[62]

To carry out the experiment, the preparation carrier was brought close to the small chamber with the micrometer screw and the coincidences were counted per unit of time. It was then removed in 0.5 mm steps and the coincidences per time unit continued to be counted until they finally dropped to zero at about 25 mm. From this, differential range curves could then be determined as in figure 6.

The Neutron Sources of the Vienna Group

The neutron sources used by the Viennese physicists had been in use before the *Uranverein* was founded. They were based on an (α,n) nuclear reaction, mostly using a Ra+Be neutron source. The disadvantage was that only limited neutron flux densities with a strongly inhomogeneous energy spectrum could be achieved. This limited the accuracy of the scattering cross sections determined.

The alternatives were particle accelerators, which could achieve much higher neutron flux densities. John D. Cockroft and Ernest Walton were the first to demonstrate an artificial nuclear reaction in an accelerator in June 1932. From then, things went from strength to strength and the Radiation Laboratory in Berkeley, under the direction of Ernest O. Lawrence, took a leading role. It is no surprise that the Austrian physicists wanted a Van de Graaff accelerator for their work. The reasons this instrument did not come to Vienna are exemplary of the work in the *Uranverein* under the Nazi dictatorship. In November 1940, the Austrian Academy of Sciences approved the purchase of a neutron generator,
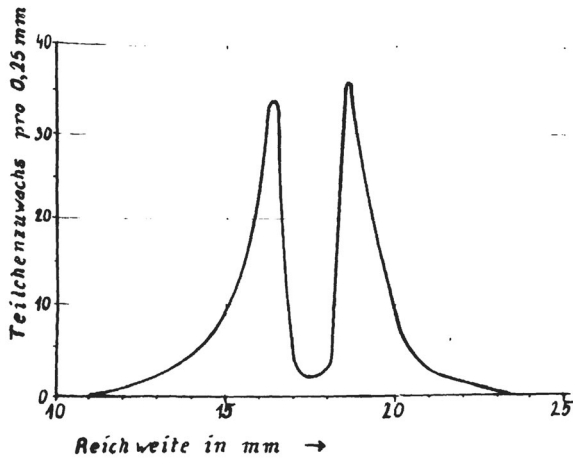
Fig. 6. Derived range distribution of nuclear fragments of uranium in nitrogen. From: ADMM, FA 002 / Vorl. No. 0096, p. 16

which was ordered in early 1941 with a delivery time of thirty-six months. In June 1942, Austrian scientists were given a higher level of urgency and the delivery time was reduced to twenty-two months, but delivery problems the German manufacturer faced delayed the completion of the generator. When the generator finally came within reach at the end of 1944, the city of Vienna refused to grant planning permission for the conversion of the institute's building in Vienna's *Boltzmanngasse*. In March 1944, a gymnasium in Krems was chosen as the new location. Ultimately, Austria's liberation from fascism ended all dreams of great power, as well as the desire for a neutron generator.[63] This failure due to constant delays, delivery problems, and more is characteristic of the entire *Uranverein*, as Mark Walker has shown.[64]

After Liberation

Like Germany, Austria was divided into four occupation zones after the war and only regained full political sovereignty under the condition of political neutrality with the signing of the Austrian State Treaty in 1955. Austrian physics in the postwar period was first addressed in a 2005 essay by Wolfgang Reiter and Reinhard Schurawitzki.[65] A somewhat more detailed account can be found in Silke Fengler's 2014 book.[66] Denazification had personnel consequences, but the lack of financial and material resources weighed much more heavily on Austrian research. These shortages prevented research from continuing, although unlike in Germany, there were no bans on nuclear research from the Allies. Rather, the Western Allies, especially the American troops, supported Austrian scientists in

rebuilding the research facilities, for example, in repatriating the radium standards and instruments that had been moved out to western Austria toward the end of the war.[67] Contemporary witnesses, such as the physicist Ferdinand Cap, who worked as a translator for the Soviet occupation forces in 1945, could not recall any restrictions in an interview.[68]

Karl Lintner, Stetter's assistant at the *Uranverein*, also recalled no restrictions on nuclear research in an interview with the author. Lintner's *habilitation*, completed in 1949, on the interaction of fast neutrons with the heaviest stable nuclei (mercury, thallium, bismuth, and lead) was methodologically based on research carried out at the *Uranverein*. Lintner arranged the elements to be investigated in spherical shells around a Ra+Be neutron source. Incidentally, this was once again precisely the Ra+Be neutron source that had been used in the Vienna *Uranverein* experiments. The structure was analogous to that in the *Uranverein*, except that uranium was no longer used after 1945. Lintner regretted not having a neutron source available that delivered neutrons with homogeneous energy:

> In the present work, the cross sections for neutron processes are now to be determined for the heaviest stable elements. No energy-homogeneous neutron source was available as a radiation source, but only a Ra+Be source, whose energy spectrum we know unfortunately very little about. For work with this natural source of radiation, however, it is precisely the knowledge of the effective cross sections, in which reference is made to the entire spectrum, that is of importance. After all, the neutrons always act in their entirety, so it is precisely this cross section of action that must be used in every further calculation.[69]

The neutron generator ordered during the war, based on a simple accelerator, remained the desired object of the Viennese nuclear physicists even after the war ended, but as the situation stood, physicists had to make do with the resources available. Delivery of the neutron generator ordered in 1941 after the war was out of the question. The provisional director of the Radium Institute did make an effort to secure it.[70] But the request was denied due to legal restrictions imposed by the Allies in Germany. In addition, parts of the neutron generator had been confiscated by the Allies. Finally, in May 1948, doctoral student Rudolf Waniek began work on building a neutron generator, which he completed in 1950.[71]

Conclusion—Breaks and Continuities

Two things stand out when looking at Vienna's work within the *Uranverein*: the continuity of the research carried out and the small spatial dimension of the experiments.

First, let us look at the continuity of the research carried out. This includes the personnel entrusted with the experiments, the methods and instruments employed, the materials used, and the publication of the results. The staff of the Radium

Institute and the University of Vienna's Physics Institute involved in the work hardly differ from those of the prewar period. Stefan Meyer and Karl Przibram were expelled after the annexation due to the racist measures of the Nazis. Willibald Jentschke forged ahead with his academic career and qualified as a professor within the *Uranverein*. His work on the energy and range of nuclear fragments was even published in the *Mitteilungen des Instituts für Radiumforschung* in 1942. The publication is practically identical to the secret *Uranverein* report of the same name from March 1941.[72] Only Karl Lintner was a newcomer to the wartime research group; he completed his dissertation as part of the *Uranverein* and the collaboration saved him from deployment to the front. His 1949 *habilitation* was based on work he had done with Stetter and Jentschke in the *Uranverein*. He even used the same neutron source.

The central instrument the Viennese researchers used was the tube electrometer, with which even individual processes in ionization chambers could be quantitatively determined. These instruments became firmly established in the tool box of the Vienna Group in the 1930s. Stetter, along with Josef Schintlmeister, Ewald Schmidt, Gustav Ortner, and Jentschke, had successfully used them to study nuclear processes during these years. In 1939, for example, Jentschke and Friedrich Prankl were able to physically demonstrate the products of uranium fission and later to determine the energy and range of uranium's nuclear fragments. Stetter's experiments to determine the scattering cross sections of fast neutrons in uranium also reveal nothing fundamentally new. The samples were arranged concentrically around the Ra+Be neutron source and the products of the nuclear reactions were counted. The layer arrangements were systematically varied. Schintlmeister's procedure for identifying the 1.8 cm α-emitter corresponds to the standard procedure of a radiochemist of the time. The dimensions of the experiments did not differ from the work carried out in the prewar period. All experiments were on a scale that could be carried out without problems in a small laboratory. Only the envisaged Van de Graaff generator would have significantly expanded the existing dimensions. It was never delivered.

All dreams of this kind were ended by the liberation. What remains is the observation that the Viennese physicists did not succeed in acquiring new resources in the *Uranverein*: they simply continued to work as before. Neither money, manpower, nor machines grew significantly or collapsed under the Nazi dictatorship.[73] The positions of displaced colleagues were filled with new researchers. What remained was a research group whose daily research routine in the laboratory was no different from that before the *Uranverein* was founded.

What does this mean in relation to the questions posed at the beginning? Why did German physicists not build a nuclear weapon during the Nazi dictatorship? This question proves meaningless in the Viennese context. The historical actors remained entrenched in the structures of academic laboratory science. Setting aside the question of a German atomic bomb allows us to understand how physics was practised under the Nazi dictatorship. What were the results for the Viennese

radium and nuclear researchers? They worked well in Imperial Austria, in the First Republic, in the corporative state, in the Nazi dictatorship, and later in the Second Republic. The global economic crisis led to the first cuts in the resources available to Viennese scientists. The corporative state further aggravated the situation. The expulsion of colleagues defined as Jewish after the annexation by Nazi Germany was a massive rupture, but its impact on the group of Viennese nuclear physicists under study was minor. This group showed persistence in its research program across the borders of Austria's political systems that was startling in every respect. They did not work in spite of, but with each of the political systems. This finding initially applies only to the Vienna group in the *Uranverein*. The next step is to investigate other research sites in the *Uranverein*. Initial work on this topic suggests that similar findings are emerging.[74]

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