Pramāṇa – J. Phys., Vol. 33, No. 1, July 1989, pp. 1–12. © Printed in India.

Discovery of nuclear fission in Berlin 1938

D HILSCHER
Hahn-Meitner-Institut Berlin, D-1000 Berlin 39, FRG

Abstract. The story of the discovery of nuclear fission, one of the most exciting stories of how a scientific puzzle was finally solved and how the scientists involved were blind to many obvious indications, is described.

Keywords. Nuclear fission; Discovery of neutron; transuranium puzzle; Hahn-Meitner collaboration; Lise Meitner.

PACS No. 01

1. Introduction

About 3 billion years after the earth formation the first known fission reactor (Neuilly *et al* 1972) burned on our planet in Oklo, Gabon, Africa. It took another 1·8 billion years until Hahn and Strassmann discovered nuclear fission in December 1938 in Berlin. More precisely Otto Hahn was sitting in his office at the Kaiser-Wilhelm Institute for Chemistry in Berlin at 11 pm on Monday, December 19, 1938 writing a letter to Lise Meitner in Stockholm (Hahn 1975) in between reading off the counters and waiting for Strassmann to come in at 11:45 pm: *But more and more we come to the frightful conclusion: our Ra-isotopes do not behave like Ra but like Ba.* Thus nuclear fission was discovered. Three days later the manuscript containing this discovery was received by the journal Naturwissenschaften and shortly thereafter it was published on January 6, 1939 by Otto Hahn and Fritz Strassmann in Naturwissenschaften 27, 11 (1939). Why "frightful" conclusion? Was Hahn really aware what his discovery meant for mankind: that the most frightful weapon ever designed by mankind would be based on his discovery and as we have realized more recently that the peaceful use of nuclear power is also frightful to many people? I doubt that this was the reason why he used the word frightful. The more likely reason was that this result contradicted all that was known or was thought to be known about nuclear physics. Otto Hahn said many years later (Fine and Herrmann, unpublished): *Therefore we could conclude that the substances.. could be really only radium because barium was prohibited by the physicists.. we were so afraid of the physicists that we didn't dare to think it barium in those times....*

To write an article as a scientist who is doing active research in this area one would like to write on the research going on in this still very active field of nuclear science. But this is almost impossible to do on a few pages and thus I can only refer to the proceedings of scientific, conferences taking place in Berlin (April 1989), Gaithersburg (April 1989) and Dresden (November 1988) to commemorate the discovery of nuclear fission fifty years ago and in particular *to review the achievements in our fundamental* *understanding of nuclear fission obtained in the last half century and indicate the directions of present research in fission* as stated in the announcement for the Berlin conference. The discovery of spontaneous fission in 1940 in Leningrad by G N Flerov and K A Petrzhak will be commemorated at a conference in Leningrad in September 1989.

The story of the discovery of nuclear fission is one of the most exciting stories of how a scientific puzzle was finally solved and how the scientists involved were blind to many obvious indications or as Bohr has put it when Frisch told him about Hahn's discovery. *Oh, what fools we have been! We ought to have seen that before* (Frisch 1967). And we all know many scientific puzzles which have been with us for many years and which are still unsolved and we all wonder what the solution finally will be. Of the famous discoveries it is also one of the best documented ones due to the numerous letters exchanged between Lise Meitner and Otto Hahn since she was forced to leave the team Hahn-Meitner-Strassmann half a year before the final discovery. Thus a lot of the normal oral discussions in a research group were made in writing. But it is also an extremely sad story showing the disastrous influence of politics on the lives and research work of scientists.

2. Discovery of the neutron

The race for the discovery of nuclear fission started in 1930 when W Bothe and H Becker found by the irradiation of beryllium with α-particles a penetrating radiation which led in 1932 to James Chadwick's discovery of the neutron (Chadwick 1932). Chadwick had worked with Geiger and Bothe at the Physikalisch Technische Reichsanstalt in Berlin. During World War I he was detained in Berlin-Ruhleben. He bombarded hydrogen and nitrogen with the new radiation and from the recoil energies he concluded that the mass of the new particle must be about equal to that of the proton and due to the penetrability it must be neutral. This new radiation was immediately used to bombard all kinds of materials. But more important it led to a model of the nucleus by Heisenberg (1932) and Iwanenko (1932). The nucleus consists only of neutrons and protons. The stability of this nucleus was ascribed to a new force, the strong interaction, which was postulated in addition to the classical gravitational force and electromagnetic interaction known in those days. Gravitation does not play a role in the stability of a nucleus but the electromagnetic interaction of course counteracts the strong interaction, and could thus split a heavy nucleus into two parts. And indeed already in 1930 a nuclear liquid drop model was developed and described in the literature by Gamow (1930) and later also by Weizsäcker, Bethe and Bohr which was finally used by Frisch and Meitner (1939) for an explanation of nuclear fission.

3. The transuranium puzzle

Fermi immediately recognized that the neutron was the ideal projectile for nuclear reactions: there is no Coulomb barrier for neutrons and thus it is easy to induce nuclear reactions with neutrons also at small energies and on all target nuclei up to uranium (Fermi 1934). *It seemed worthwhile to direct particular attention to the heavy radioactive elements, thorium and uranium, as the general instability of nuclei in this* *range of atomic weight might give rise to successive transformations.* By 'instability' Fermi certainly didn't mean shape instability. Fermi and his coworkers F Rasetti and O D'Agostino observed very complex decay curves when they bombarded uranium and thorium with neutrons. Fermi put special attention to a 13-minute decay period produced by neutron irradiation of uranium. By radiochemical methods he could exclude that this radioactivity was due to isotopes with Z between 86 and 92 as well as 83. Following the findings from nuclear reactions on light nuclei he indicated the possibility of the existence of element 93 or may be also 94. Thus the transuranium elements were thought to be found and the transuranium puzzle started. The transuranium hypothesis didn't really explain the finding of a large number of different radioactivities. Fermi got the Nobel Prize in 1938 for the *disclosure of artificial radioactive elements produced by neutron irradiation.* He gave his Nobel Prize talk on December 10, 1983 in Stockholm, that is just about a few days before Hahn was almost certain that the so-called transuranium elements were barium, lanthanum, cerium. etc. and thus had together with Strassmann finally disclosed the neutron-induced artificial radioactivities in uranium. The 13-minute activity found by Fermi was actually the activity of $^{101}_{43}$Tc with a half-life of 14 minutes (Menke and Herrmann 1971).

The findings of Fermi were immediately criticized in the literature but in the following years several papers were published which also erroneously confirmed Fermi's findings including several papers by Meitner, Hahn and Strassmann. But the harshest criticism came from Ida Noddack, who worked with her husband at the Physikalisch Technische Reichsanstalt in Berlin. She and her husband together with O Berg had discovered (Noddack *et al* 1925) in 1925 the ekamanganese element 75 rhenium, named after the German river Rhine and the Rhineland from where Ida Noddack came from. And may be also element 43, which they called masurium, a prussian province from where Walter Noddack originated from. The discovery of both elements also received a lot of criticism, and since the authors were not able to reproduce their results for element 43 the discovery of this element was ascribed to C Perrier and E Segrè who found it in 1937 by bombarding molybdenum ($Z = 42$) with deuterons (Perrier and Segrè 1937). They named element 43 technetium since it was produced technically. Concerning Fermi's findings she wrote (Noddack 1934) that the chemical exclusion of neighbouring elements of uranium is not sufficient to prove the existence of a new transuranium element since: *It might be thinkable that by bombarding heavy nuclei with neutrons these nuclei decay into several heavy fragments which are isotopes of known elements but not neighbours of the irradiated elements.*

With this sentence the idea of a cleavage of the uranium nucleus was born already on September 10, 1934 but everybody, including Hahn and Meitner, who read this paper from I Noddack considered such an idea as unphysical. Or one can also put it this way that physicists and chemists influenced by their colleagues in physics really believe in their theories. Everybody was aware of the nuclear decay modes α-, β-, and γ-decay as well as more or less instantaneous nuclear reactions like (n, α), (n, p) and (n, γ). The physicists were using the equations for the α-decay (Gamow 1929; Gurney and Condon 1928) put forward by Gamow who was at that time in Göttingen, also for the emission of heavier fragments. But the tunnelling probability for the emission of such heavy elements was calculated to be too small to cause such huge decay probabilities for the newly found radioactivity. Bohr and Wheeler estimated in their famous paper on the mechanism of nuclear fission (Bohr and Wheeler 1939) the mean fission lifetime for an uranium nucleus in its ground state to be 10^{22} years

(10^{16}a, present value). Similarly the possibility of much more than 2 or 3 successive α-decays was excluded. Or as Meitner and Frisch (1939) formulated it in their paper on the disintegration of uranium by neutrons. *The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear-cut.* Sometimes the lack of communication between the Noddacks at the Physikalisch Technische Reichsanstalt in Berlin-Charlottenburg and Hahn and Meitner at the Kaiser-Wilhelm Institute for Chemistry in Berlin-Dahlem is ascribed to the allegation that the Noddacks had a very positive attitude towards National Socialism (Krafft 1981). Strassmann remembers also that mentioning the name of the Noddacks was a taboo at the Kaiser-Wilhelm Institute in the groups of Hahn and Meitner. In any case the spelling out of the possibility that the nucleus can split into several pieces didn't have any influence on the discovery of nuclear fission. Ida Nodack didn't do anything to prove her hypothesis. Furthermore Fritz Strassmann didn't even know about Ida Noddack's paper so that we can exclude that the suggestion of Noddack played any role as a working hypothesis in the discovery of nuclear fission (Krafft 1981).

After the findings of Fermi were published Lise Meitner had doubts and thus she persuaded Otto Hahn to help her to disentangle all the new neutron-induced radioactivities found by Fermi. In this effort they were joined in the fall of 1934 by Fritz Strassmann who in 1929 had come to the Kaiser-Wilhelm Institute for Chemistry. He contributed in particular his outstanding abilities in analytical chemistry to the team Hahn-Meitner-Strassmann.

4. The Hahn-Meitner team

Hahn had become an expert in radiochemistry when he worked with William Ramsey in England where he went in 1904 to learn English. The first problem he was working on led him to the discovery of a new radio isotope, radiothor or ^{225}Th. Ramsey persuaded Hahn to change from chemistry to radiochemistry and not to go to the chemical industry. With Ramsey's support Hahn got a position as Privatdozent (private lecturer) at the University of Berlin. Before he started in his new position he went for a few months to Rutherford in Montreal. In Berlin he met in 1906 Lise Meitner who had just arrived from Vienna where she had worked with Boltzmann. She was the second woman in Austria to get the doctor's degree in physics. Lise Meitner was looking for experimental experience and Otto Hahn was looking for help by a physicist in his research in radioactivity. Thus an extremely fruitful scientific collaboration and lifelong friendship started. Lise Meitner worked without pay for Hahn. In 1912 she became the assistant of Max Planck. His presence in Berlin had actually been the reason that she came to Berlin in order to learn more about theoretical physics. In 1911 the Kaiser-Wilhelm Gesellschaft was founded by the Emperor Wilhelm II on the occasion of the centenary of the University of Berlin, to promote research in chemistry and to duplicate the great successes of the Physikalisch Technische Reichsanstalt founded in 1887 (Lemmerich 1933). In 1912 Otto Hahn and Lise Meitner moved to the new Laboratory in Dahlem, a small suburban village of Berlin in those days. Hahn was head of a small but independent department, in 1926 he became the acting director and in 1929 the director of the Kaiser-Wilhelm Institute for Chemistry in Dahlem. Lise Meitner was appointed a scientific member of the Kaiser-Wilhelm Gesellschaft in 1913 and in 1917 she became head of her own department. She was the first woman to 'habilitieren' (i.e. she got the venia legendi, the right to teach) in physics at the University of Berlin in 1922. How extraordinary a woman physicist in those days was may be indicated by the way a Berlin newspaper announced her first lecture, titled *On the importance of radioactivity on cosmic processes*, as a contribution to cosmetic physics. In 1926 she became associate professor at this university.

Hahn, Meitner and von Bayer studied the beta spectra of several radio isotopes by employing a magnetic beta spectrometer and were providing lists of elements with the corresponding beta spectra. Continuing Hahn's previous work on mesothorium Hahn and Meitner discovered in 1918 element 91 which they called protactinium. Very recently the history of this discovery was uncovered by Sime (1986). Starting with an idea of Hahn, Lise Meitner actually did all the research resulting in the finding of this new element by herself. Hahn was serving in the German army and helped her during two short vacations in Berlin in January and April 1917. The decisions of how to proceed in the research and the interpretations of results were communicated by letters between Meitner and Hahn, very similar to the numerous letters between Hahn and Meitner in 1938 when Hahn was in Berlin and Meitner in Stockholm. She sent the draft of the paper to Hahn who agreed to it before Lise Meitner submitted it on March 16, 1918 to the *Physikalische Zeitschrift* with the authors: O Hahn and L Meitner. When Hahn returned to Berlin his interests shifted to more chemical questions by employing radiochemical methods, whereas Meitner worked on atomic

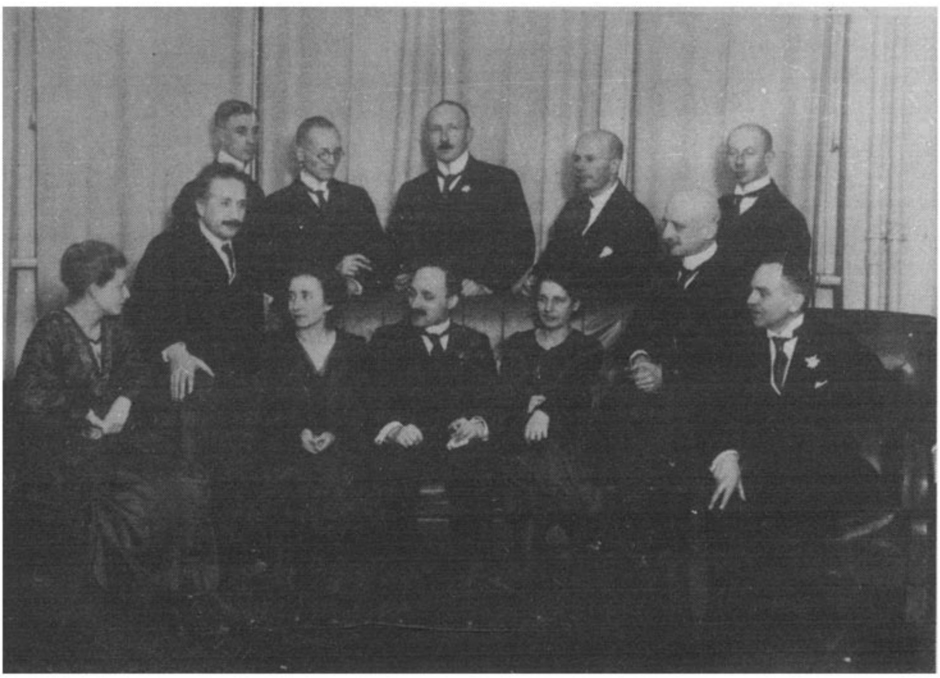

Figure 1. Some of them can be seen on a photograph from those days: standing from left to right: Walter Grotian, Wilhelm Westfall, Otto von Bayer, Peter Pringsheim, Gustaf Hertz. Sitting from left to right: Hertha Sponer, Albert Einstein, Ingrid Franck, James Franck, Lise Meitner, Fritz Haber and Otto Hahn.

problems. She observed and described the Auger effect two years before Auger published his paper (Lemmerich 1984):

Despite the fact that material life in post-war Berlin was very difficult, the scientific life flourished probably more than ever before and after, certainly in physics and chemistry. Between 1918 and 1938 14 Nobel prizes in physics and chemistry went to scientists working in Germany, of which 5 were in Berlin. In January 1937 Hitler forbade all Germans to accept Nobel prizes, thus Richard Kuhn had to decline the Nobel Prize for Chemistry in 1938, the same year when Fermi got the above mentioned Nobel Prize in Physics. The physics community of the early twenties was led by the Nobel prize winners Einstein, Franck, Nernst, and Planck.

But there was also jealousy between some of them; in particular Lenard and Stark attacked Einstein with antisemitic speeches. Einstein kept his humour and was laughing with his friends Max von Laue and Nernst who vigorously defended Einstein (Lemmerich 1984). But when Hitler took absolute power on January 31, 1933 this ended very abruptly. Many of the best scientists in those days had to leave Germany, Nobel prize winners as well as young students. One of those students who wanted to start his graduate work with Lise Meitner but had to emigrate was Henry Herman Barschall. Many years later I worked as a post doc in Barschall's group at the University of Madison, Wisconsin.

5. Lise Meitner had to leave Berlin

Lise Meitner, a Jew according to the radical race laws of Hitler's Nazi Germany, stayed in Berlin since she was protected by her Austrian citizenship. The right to teach was withdrawn from her already on September 6, 1933 and subsequently she was not allowed to enter the university nor to participate in colloquia or to give talks outside the university. Thus she was essentially isolated at the Kaiser-Wilhelm Instiute for Chemistry in Dahlem where she also had an apartment in the neighbouring Institute's villa. The fact that she, nevertheless, always considered Berlin as her home must have been due to the many friends she had in Berlin. With the annexation of Austria in March 1938 she became a German citizen. Now it became very dangerous for her to stay in Berlin. Hahn and Carl Bosch, the President of the Kaiser-Wilhelm Gesellschaft, tried to get a permit for her to leave Germany which was however denied. With the help of Peter Debye, the Director of the Kaiser-Wilhem Institute for Physics, and his Dutch colleague Dirk Coster, Lise Meitner got the permission to immigrate to the Netherlands without a visa. Dirk Coster came to Berlin to pick Lise Meitner up on July 14, 1938. She was at that time almost 60 years old and half of this time she had lived and worked in Berlin. With some luck they got through all railway checks and arrived at Groningen from where she went to the newly founded Nobel Institute for Physics in Stockholm after a couple of weeks. She had left Berlin just in time before Nobember 9-10, 1938, the 'Crystal Night', so called because the glass shattered in shop windows of Jewish-owned stores which initiated a progrom that in Berlin reduced a Jewish population of 170,000 to 5,000 by 1945. She left Berlin very reluctantly and she was not aware of the real danger to her life, in common with many other Jews in Germany in those days. The great tragedy of her scientific career was that she had to leave Berlin just before the final race for the solution of the transuranium puzzle. From 1935 to 1938 the team Meitner-Hahn-Strassmann had published seven articles on the transuranium elements.

6. The final race to the solution of the transuranium puzzle

In Paris Irène Curie and Paul Savitch were also working on the transuranium puzzle and there was considerable competition between the groups in Berlin and Paris. Irène Curie and Paul Savitch had found a 3·5 h activity which they first identified as thorium. They could however not maintain this claim after Hahn and Meitner had objected. On October 22-23, 1938 Hahn and Strassmann read an article of I. Curie and P Savitch in the latest issue of the *Journal de Physique et le Radium* (Curie and Savitch 1938), in which the latter reported that the chemical properties of the 3·5 h body are those of lanthanum and could be separated only by fractionation. As we know today Curie and Savitch were very close to the solution since this activity was ^{141}La with a half-life of 3·9 h but contained probably also ^{92}Y with a half-life of 3·5 h. The findings of the Paris group raised considerable criticism in Berlin but it certainly accelerated the efforts of Hahn and Strassmann.

These efforts resulted in a paper submitted to 'Naturwissenschaften' on November 8. Hahn and Strassmann (1938) had shown that by the irradiation of uranium in addition to several supposedly transuranium elements other products resulted which were thought to be due to two successive α-decays:

$$^{238}_{92}\mathrm{U} + n \xrightarrow{\alpha} {}^{235}_{90}\mathrm{Th} \xrightarrow{\alpha} {}^{231}_{88}\mathrm{Ra}.$$

These two α-decays were hard to understand energetically and thus received considerable criticism from Niels Bohr, Lise Meitner and Otto Robert Frisch during a visit of Hahn on November 13, 1938 in Copenhagen where Meitner was spending a week in Bohr's Institute. Though neither Bohr nor Meitner could present another explanation they told Hahn that from a physical point of view this seems to be very unlikely if not impossible. This forced Hahn and Strassmann to check again the radium hypothesis. Since radium is an alkaline-earth metal barium chemistry was employed to separate chemically the supposedly radium activity. The first part of the famous paper of Hahn and Strassmann (1939): *On the detection and the behaviour of the alkaline-earth metals produced by neutron irradiation of uranium* was to show the genetic sequence of isomeric chains:

$$\text{“RaI”?} \xrightarrow[<1\,\text{min}]{\beta} \text{AcI} \xrightarrow[<30\,\text{min}]{\beta} \text{Th?}$$

$$\text{“RaII”?} \xrightarrow[<14\pm2\,\text{min}]{\beta} \text{AcII} \xrightarrow[\sim2{\cdot}5\,\text{h}]{\beta} \text{Th?}$$

$$\text{“RaIII”?} \xrightarrow[86\pm6\,\text{min}]{\beta} \text{AcIII} \xrightarrow[\approx\text{several days?}]{\beta} \text{Th?}$$

$$\text{“RaIV”?} \xrightarrow[250-300\,\text{h}]{\beta} \text{AcIV} \xrightarrow[<40\,\text{h}]{\beta} \text{Th?}.$$

But then they performed a calibrated fractional crystallization which they called the indicator method: a mixture of the purified long living "RaIV" and pure $^{228}_{88}$Ra (MsTh$_1$ with $\tau = 5{\cdot}75$a) with bariumbromide as carrier was subjected to this method. They used, in a way, the known radioactivity of $^{228}_{88}$Ra as a monitor for the chemistry. They found that the well-known activity of $^{228}_{88}$Ra was enriched whereas "RaIV" was not. Since the activity in question could be only radium or barium they were forced to conclude that the radium isotopes I through IV were not radium but barium. Hahn actually wrote in the paper: *as chemists we ought to say the bodies are not radium but barium; since other elements as radium or barium are out of question.* Following up this finding, Hahn and Strassmann employed the indicator method also for AcII with the actinium isotope $^{228}_{89}$Ac ($\tau \approx 6{\cdot}13$h) as indicator or monitor. Here again they found an enrichment of $^{228}_{89}$Ac in lanthanum oxalate whereas for "AcII" no enrichment could be identified, again the chemical conclusion was "AcII" is lanthanum. The cerium test was however not performed as they mentioned in the paper. Thus Hahn wrote: *as chemists we ought to rename the above given scheme and substitute the symbols Ba, La, and Ce for Ra, Ac, and Th.* This I have done below by employing for comparison the latest information from an isotopic table of 50 years later:

$$^{143}_{56}\mathrm{Ba} \xrightarrow[13{\cdot}7\mathrm{s}]{\beta^-} {}^{143}_{57}\mathrm{La} \xrightarrow[14{\cdot}1\,\mathrm{min}]{\beta^-} {}^{143}_{58}\mathrm{Ce}\left(\xrightarrow[33\mathrm{h}]{\beta^-} {}^{143}_{59}\mathrm{Pr} \xrightarrow[13{\cdot}6\mathrm{d}]{\beta^-} {}^{143}_{60}\mathrm{Nd}\ \text{stable}\right)$$

$$^{141}_{56}\mathrm{Ba} \xrightarrow[18{\cdot}2\,\mathrm{min}]{\beta^-} {}^{141}_{57}\mathrm{La} \xrightarrow[3{\cdot}93\,\mathrm{h}]{\beta^-} {}^{141}_{58}\mathrm{Ce}\left(\xrightarrow[32{\cdot}5\,\mathrm{d}]{\beta^-} {}^{141}_{59}\mathrm{Pr}\ \text{stable}\right)$$

$$^{139}_{56}\mathrm{Ba} \xrightarrow[83{\cdot}2\,\mathrm{min}]{\beta^-} {}^{139}_{57}\mathrm{La}\ \text{stable}$$

$$^{140}_{56}\mathrm{Ba} \xrightarrow[12{\cdot}8\,\mathrm{d}]{\beta^-} {}^{140}_{57}\mathrm{La} \xrightarrow[40{\cdot}2\,\mathrm{h}]{\beta^-} {}^{140}_{58}\mathrm{Ce}\ \text{stable.}$$

Thus nuclear fission was discovered and the chemical solution for the transuranic puzzle was found. Though Hahn and Strassmann still expressed in their paper some doubts on their finding, the above mentioned title of their publication was clear enough. Indeed all the other radioactivities or "bodies" attributed to the transuranic elements were fission fragments as Hahn hypothesized in this famous paper (Hahn and Strassmann 1939) by writing: *Concerning the transuranic elements they are relatives of their lower homologous elements rhenium, osmium, iridium and platinum but they are not equal. Whether they are actually chemically equal to their even lower homologous masurium* (technetium), *ruthenium, rhodium and palladium still has to be checked.* Indeed this hypothesis turned out to be correct. The essential mistake made by all the transuranium researchers starting with Fermi was that they assumed element $Z = 93$ to be homologous to rhenium though it is actually chemically similar to uranium as might have been recognized by the chemists extrapolating from the chemical similarity of the rare earth elements to those of the actinides.

7. Physical solution of the transuranium puzzle

The chemical solution of the transuranium puzzle had become now a challenge for the physicists: how can a nucleus split into two heavy fragments of about equal size.

Lise Meitner was the first physicist to learn about this finding by the above mentioned letter of Otto Hahn of December 19, 1938. Before he had to go back to his counters he suggested that Lise Meitner should try to give a physical explanation of this frightful conclusion so that *finally this would be a work of three* indicating some uncertainty that L Meitner was not coauthor of the publication on the discovery of nuclear fission. L Meitner never indicated such an expectation though she was unhappy that all the findings of the previous 3 years were now shown to be incorrect by only two of the previous three authors.

Lise Meitner was spending the New Year holiday together with her nephew Otto Robert Frisch, also a physicist, in Kungälv near Goteborg in Sweden. O R Frisch remembers their discussion (Fine and Herrmann 1988): *...barium, I don't believe it. There's some mistake... You couldn't chip a hundred particles off a nucleus in one blow. It's fantastic. It's quite impossible. A single neutron couldn't do that.* Nevertheless, they found the physical solution of the transuranium puzzle (Meitner and Frisch 1939):*... the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.* **Thus the physical process was described with a classical picture** without having to consider the quantum-mechanical tunnelling-effect. This paper was received by *Nature* on January 16, 1939. Frisch and Meitner also calculated the kinetic energy release to be about 200 MeV (168·3 ± 1·7 MeV) (Vandenbosch and Huizenga 1973). Given such huge energies, O R Frisch immediately realized that this should also be observable in an ionization chamber. After he returned to Copenhagen he performed the experiment and was able to show that the kinetic energies were about 70 MeV per fragment (Frisch 1939). **Thus nuclear fission was also physically confirmed.** The term fission used by Meitner and Frisch in their New Year paper was suggested to Frisch by an American biochemist, W A Arnold (Stuewer 1985) to whom he must have described the process in such a pictorial way that the latter thought of the division of a cell, which he probably had seen many times in the microscope. Due to the difficulties of seeing nuclear collective motion, this dynamical aspect of nuclear fission has only recently started to be investigated.

8. Subsequent discoveries

O R Frisch told Bohr about the new discovery just before Bohr left Copenhagen for America on January 7, 1939 and he gave him a first draft with Meitner's and Frisch's explanation of nuclear fission (Meitner and Frisch 1939). Bohr travelled together with Léon Rosenfeld by ship and arrived on January 16, 1939 in New York. Rosenfeld told the news of nuclear fission on the same day at Princeton's Journal club and Bohr gave the news to a more general physics community on January 26, 1939 at the Fifth Washington Conference on Theoretical Physics. In the following weeks and months the number of publications and exciting new results almost exploded. In France the neutron multiplicity was found to be 3·5 ± 0·7 (2·42 today) on April 7, 1939, thus the possibility of a chain reaction was found by Hans von Halban, Frédéric Joliot and Lew Kowarski. The basic theory of nuclear fission, still valid today, was immediately developed by Bohr and Wheeler. Already on June 28, 1939 their manuscript was received by *Physical Review* and published in September 1939.

9. The first transuranium element

The first real transuranium element was identified in 1940 by E M McMillan and P H Abelson (1940) by irradiating uranium with neutrons produced with a cyclotron in Berkeley:

$$^{238}_{92}U + n \rightarrow ^{239}_{92}U \xrightarrow[23\cdot 5\,\text{min}]{\beta^-} ^{239}_{93}Np.$$

However in order to separate the uranium activity from all the fission fragments also produced in this reaction McMillan and Abelson employed the knowledge of nuclear fission. Fission fragments are energetic enough to penetrate thin cigarette paper whereas the recoiling uranium is stopped in this catcher paper. By this ingenious trick fission fragments and transuranic elements were finally separated. They could then also disprove Fermi's original hypothesis that element 93 is homologous to rhenium.

10. Post war

Hahn got the 1944 Nobel Prize for Chemistry for the *discovery of the fission of heavy nuclei*. However, before the news of the Nobel Prize award reached him in Cambridge, England, where he and other German nuclear scientists were detained, he was profoundly affected by the announcement of the explosion of the atomic bomb

Figure 2. Otto Hahn and Lise Meitner at the inauguration of the Hahn-Meitner Institut for Nuclear Research in Berlin on 14 March 1959.

at Hiroshima and Nagasaki on August 6 and 9, 1945. On April 1, 1946 Hahn became director of the Kaiser-Wilhelm Gesellschaft which was later renamed Max-Planck Gesellschaft. Fritz Strassmann became Professor at the new University of Mainz in 1946 where he trained students in nuclear chemistry and thus became the actual father of this subject in Germany. Lise Meitner was appointed a research professor in Stockholm in 1947 at the age of 69. The former Kaiser-Wilhelm Institute for Chemistry was named the Otto-Hahn-Building of the Free University of Berlin in 1956. The former laboratory of Hahn and Meitner is now used by biochemists. Otto Hahn and Lise Meitner (both at the age of 88) and Fritz Strassmann (65) got the Enrico Fermi Award on September 9, 1966.

On March 14, 1959 a centre for nuclear research with a small research reactor was founded in Berlin and named the Hahn-Meitner-Institut for Nuclear Research. The qualification 'for Nuclear Research' has been dropped recently. Lise Meitner and Otto Hahn participated at the inauguration of this new institute and are shown in the lecture hall of the Hahn-Meitner-Institute for Nuclear Research. Karl Eric Zimen, a former student of Otto Hahn who had worked from 1935 until 1939 at the Kaiser-Wilhelm Institute for chemistry, became the first director of the Hahn-Meitner-Institute for Nuclear Research. Even fifty years after the discovery of nuclear fission this nuclear process together with heavy-ion fusion is still one of the most interesting processes of collective flow of nuclear matter and an ideal example of the yet unsolved nuclear many-body problem. Basic research in nuclear fission and fusion has retained its scientific and intellectual attraction. A small group of scientsts are still doing research theoretically and experimentally in this field at the Hahn-Meitner-Institute in Berlin, 1988.

I would like to conclude by pointing out that I left out an important aspect of the discovery of nuclear fission. The impact of scientific research on society and vice versa is an important topic and the discovery of nuclear fission might be the ideal example to study it and to indicate solutions: with increasing knowledge mankind has to learn how to apply pramāna. Sometimes the question is asked whether it would have been better if nuclear fission would not have been discovered. This, however, is a useless question, as useless as the request that mankind should have prevented the burning of the Oklo nuclear fission reactor on our planet 1·8 billion years ago.

References

Bohr N and Wheeler J A 1939 *Phys. Rev.* **56** 426

Chadwick J 1932 *Nature (London)* **129** 312

Curie I and Savitch P 1938 *J. Phys. Radium* **9** 355

Fermi E 1934 *Nature (London)* **133** 838

Fine L and Herrmann G 1988 *Discovery of nuclear fission*, Audio scripts, unpublished

Frisch O R 1967 *Phys. Today* November p. 47

Frisch O R 1939 *Nature (London)* **143** 276

Gamow G 1929 *Z. Phys.* **51** 204

Gamow G 1929 *Z. Phys.* **52** 510

Gamow G 1930 *Proc. R. Soc. (London)* **A126** 632

Gurney R W and Condon E U 1928 *Nature (London)* **122** 439

Hahn D 1975 Otto Hahn Erlebnisse und Erkenntnise, Dousseldorf-Wien (Econ Verlag)

Hahn O and Strassmann 1938 *Naturwissenschaften* **26** 755

Hahn O and Strassmann 1939 *Naturwissenschaften* **27** 11

Heisenberg W 1932 *Z. Phys.* **77** 1
Iwanenko D 1932 *Nature (London)* **129** 798
Kraffit F 1981 Im Schatten der Sensation (Verlag Chemie)
Lemmerich J 1984 in *Electronic and atomic collisions* (eds) J Eichler, I V Hertel, N Stolterfoht (Amsterdam: Elsevier)
McMillan E and Abelson P H 1940 *Phys. Rev.* **57** 1185
Meitner L and Frisch O R 1939 *Nature (London)* **143** 239
Menke H and Herrmann G 1971 *Radiochim. Acta* **16** 119
Neuilly M, Bussac J, Frèjacques C, Nief G, Vendryes G and Yvon J 1972 *C. R. Hebd. Seances Acad. Sci., Ser* **D275** 1847
Noddack I 1934 *Angew. Chem.* **47** 653
Noddack W, Tacke I and Berg O 1925 Die Naturwissenschaften **13** 567 (Tacke was the maiden name of I Noddack)
Perrier C and Segrè E 1937 *J. Chem. Phys.* **5** 712
Sime R L 1986 *J. Chemi. Ed.* **63** 653
Stuewer R H 1985 *Phys. Today*, October, p. 49
Vandenbosch R and Huizenga J R 1973 in *Nuclear fission* (New York: Academic Press)
Wohlfahrt H 1979 *Wiss. Buchgesellschaft Darmstadt*