The Nuclear Fission Table in the Deutsches Museum: A Special Piece of Science History on the Eve of World War II

Susanne Rehn-Taube

Deutsches Museum, Museumsinsel 1, 80538 München, Germany

The Deutsches Museum in Munich is one of the largest science and technology museums in the world. At 50,000 square meters, we show masterpieces from such diverse disciplines such as chemistry, physics, aircraft, marine, biotechnology or glass technology.

Since the beginning of the museum, there was an exhibition about chemistry. The chemical collection has a long tradition. Dye samples, laboratory equipment, and many other objects - about 10,000 in total - make up our collection.

One of the most famous objects is the table displaying the original equipment used by the researchers who discovered nuclear fission of uranium atoms in 1938: Otto Hahn, Lise Meitner and Fritz Straßmann.[1]

The discovery of nuclear fission

Since the 1890s, the scientific community had formed an increasingly accurate idea of the atom. After the first investigations of radioactive substances by, for example, Becquerel discovering the peculiar radiation emitted by uranium compounds, the Curies discovering the element radium and creating the term "Radioactivitity", Ernest Rutherford explaining correctly the nature of α-, β-rays, he and his coworker Frederick Soddy noticed in 1902 that by radioactive decay chemical elements change into each other. In 1913, Niels Bohr established his atomic model, postulating a positive nucleus with negative electron shells. In 1919, the first man-made change of elements took place, again by Rutherford: By bombarding nitrogen atoms with helium nuclei, he obtained oxygen atoms and a positively charged particle which, a short while later, he identified as the proton.[2] As a result, several research groups attempted to obtain element changes by bombarding atomic nuclei with protons. In this case, however, the repulsion of the positive particles and the positive nucleus always was an obstacle.

It was not until the discovery of the neutron by James Chadwick in 1932 that a new possibility was opened: This nucleon should be able to penetrate the nucleus without electrostatic repulsion.[3] At that point, the atom had become anything but indivisible. Bohr

1. S. Rehn, Kultur und Technik 3/2013, p. 18-25
2. For milestones in Rutherford's scientific life, see: http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1908/rutherford-bio.html
3. J. Chadwick, Nature *129*, 1932, S. 312; J. Chadwick, Proc. Roy. Soc. A. *136*, 1932, p. 692-708

spoke of a possible "explosion" [4] or "breaking" [5] of atomic nuclei. He formulated the theory that the nucleus behaves similar to a large water drop.

Enrico Fermi then irradiated a variety of elements with neutrons. By neutron capture and subsequent β-decay, he was hoping to obtain elements with an atomic number increased by one compared to the starting materials. In the case of uranium, at the time believed to be the heaviest chemical element, this transformation would lead to an artificial element. A transuranic element should arise.[6]

Lise Meitner thought these results so fascinating that in 1934 she persuaded Otto Hahn to join forces again in trying to bombard heavy nuclei, including uranium and thorium, with neutrons, in order to obtain transuranic elements.[7] The two scientists had known each other since 1907.[8] In the late 1930ies, Hahn led the Department of Radiochemistry and was director of the Kaiser Wilhelm Institute for Chemistry in Berlin. Lise Meitner directed the Radio-Physical Department.

The collaboration of the physicist and the chemist must have been extremely fruitful and affected by great friendship. Hahn described it in 1963 as "stroke of luck" to have met Lise Meitner.[9] Together with the chemist Fritz Straßmann, they conducted the following experiments: A sample of purified uranium was brought into a paraffin block and put next to a neutron source of beryllium and radium. After different exposure times, the uranium sample was removed and chemically analyzed. After dissolving it in hydrochloric acid, a compound similar to the suspected product was added. By doing so, the team expected that this added compound and the reaction product should precipitate together from the solution. Excessive uranium remained in the solution. Subsequently, the filtrates were dried and the filter papers were glued into the cylindrical hollow of a lead block. Home-made Geiger-Muller counters were set onto the filter papers. The counter tube consisted of an aluminum cylinder filled with a special argon gas mixture with a wire in the center. Strong batteries put the wire under voltage. The negative β-particles emitted from the radioactive sample were accelerated toward the wire and caused a cascade of ionizations and an electrical pulse. This pulse was amplified and displayed by a mechanical counter. Plotting the counts against time yielded the radioactive decay rates of the reaction products.

Indeed, the team found reaction products emitting β-particles and concluded that transuranic elements were formed. They assumed that nuclei with atomic numbers 93-96 were formed and found that their chemical properties met the expectations. Since they found new radioactive compounds which could be precipitated with platinum salts they took this as prove for the chemical similarity of the elements. Despite the probably long series of β-decay, which was never observed before, the finding of new chemical elements was published and not doubted by anyone.[10] But why do we today read eka-osmium, eka-rhenium, eka-iridium and eka-platinum in these publications? To answer this question, we have to have a look at

4. N. Bohr, Nature *137*, 1936, p. 344-348
5. N. Bohr, Science *86*, 1937, p. 161-165
6. E. Fermi, Nature *133*, 1934, p. 757; E. Fermi, *ibid*., p. 898-899
7. Lise Meitner: Wege und Irrwege zur Kernenergie (1963). In: L. Meitner, D. Hahn (Ed.), Erinnerungen an Otto Hahn. Hirzel Verlag Stuttgart, 2005, p. 69 – 73
8. F. Krafft, Otto Hahn und die Kernchemie, Museumsverein für Technik und Arbeit, Mannheim, 1991, p. 14 - 15
9. Otto Hahn – 25 Jahre Atomzeitalter. Television movie produced by the North German Television Network NDR, 1963. In German, Hahn uses the term "Glückszufall", which is a mixture of the words "luck" and "chance". Deutsches Museum archive, AV-F 0026 & 1743. (All translations of original German quotes by S. Rehn-Taube.)
10. a) L. Meitner, O. Hahn, F. Straßmann, Z. f. Physik *106*, 1937, p. 249 - 270; b) O. Hahn, L. Meitner, F. Straßmann, Chem. Ber. *70*, 1937, p. 1374-1392

the periodic table of the time: Despite the knowledge of the Lanthaoids, the scientists believed that the chemical elements following uranium had to be heavier homologes of the *transition metals*. Since the Berlin groud found new radioactive compounds which could be precipitated with platinum salts they took this as prove for the chemical similarity of the elements.

In the year 1937, Irène Joliot-Curie and her colleague Paul Savitch in Paris conducted similar experiments and found a product with a half-life of 3.5 hours. The group gave various explanations for the chemical nature of this nucleus, claiming to have found lighter elements as well as transuranic elements.[11]

Hahn and his team were very clear about the fact that they weren't the only ones working on this particular topic.

It was the summer of 1938. At this exciting point of their work, Lise Meitner had to flee from Germany. After the "Anschluss" of Austria by Germany, she was threatened with persecution by the Nazis as an Austrian Jew. With the help of Otto Hahn and other colleagues, she left Germany on July 13th, 1938 for the Netherlands and eventually Sweden. Her scientific celebrity status did not protect her in any way: She could only cross the German border because she was fortunate enough to not be controlled by the SS guards on the train. The flight must have left a great break in the Berlin team. Otto Hahn wrote later: "I'll never forget the 13th of July 1938".[12] "Hähnchen" and "Lieschen", as they called themselves according to legend, remained in intensive contact by correspondence nonetheless.

In Berlin the team focused on the chemical analysis of the irradiation product. The results seemed to indicate radium as product.[13] This could be the result of two consecutive α-decays of uranium. Two consecutive α-decays had never been observed before, and many experts were skeptical.

To identify radium chemically, Hahn and Straßmann first added barium chloride to the uranium solution and hoped to precipitate a radium barium mixture. The precipitate was filtered and dissolved again. From this solution the team tried to separate barium and radium by fractional crystallization. The solution was heated and first treated with acid, until a small portion crystallized. This precipitate was filtered off. The solution formed a second precipitate which was also filtered off. Subsequently, a third fraction was crystallized. Since radium salts are usually less soluble than barium salts, the former should be enriched in the first fraction and the latter in the last fraction. The radioactive decay of all fractions was analyzed. Since different nuclei were assumed to be present, each fraction should emit their specific radioactive activity. However, Hahn and Straßmann discovered that there were no differences in the activities of the fractions. Apparently, a chemical separation had not taken place.

To verify this, the team also conducted the fractional crystallization with radium salts. It seemed possible that radium in such small quantities behaved in a peculiar and unexpected way. And afterwards, the famous indicator experiment should bring final clarity: Hahn and Straßmann irradiated the uranium sample, mixed it with a radium sample of known radioactive activity and conducted the fractional crystallization with this mixture.[14] And all these series of experiments showed that all the differences in the activity of the separate fractions were only due to the "honest" (quote: O. Hahn [9]), *i.e.* the added radium. The artificial radium showed constant activity through all fractions. Thus, it was a nucleus

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11. a) I. Curie, P. Savitch, J. Phys. Radium *7*, 1937, p. 385 - 387; b) I. Curie, P. Savitch, C. R. *206*, 1938, p. 906 - 908; c) I. Curie, P. Savitch, J. Phys. Radium *9*, 1938, p. 355 - 359
12. O. Hahn, Mein Leben. Bruckmann, München,1968, p. 150
13. O. Hahn, F. Straßmann, Naturwissenschaften *46*, 1938, p. 755 - 756
14. A very detailed description of the experiments is given in: F. Krafft, Im Schatten der Sensation. Leben und Wirken von Fritz Straßmann. Verl. Chemie, Weinheim 1981, p. 212 and following pages.

inseparable from barium. The product of the irradiation experiments had to be barium. These results left Hahn and Straßmann clueless. They had no explanation how irradiation of uranium could lead to barium, a much lighter element.

In a letter written on December 19th, 1938 Otto Hahn asked Lise Meitner for an explanation, because he knew that "[uranium] cannot burst into barium". "The more we think about it, the more we come to this terrible conclusion: Our radium isotopes do not behave like radium, but like barium. [...] If you could suggest anything, it would still be like a result of the three of us!" [15]

His point of view that Lise Meitner was still part of the team led to this wish that the results would still be a work of the whole team. Meitner was skeptical and asked very critically whether all other possibilities had been ruled out.[16] She spent Christmas of 1938 with her nephew, physicist Otto Frisch, in Kungälv, Sweden. According to legend, the pair spent hours of walking in the snow and they developed a revolutionary interpretation of the experiments. According to Bohr's liquid drop model, the uranium nucleus started to move after penetration by a neutron.[17] Afterwards appeared constriction and finally separation into two roughly equal-sized fragments, which were each much smaller than the uranium nucleus itself. Thus, an explanation for the light nucleus barium was found. The fragments flew apart with high kinetic energy. Otto Robert Frisch had the honor of giving the new process its name: *nuclear disintegration* and later *nuclear fission*. On New Year's Day, 1939, Lise Meitner told Otto Hahn in a letter that "perhaps it is energetically possible that such a heavy nucleus bursts into pieces." [18]

Today, one can only try to sympathize with Meitner's feelings, which oscillated between frustration and excitement. Her entire life had been turned upside down, apparently she had missed the most important discovery, and this discovery also questioned her own work about the transuranic elements. Hahn and Meitner also corresponded about their feelings in their letters. Hahn wrote: "How beautiful and exciting it would be if we could have done this work together like before." From Meitner's reply he could read the fear that her participation in the discovery could not be adequately approved. And Hahn replied immediately: "It shocked me to see you so depressed." [19]

On January 6th, 1939, the results of Hahn and Straßmann were published. The interpretation culminated in the famous phrase: "As chemists, we should actually call the new nuclei not radium but barium." [20] And the next major publication by Hahn and Straßmann followed February 10th, 1939. [21] The authors reported with absolute certainty that all the previously suspected radium isotopes were in truth barium isotopes. Hahn and Straßmann apparently tried to show that there was indeed a group of three that had obtained the results. The previous publications of the trio and Lise Meitner's name were mentioned several times. Hahn and Straßmann mentioned the transuranic elements: "We are still certain, that the transuranic

15. Letter quoted in: a) J. Lemmerich, Die Geschichte der Entdeckung der Kernspaltung. Catalogue of the exhibition by the Deutsches Museum and the Hahn-Meitner-Institute of the Technical University, Berlin, 1989, p. 166 - 170; b) W. Gerlach: Otto Hahn, Ein Forscherleben in unserer Zeit. Deutsches Museum Abhandlungen & Berichte, *37*, 1969, p. 52 - 53
16. J. Lemmerich (note 15a), p. 171
17. A modern essay about the finding of nuclear fission and the liquid-drop model is found in: H. J. Krappe, K. Pomorski, „Theory of Nuclear Fission". Springer Verlag Berlin, Heidelberg, 2012
18. Letter quoted in: J. Lemmerich (Ed.), Gedächtnisausstellung zum 100. Geburtstag von Albert Einstein, Otto Hahn, Max von Laue, Lise Meitner 1.3. – 12.4. 1979. Catalogue of the exhibition held in the Staatsbibliothek Preußischer Kulturbesitz, Berlin. Berlin, 1979, p. 122
19. Letters quoted in: J. Lemmerich (note 15a) p. 171, 177
20. O. Hahn, F. Straßmann, Naturwiss. *27*, 1939, p. 11 - 15
21. O. Hahn, F. Straßmann, Naturwiss. *27*, 1939, p. 89 - 95

elements remain." The second fission product was stated to be a noble gas, either krypton or xenon. The publication concluded with the statement that the finding of the new irradiation products was "only possible by the experience we have gained in the earlier, systematic experiments on the transuranic elements, carried out in association with L. Meitner."

Meitner and Frisch published their conclusions in *Nature* in February 1939. [22] They predicted the other fission product correctly: subtracting the atomic number barium (56) from uranium (95) led to krypton (36). This work also explicitly stressed the existence of transuranic elements. In subsequent publications, Frisch and Meitner already provided calculations of the enormous amount of energy released during the reaction and found experimental proof for the fission fragments.[23, 24]

After those publications, various groups all over the world instantly began to repeat, confirm and continue the experiments. Frédéric Joliot-Curie realized that the fission reaction led to the emersion of free neutrons. These could lead to the subsequent fission of further uranium atoms and a self-maintaining chain reaction was thinkable.[25] Soon the whole world was interested in nuclear fission. Frisch and Bohr explained the energy released during the reaction with Einstein's equation $E = mc^2$. [26] The fragments of the nuclear fission reaction combined had a smaller mass than the uranium core. The equivalent of this mass difference was released as free energy.

The different isotopes of uranium have been extensively studied. As early as 1939, Niels Bohr recognized that the fission process only occurs in the rare uranium isotope ^{235}U.[27] In the following year, the American group led by McMillan and Abelson published confirmation that, by irradiation of uranium-238, a transuranic element could be produced. However, this element had different chemical properties than the assumed eka-rhenium. In the article, it is somewhat uncertainly stated that the results, in particular the chemical similarity to uranium, would suggest that there could be a second series of rare earths subsequent to uranium.[28] Thus, the path was clear for the periodic system we know today: Below the lanthanide series follows a series of elements later called actinides. Hahn and Straßmann confirmed and supplemented the results. They provisionally named the new element group "Uranides".[29]

Otto Hahn later said that because they did not recognize the uranium isotope with the half-life of 23 minutes as a precursor of the chemical element neptunium, they missed a Nobel Prize.[30] Later [31] McMillan and others also found the heaviest natural element, plutonium, with an atomic number of 94. It emerged from the bombardment of uranium atoms with deuterium nuclei.[32]

The transuranic elements 93 and 94 were later called neptunium and plutonium in the order of the planets Uranus, Neptune, and Pluto.[33] Plutonium is considered the heaviest naturally

22. L. Meitner, O. R. Frisch, Nature *143*, 1939, p. 239 - 240
23. O. R. Frisch, Nature *143*, 1939, p. 276
24. L. Meitner, O. R. Frisch, Nature *143*, 1939, p. 471 - 472
25. H. v. Halban, F. Joliot, L. Kowarski, Nature *143*, 1939, p. 470 - 471
26. N. Bohr, J. A. Wheeler, Phys. Rev. *56*, 1939, p. 426-450
27. N. Bohr, Phys. Rev. *55*, 1939, p. 418 - 419
28. E. McMillan, P. H. Abelson, Phys. Rev. *57*, 1940, p. 1185 - 1186
29. F. Straßmann, O. Hahn, Naturwissenschaften *30*, 1942, p. 256 - 260
30. O. Hahn (Note 12), p. 167
31. The results were not published until 1946. In the publications it was mentioned that the corresponding experiments took place in 1941.
32. a) G. T. Seaborg, E. M. McMillan, J. W. Kennedy, A. C. Wahl, Phys. Rev. *69*, 1946, p. 366 - 367; b) G. T. Seaborg, A. C. Wahl, J. W. Kennedy, Phys. Rev. *69*, 1946, p. 367; c) J. W. Kennedy, A. C. Wahl, Phys. Rev. *69*, 1946, p. 367 - 368; d) J. W. Kennedy, G. T. Seaborg, E. Segrè, A. C. Wahl, Phys. Rev. *70*, 1946, p. 555 - 556
33. Uranium was discovered in 1789 and named after the recently discovered planet Uranus.

occurring element. It was found in trace amounts in natural uranium ore. The naturally occurring transuranic elements are just like the ones in the laboratory created via neutron capture by uranium-238 atoms.

All other transuranic elements were produced during the following period in nuclear reactors, in part in such large quantities that they found their own technical application. One example is americium, an artificial element with the atomic number 95, which used to be in use in smoke detectors. Other transuranic elements were later detected after collisions in particle accelerators. Those elements produced as individual atoms fell apart after a few seconds.

During World War II, Otto Hahn was a member of the "Uranium Association," a group of scientists who were supposed to work on the technical use of nuclear fission in Germany. But the next generation of radio chemists and physicists had already taken over. During his captivity in England, Otto Hahn learned of the nuclear explosions in Japan by the Americans and of the fact that he had been awarded the Nobel Prize for Chemistry in 1944. Later, Otto Hahn referred to the use of nuclear fission for military purposes as a "mess" [34] that he wanted no part of. He initiated actions against the military use of nuclear power, such as the Mainau Declaration in 1955 or the Göttingen Declaration in 1957.

To receive his Nobel Prize, Hahn had to wait until the ceremony of 1946. He met with Lise Meitner, who expressed her displeasure at having been sent to Sweden by Hahn.[35] Hahn took this for a certain disappointment that he alone was awarded the prize. In fact, awarding the prize to Otto Hahn alone probably remains one of the most debated decisions of the Nobel committee until today. Hahn and Meitner were both nominated several times. Meitner wrote to a friend, "Hahn surely earned the Nobel Prize in Chemistry, there is really no doubt. But I believe that Frisch and I have contributed something essential to the investigation of the uranium fission process – how it is explained, and that it is connected with such a large energy release, Hahn was not aware."[36] Lise Meitner obviously addressed problems directly and spoke clearly about them.

In his Nobel Lecture on December 13th, 1946, Hahn explained the work of the team Hahn, Meitner, and Straßmann in great detail.[37] Being a Nobel Laureate, Otto Hahn later led the Kaiser-Wilhelm-Gesellschaft and its successor, the Max-Planck-Gesellschaft, whose presidency he held until 1960.

But the developments that occurred in other fields after the discovery of nuclear fission have certainly had a much greater impact on humanity. The enormous energy release of the fission process soon led the scientific community to think about the possibilities of a power reactor or an explosive bomb, in the beginning cautiously called “machine”. The first nuclear reactor in the world was built by Enrico Fermi in Chicago in 1942. The first atomic bomb was developed in the *Manhattan Project*. With an incredible amount of money and manpower, the Americans pushed their nuclear program. Today, we see it as the beginning of a new era when the first atomic bomb was detonated on July^{16th}, 1945 in the New Mexico desert. This development is still especially real to the people in Japan since the Japanese people were victims of the two terrible atomic bombings on Hiroshima and Nagasaki on August^{6th} and August^{8th}, 1945. From today's perspective, one might assume that the images of the destroyed

34. Radio interview with Otto Hahn (1967), Deutsches Museum archive, AV-T 0457
35. O. Hahn (Note 12), p. 206
36. L. Meitner to Mrs. B. Aminoff, 20.11.1945, letter quoted in: J. Lemmerich, Dahlemer Archivgespräche, *6*, 2000, p. 158 – 167
37. O. Hahn (Note 12), p. 247 and following pages

cities would have caused those responsible to rethink, but no: The nuclear arms race was just beginning. To this day, the earth has been shaken by 2053 nuclear explosions.[38]

The artifact: The "Otto-Hahn-table"

In 1952, the director of the Max Planck Institute for Chemistry in Mainz got in touch with the Deutsches Museum to discuss the existing equipment by Otto Hahn. Parts of the original equipment that had been moved after the war from Berlin via the small city of Tailfingen to Mainz, had been arranged there on a table and presented to the public. Neither the museum nor any of the parties involved ever cast doubt on the authenticity of the devices. A description of the exhibit by Fritz Straßmann in 1974 was pragmatic: The table would certainly be one of the then usual work tables from Berlin, but the devices "not entirely the same."[39] "But never mind," Straßmann said, pointing out that some parts "had to be replaced" already during the experiments. One can try to imagine how big the probability is that all the batteries, amplifier tubes and wires survived World War II and at least three moves across Germany after being in Meitner's, Hahn's, and Straßmann's hands.

Once the table and the apparatus were erected in the museum, they waited for a text to explain their meaning. It was planned that a marble tablet should bear the following text:

OTTO HAHN

discovered in 1938, together with Fritz Straßmann, the fission of uranium by neutrons, thus creating the basis for the technical realization of atomic energy.

Otto Hahn was specifically asked by the general director Jonathan Zenneck about his opinion of this synopsis. In his reply dated April 8th, 1953 Hahn was unenthusiastic about the plans of the Museum:

"As much as I am delighted about the attention [...] I'm a little depressed about the presentation that is apparently intended. It seems to me somewhat exaggerated to construct a special niche with a marble table, because if the fission of uranium has been found in aftermath to be very important, neither Mr. Straßmann nor I had any share in this development." In his letter, he goes on to mention Lise Meitner and again asks for his name not to be "mentioned with a special appearance".[40]

This letter clearly contradicts the image that has sometimes been drawn of Otto Hahn that he had spoken too rarely about the share of his colleagues in the discovery, particularly Lise Meitner's share. The mere mentioning of the two colleagues in this letter should have demonstrated to Zenneck that the display as "Otto Hahn table" was wrong. Zenneck and his successors, however, did not change anything for several decades and the name "Otto-Hahn table" stuck.

And this is how the visitors found the artifact: It was called "workbench" but displayed devices which were never used together on one table. The paraffin block and the neutron sources (which were displayed as reproductions) were used in an irradiation room, while the chemical analysis was undertaken in the chemical laboratory of Straßmann. The measurement of the radioactive activities was conducted in the measuring room. The pairwise arrangement

38. http://www.ctbto.org
39. Quote by F. Straßmann in: F. Krafft (note 14), p. 227
40. Hahn to Zenneck, 8.4.1953, Archive of the Max-Planck-Gesellschaft, Abt. III, Rep. 14, Nr. 5287, Bl. 14

of the counters on the table had no scientific grounding, but gave the whole thing a wonderful symmetry. Interestingly, Hahn always talked about three counters that were available (and thus limited the number of possible parallel experiments).[41] That the measurements would have been impossible if set so closely to the neutron source was never mentioned in one of the museum texts.[42]

Otto Hahn was in the museum in 1963 on the occasion of the 25th anniversary of the discovery. He gave a television interview in which he told the entire story in great detail.[9] Hahn emphasizes the contributions and the great teamwork between himself, Meitner and Straßmann. A still image from the movie is now regarded as the moment Hahn arranges the devices for the museum himself, a legend that is just as wrong as it is persistent.

Only in 1989, on the occasion of a major exhibition, a balanced and correct presentation of Meitner's and Straßmann's contributions was finally shown in the museum.[43]

In 1998, the table was lent to the branch musem in Bonn. When lifting the paraffin block, the museum professionals found a trace of historical uranium powder. They locked the paraffin block with a tight fitting glass hood. Since that time, repeated measurements have shown that this museum artifact does not radiate anymore. Since December 2012, the table has been on display in the permanent exhibition.

The majority of visitors connect the object to the development of nuclear power and all its consequences, rather than to the various stories around the discovery of nuclear fission. In the museum, the table became an icon of the history of science, an art object whose aura is fueled not only by its history, but also by its altar-like arrangement.

41. Hahn to Meitner (21.12.1938), letter quoted in: J. Lemmerich (note 15a), p. 171
42. The author thanks Jost Lemmerich for this special note. Personal message (16.4.2013)
43. R. L. Sime, Phys. Perspect, *12,* 2010, p. 190 - 218