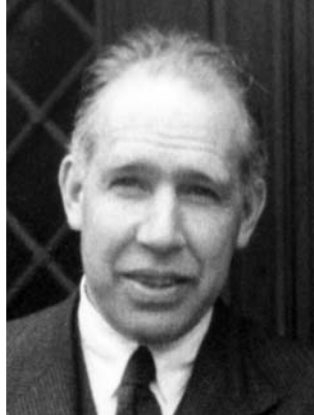




On the belated discovery of fission

J. Michael Pearson

A remarkable sequence of missteps, misfortune, and oversights delayed the discovery of nuclear fission until the eve of World War II—and likely altered history's course.

Experiments on the bombardment of uranium by neutrons began in Rome under Enrico Fermi and his collaborators in 1934 and culminated in December 1938 with Otto Hahn and Fritz Strassmann's discovery of fission in Berlin. Unlike, for instance, the neutrino and the Higgs boson, which were predicted to exist long before they were discovered, fission was totally unexpected. So surprised were Hahn and Strassmann to find that the bombardment of uranium (atomic number $Z = 92$) by neutrons led to the appearance of barium ($Z = 56$) that in their paper announcing the discovery, they included—in rough translation—the following celebrated passage:

As chemists we are obliged to accept the assignment of barium to the observed activity, but as nuclear chemists working very closely to the field of physics we cannot yet bring ourselves to take such a drastic step, which goes against all previous experience in nuclear physics. It could be, however, that a series of strange coincidences has misled us.¹

Seldom has Nobel Prize-winning work been presented so hesitantly and with such reluctance.

Hahn and Strassmann's discovery came at a fateful moment, a mere nine months before the outbreak of World War II, which would be brought to an end six years later by nuclear weapons—a direct outcome of the discovery made in Nazi Germany. The irony was compounded by the vital role that refugees from the Nazis played in the US-led effort to produce the weapons.

Two of Fermi's collaborators, Emilio Segrè and Edoardo Amaldi, have each suggested² that fission could have been discovered as early as 1935. Of course, with the benefit of hindsight it is easy to argue that most scientific discoveries could have been made sooner than they actually were, and a four-year delay might not be unusual. In the case of fission, however, the implications for world history are staggering. The war almost certainly would have taken a different form had fission been discovered even two years earlier. Quite possibly it would have gone nuclear earlier, although the fear of nuclear weapons could conceivably have prevented war altogether—and, as a side effect, allowed the Nazi regime to survive. On the other hand, that same fear might well have accelerated the outbreak of



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Opening photo gallery, clockwise from far left: Enrico Fermi, Niels Bohr, Lise Meitner, Otto Frisch, Fritz Strassmann, Otto Hahn, and Ida Noddack. (Photos courtesy of the American Institute of Physics, Emilio Segrè Visual Archives.)

war, with each side seeking to destroy the other's nuclear installations with conventional arms.

Fascinating as those speculations may be, my intention in this article is not to explore the byways of counterfactual history. I simply mention some of the possibilities to suggest that in raising the question of the timing of fission's discovery, one raises what must be one of the great what-ifs of world history.

Rome

Modern nuclear physics began in 1932 when James Chadwick of the University of Cambridge identified the neutron as the penetrating radiation produced by the bombardment of beryllium with alpha particles (helium-4 nuclei). Fermi recognized in neutrons a powerful new tool for probing the nucleus, since the uncharged particles could enter nuclei unhindered by Coulomb repulsion. Accordingly, in 1934 he and his group in Rome began bombarding elements of systematically increasing atomic number with 11-MeV neutrons generated by a beryllium-radon source. For a large fraction of the elements lighter than thorium ($Z = 90$), the result was neutron capture followed by beta decay—the spontaneous conversion of a neutron into a proton, accompanied by emission of an electron and an antineutrino.

Since the net effect was to increase Z of the target nucleus by one, the case of uranium was of particular interest; with $Z = 92$, it was the heaviest element known at the time. Through neutron bombardment, Fermi hoped to synthesize element 93, later named neptunium, though he could not exclude the possibility of a second beta decay leading to element 94, later named plutonium. He and his colleagues succeeded in inducing beta radioactivity in uranium, but the decay schemes were much more complicated than they had expected. Instead of one half-life corresponding to the formation of element 93, or two corresponding to the formation of both element 93 and element 94, they reported more than four half-lives.³

One possible explanation was that the bombarding neutrons, rather than being captured, were ejecting charged particles from the uranium nuclei, which would mean that the nuclei whose beta decays were observed had a lower rather than a higher atomic number than that of the uranium target. Fermi thus had to rule out the possibility of such knock-out processes before he could claim to have formed transuranic elements.

The elements responsible for the observed beta decays could only be identified radiochemically. Concentrating on the 13-minute half-life, Fermi found that it could not be attributed to any element having Z between 86 and 92. In view of the firmly held belief that nothing heavier than an alpha could

be ejected from a target nucleus by neutrons, he concluded that he had more than sufficient evidence to rule out knock-out processes. It followed that the 13-minute activity had to be associated with elements having Z of 93 or greater.

Paris and Berlin

Although virtually no one contested Fermi's claim to have created transuranics, there remained the problem of elucidating all the other radioactive decays that Fermi observed. When he and his team abandoned their uranium work in 1935, two other groups became particularly active in the field: Irène Joliot-Curie and Pavel Savić in Paris, and Lise Meitner, Hahn, and Strassmann in Berlin. As radiochemical techniques improved, both groups found more and more complexity in the decay schemes of neutron-irradiated uranium, which only made the experiments more difficult to interpret. The puzzle was all the more confusing because no one was looking for fission. Rather, everyone accepted uncritically that a nucleus could emit nothing heavier than an alpha particle.

By 1937 the Berlin researchers had identified at least nine radioactive decays. To explain those decays, they were obliged to propose that some of the intermediate nuclei had several metastable excited states, or isomers—a most unusual feature. Moreover, by July 1938 Joliot-Curie and Savić had found a 3.5-hour beta activity that was chemically similar to lanthanum ($Z = 57$). It later transpired that the activity really did correspond to an isotope of lanthanum, but the idea that Z could change by 35 units was unthinkable at the time.² They therefore supposed the activity might belong to lanthanum's chemical homologue actinium ($Z = 89$), which was seemingly the only viable candidate with an atomic number close to uranium's. When they established that the half-life wasn't attributable to actinium, the uranium puzzle entered a state of crisis.

Soon thereafter, the Berlin group renewed their effort minus Meitner, who, being of Jewish origin, had been obliged to flee to Sweden. In November 1938 Hahn and Strassmann found three previously undetected beta-decay chains, which they thought might have originated in different isomers of radium ($Z = 88$). But that explanation, too, seemed implausible: Quite aside from the embarrassment of the further proliferation of isomerism, simply getting from uranium to radium would have required the simultaneous emission of two alphas, which was generally believed to be impossible.

Resolution came quickly, in December 1938, when Hahn and Strassmann showed conclusively that what they had believed to be radium was its chemical homologue, barium. Hahn consulted Meitner by mail in the hope that she could provide a plausible physical explanation of the strange goings-on and thereby add to the credibility of the paper that he and Strassmann were writing. No such explanation was immediately forthcoming. Hahn and Strassmann's paper was published the following month, and Meitner's name does not appear on it anywhere, not even in the acknowledgments.⁴ (For more on Meitner's exclusion, see the article

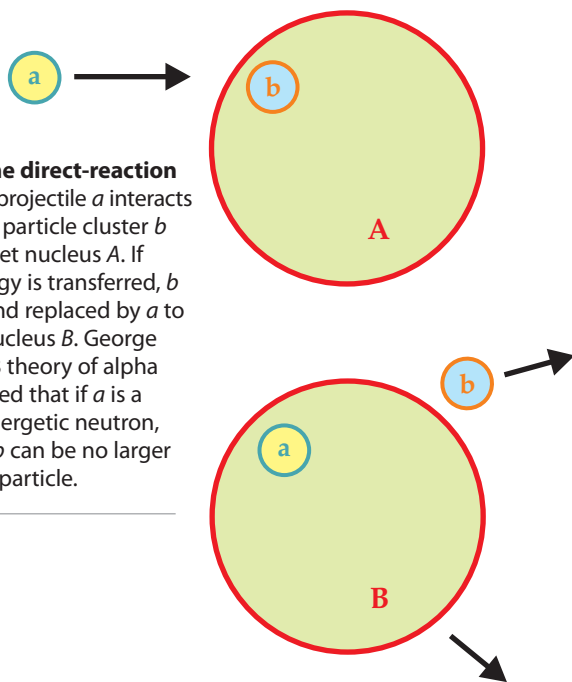


Figure 1. In the direct-reaction mechanism, a projectile a interacts with a specific particle cluster b inside the target nucleus A . If sufficient energy is transferred, b is dislodged and replaced by a to leave a new nucleus B . George Gamow's 1928 theory of alpha decay suggested that if a is a moderately energetic neutron, the fragment b can be no larger than an alpha particle.

by Elisabeth Crawford, Ruth Lewin Sime, and Mark Walker, *PHYSICS TODAY*, September 1997, page 26.)

Just 12 days before Hahn and Strassmann submitted their landmark paper, Fermi received the Nobel Prize in Physics, in part “for his demonstrations of the existence of new radioactive elements produced by neutron irradiation.” It quickly became clear that this part of the citation was wrong: The beta activity that Fermi had attributed to the formation of transuranics actually belonged to technetium, a fission product.

Why fission was unthinkable

The primary obstacle delaying fission's discovery was the belief that nothing heavier than alpha particles could be ejected from a nucleus under neutron bombardment. Beyond the empirical fact that hitherto no exception had ever been seen, the rule received considerable theoretical support from the success of George Gamow's 1928 theory of alpha decay.

Until 1936, most scientists believed that in a nuclear reaction of the type $A + a \rightarrow B + b$, the projectile a always interacts directly with a cluster b within the target A , as shown in figure 1. The other nucleons were thought to be passive spectators. In that process, known as the direct-reaction mechanism, the emergence and separation of the two final-state nuclei b and B are hindered by the Coulomb barrier that the nuclei mutually generate.

According to Gamow's theory of alpha decay, the probability of penetrating the barrier decreases exponentially with respect to a quantity that's proportional to $Z_b Z_A Q^{1/2}$, where Q is the energy released in the reaction. For an initial pair of nuclei with given Z_a and Z_A , the product $Z_b Z_B$ becomes larger the closer Z_b and Z_B are to each other, hence the low probability of emissions heavier than an alpha particle. In the specific case of uranium bombarded by

low-energy neutrons, Gamow's theory shows that symmetric fission into two identical fragments is 10^{-453} times as probable as the ejection of an alpha.

Such calculations would have provided the most secure foundation of the rule against heavy-particle emission, but they relied crucially on the validity of the direct-reaction mechanism. And the picture represented by that mechanism was clearly an idealization, since at the very least the projectile a will drag or push some of the target nucleons on its way into the nucleus, and the fragment b will drag or push some on the way out.

The idea that actual nuclear reactions must involve more nucleons than are assumed by the direct-reaction model was pushed to its logical extreme in the compound-nucleus model,⁵ proposed in 1936 by Niels Bohr in Copenhagen. The model was inspired by the extreme sensitivity of low-energy neutron capture to the bombarding energy. In the case of a heavy target nucleus, the rate of absorption could fluctuate by orders of magnitude over energy intervals ΔE as small as a few eV. Those so-called resonances were reminiscent of the lines seen in atomic spectra and pointed to the existence of quasi-stable nuclear states, which were indicated by the Heisenberg principle to have half-lives on the order of 10^{-16} s. The direct-reaction mechanism, however, predicts time scales corresponding roughly to the time it takes the projectile to traverse the target nucleus—about 10^{-21} s in a typical case. The implication was that in resonant reactions a large number of internucleonic collisions must occur before the reaction is completed, and any excess energy must be shared among all the nucleons.

In Bohr's mechanism, valid particularly for bombardment by low-energy neutrons, the incident neutron collides and shares its energy—the 6 or 7 MeV of its binding energy in the nucleus plus the bombarding energy—with a nucleon in the target nucleus. Since both particles will then lack the energy to readily escape, they instead proceed to collide and share their energy with other target nucleons until a thermal equilibrium is established. The reaction is completed with a process akin to evaporation: Through some statistical fluctuation, a very large number of collisions of the nucleons in the compound nucleus concentrates enough energy on one nucleon or cluster of nucleons b for it to escape.

But even the formation of a compound nucleus is only a necessary, not a sufficient, condition for fission, since the charged particle b emitted through evaporation from the compound nucleus still has to penetrate the same Coulomb barrier it would have faced in the direct-reaction process. Thus to explain fission, some other mode of disintegration of the compound nucleus had to be found.

The liquid-drop model

Although Bohr didn't see it this way, his compound nucleus, with its emphasis on collisions between individual nucleons, can be regarded as a natural extension of the liquid-drop model of the nucleus introduced by Gamow in 1930. Gamow's model was motivated by measurements indicating that all nuclei, like all liquid drops, have more or less the same

density. According to his picture, the short range of the internucleonic forces ensures that each nucleon interacts with only its nearest neighbors. (For the moment, we neglect the long-range Coulomb forces between protons.) It follows that, to first approximation, the internal energy E of a nucleus is proportional to its mass number, which means that all nuclei should have roughly the same energy per nucleon.

Measurements of nuclear masses verified the prediction of the liquid-drop model only very roughly. By 1936, however, Carl von Weizsäcker⁶ in Leipzig, Germany, and Hans Bethe and Robert Bacher⁷ at Cornell University had shown that they could largely account for the deviations by making a few refinements to the model. The first correction was to recognize that nuclei, like liquid drops, must have surface tension, simply because nucleons at the surface have fewer close neighbors than do nucleons in the interior. The second correction was to include the Coulomb energy associated with the protons. The last important correction was quantum mechanical and took into consideration the Pauli principle; it accounted for the fact that, absent Coulomb forces, an element's most energetically stable isotope would be the one with an equal number of protons and neutrons.

With just four adjustable parameters, the refined model, known as the semiempirical mass formula, can account for key features of binding-energy systematics. First, it explains why light beta-stable nuclei have roughly equal numbers of protons and neutrons but larger nuclei have an excess of neutrons that grows as Z increases. That trend has enormous significance: It means that fission of heavy elements should be accompanied by the liberation of neutrons. Since those neutrons can be expected to induce further fissions in turn, the possibility of a chain reaction becomes apparent.

Second, the formula predicts that a plot of the energy per nucleon of beta-stable nuclei as a function of mass number shows a minimum in the vicinity of iron; both lighter and heavier nuclei are less stable. (See figure 2.) Moreover, from the curve, one can deduce that the fission of a uranium nucleus should release an enormous amount of energy—about 200 MeV—although that point does not seem to have been appreciated until after the discovery of fission. All of the above features were established qualitatively by Werner Heisenberg in 1933, even before Fermi began his transuranic work.^{8,9}

Despite its success, the liquid-drop model as it existed in 1936 was an essentially static model and, as such, could not throw much light on fission. The key to understanding fission was to allow the liquid drop to vibrate.

Meitner and Frisch

Hahn and Strassmann's paper was submitted for publication on 22 December 1938, and by the time it appeared in print on 6 January 1939, the puzzle of fission had been resolved. Meitner spent the 1938 Christmas holidays in a Swedish village, where she was visited by her nephew Otto Frisch, who was working with Bohr in Copenhagen. Hahn and Strassmann had shared their results with no one but

Meitner, who now began to discuss the problem with Frisch.

Meitner and her nephew tried to visualize in purely classical terms how fission might occur. They supposed that the incident neutron, instead of cutting the nucleus cleanly in two, was captured to form the sort of compound nucleus that Bohr had proposed. Meitner and Frisch went beyond Bohr, however, in picturing the nucleus as a liquid drop that could vibrate as a result of the excitation energy deposited by the neutron. Fission of the liquid drop might then occur through the sequence of configurations shown in figure 3.

In the case of an actual liquid drop, whether the sequence follows through to scission depends on the surface tension: The larger it is, the less likely the drop is to break up. In the nuclear drop, Coulomb repulsion between protons tends to inflate the nucleus and thereby oppose the surface tension. As a result, the drop has an effective surface tension that decreases as Z increases and eventually vanishes at some critical value of Z , which Meitner and Frisch estimated¹⁰ to be of the order of 100.

Beyond the critical value of Z , nuclei could not have any meaningful existence—they would fall apart the instant they were formed. The researchers further recognized that, below that limit, nuclei should become increasingly unstable as their atomic number increased. Sufficiently energetic perturbations, such as the capture of a neutron, could cause a nucleus whose Z lies just below the critical value to disintegrate. Thus fission, far from being impossible, had become an inevitable feature of sufficiently heavy nuclei.

Meitner and Frisch recognized that neutron capture and the subsequent formation of a compound nucleus were essential first steps in the

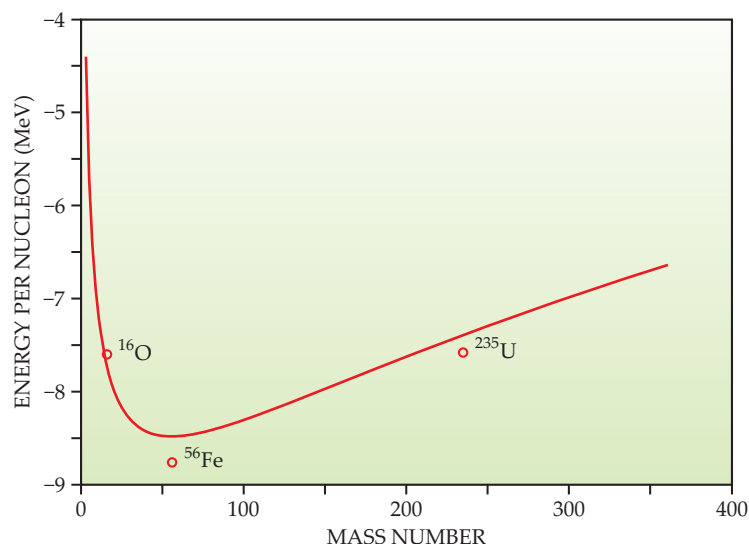


Figure 2. The semiempirical mass formula, developed in 1935 and 1936, predicts that the average energy per nucleon in beta-stable nuclei should be lowest for nuclei with a mass number in the vicinity of iron's. (The model prediction is given by the solid curve.) That result was consistent with contemporary experimental data (open circles) and suggested that the fission of uranium and other heavy nuclei should be accompanied by a large, easily detectable energy release.

fission process. The liquid-drop oscillations that they proposed were a collective phenomenon involving essentially the entire nucleus and were possible only if the incident neutron's energy was rapidly shared. Without the formation of the compound nucleus, neutron-induced fission would have been impossible.

Actually, Bohr and Fritz Kalckar had already considered the possibility of collective vibrational modes in the compound nucleus, but the picture they adopted was not that of a liquid drop.¹¹ Rather, they treated the compound nucleus as a solid bead whose elastic vibrations accounted for the many closely spaced resonances that were observed in experiments. Had they examined the collective modes of a liquid drop, they might well have been able to predict fission. Given that Bohr's very first paper was devoted to the dynamical properties of real liquid drops, one might find the omission surprising. But it was not an oversight: The authors found unlikely the possibility of shape oscillations governed by surface tension. (See reference 12 for an interesting account of Bohr's relation to the liquid-drop model.)

Frisch returned to Copenhagen on 1 January 1939. In the next two weeks, he not only completed the paper with his aunt by telephone but also performed a simple ionization-chamber experiment showing the strong pulses from the fission fragments carrying the 200 MeV or so of released energy. (See figure 4.) His paper¹³ on that work and his paper¹⁰ with Meitner were both submitted on 16 January 1939, less than three weeks after they had begun their discussions in a state of deep incredulity. Together, the two papers confirmed beyond all doubt the hesitant conclusions of Hahn and Strassmann. Frisch and Meitner also recognized that the elaborate schemes that had been proposed to accommo-

date the numerous observed radioactive decays were invalid and that the bulk of those decays belonged instead to fission products.

While writing the paper with his aunt, Frisch briefly discussed it with Bohr, who was already familiar with all the paper's components: Bohr himself had conceived the compound-nucleus model; he had discussed the "uranium puzzle" extensively with both Hahn and Meitner; and he surely must have remembered his early work on the dynamics of water drops. Not surprisingly, he understood Frisch at once and exclaimed, "Oh, what idiots we have all been!"

A few days later Bohr set sail for a previously planned visit to the US and immediately plunged into a deep examination of the new phenomenon. He was uniquely well prepared for the undertaking. Although Meitner and Frisch established the plausibility of fission, it was Bohr and his collaborator, Princeton University's John Wheeler, who showed in detail how it worked.¹⁴

Opportunities missed

When Fermi published the results of his uranium experiments in 1934, his transuranic interpretation was almost universally accepted. However, almost immediately a German chemist, Ida Noddack, pointed out that he had not eliminated the possibility that the bombarded uranium was breaking up into two or more comparably sized nuclei.¹⁵ Fermi was aware of her suggestion, and though he never published a refutation, he certainly declined to act on it.

Postwar reminiscences of Segrè and Amaldi confirm that there was some discussion of Noddack's paper within Fermi's group, but there is no clear recollection of why Fermi decided to ignore it.² In a 1967 interview for the American Institute of Physics, Segrè suggests a personal motive: Although Noddack and her husband, Walter Noddack, enjoyed a solid reputation as the codiscoverers of rhenium, the couple's incorrect claim to have discovered element 43, technetium, raised suspicion that they were prone to making premature claims in the hope of eventually establishing priority.

Even more remarkable in Fermi's indifference to the Noddack proposal was his apparent failure to consider the energetics of a possible uranium fission reaction. Those energetics had already been well established by the time Fermi began bombarding uranium.⁸ Had he considered them, he would have seen that a fissioning nucleus should release not only an enormous amount of energy but also some free neutrons. The prospect of a fission chain reaction sustained by neutrons would surely have motivated Fermi to pay a little more attention to the Noddack paper.

Actually, preoccupied with the potentialities of the neutron, Hungarian-born physicist Leo Szilard had been searching, unsuccessfully, for just such a chain reaction. When he heard about the experiment of Hahn and Strassmann in 1939, he understood at once the implications, and he and Fermi went on to lead the development of the first nuclear reactor. Had Szilard heard of the Noddack paper in 1934, he would surely have pursued it. That he was unaware

Figure 3. In the liquid-drop model of fission, the nucleus behaves like a fluid with an effective surface tension that's determined by strong nuclear and Coulomb interactions. A sufficiently energetic perturbation can cause the nucleus to oscillate and eventually break into two fragments of roughly equal size.

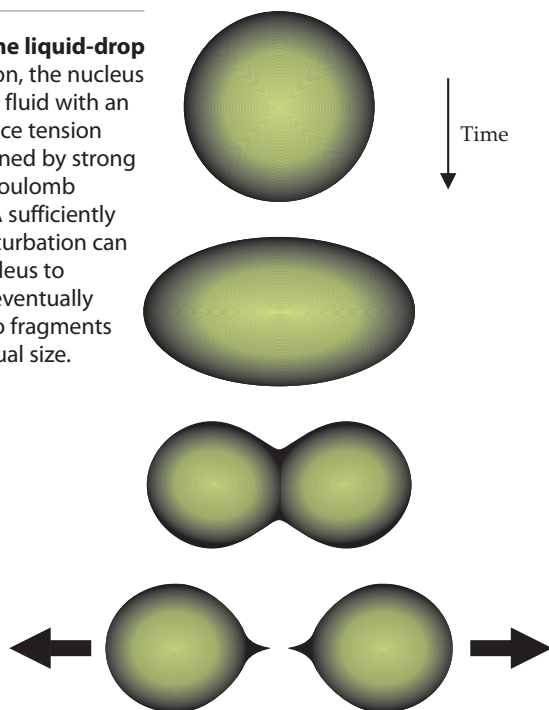


Figure 4. A portion of a January 1939 letter from Otto Frisch to Niels Bohr, relaying news of Frisch's recently completed fission experiments. (Photo courtesy of the American Institute of Physics, Emilio Segrè Visual Archives.)

of the paper is hardly surprising, given the unfamiliarity of most physicists with the journal in which it was published.

Indeed, it is as though Noddack's suggestion had been expunged from the scientific consciousness; Hahn and Strassmann knew of it but did not refer to it in their crucial paper.¹ Conceivably, had Noddack's paper appeared a year or two later, it might have had a bigger impact. From Savić's reminiscences, it seems clear that if he had been reminded of her proposal while he was confronting the lanthanum problem, he would soon have found the solution.²

If the scientific community had taken Noddack's suggestion a little more seriously, the idea of the Frisch experiment might well have occurred to someone long before 1939. Since the ionization-chamber experiment was no more difficult to execute in 1935 than in 1939, it would surely have been eagerly performed, if only to firmly refute her proposal.

Curiously enough, Fermi did perform the ionization-chamber experiment, but with a totally different objective: He wanted to see whether or not alphas were emitted by uranium under neutron irradiation. To do so, however, he shielded out the background of low-energy, spontaneously emitted alphas by wrapping his uranium sample in thin aluminum foil. Unfortunately, that foil also stopped the fission fragments, despite their high energy, because of their large charge. Thus Fermi missed the large pulses that Frisch saw. Other groups performing similar experiments apparently did see the characteristic pulses associated with fission but attributed them to bad electronics.²

Another missed opportunity came in 1936 when Strassmann, the chemist, claimed to have found evidence for barium in neutron-irradiated uranium. Meitner dismissed the conclusion with a remark to the effect of "Leave that to us physicists, and throw your results in the garbage can."¹⁶

Fission's fallout

After the saga of near misses and egregious oversights leading up to fission's discovery, events moved much more quickly. Within a couple of years, the rich brew obtained from neutron-irradiated uranium was shown to contain not only fission products but Fermi's transuranics, neptunium and plutonium. Likewise, the possibility of fission chain reactions was rapidly confirmed, and that cleared the way for the large-scale release of fission energy both in a controlled form of commercial interest and in a catastrophically explosive form. The first of those two forms was realized with Fermi's Chicago Pile-1 reactor in December 1942. The second was realized in the summer of 1945, when the fact of fission, in both uranium and plutonium, was brought

to the world's attention in the most dramatic and violent way imaginable.

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