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The discovery of the neutron and its consequences (1930–1940)

La découverte du neutron et ses conséquences (1930–1940)

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ABSTRACT

In 1930, Walther Bothe and Herbert Becker performed an experiment, which was further improved by Irène and Frédéric Joliot-Curie. These authors, however, misinterpreted their results and believed to have observed γ-rays while they had seen neutrons. After additional experimental verifications, James Chadwick gave the correct interpretation of these experiments in 1932. Immediately, the new particle, the neutron, became an essential actor of nuclear and elementary particle physics, and completely changed the whole research landscape. Enrico Fermi and his group applied it to artificial radioactivity, substituting neutrons to α-rays initially used by Joliot-Curies. They also discovered that slow neutrons were more efficient than fast ones in certain nuclear reactions. A crucial discovery of Otto Hahn, Fritz Straßmann, Lise Meitner, and Otto Frisch, after several misinterpretations of complicated experimental results, was nuclear fission. When Joliot, Halban, and Kowarski demonstrated the possibility of a chain reaction by neutron multiplication due to fission, nuclear physics became a military science, at the very moment when the Second World War was beginning. Later it led to nuclear power applications and use of neutrons as an important tool and object of scientific research at large-scale neutron facilities. The *Comptes rendus de l'Académie des sciences* were partner of a vivid international debate involving several other journals.

RÉSUMÉ

En 1930, Walther Bothe et Herbert Becker réalisèrent une expérience qui fut améliorée ensuite par Irène et Frédéric Joliot-Curie. Ces auteurs, cependant, n'interprétèrent pas correctement leurs résultats et crurent avoir observé des rayons γ, alors qu'ils avaient vu des neutrons. Après des vérifications expérimentales supplémentaires, James Chadwick donna l'interprétation correcte de ces expériences en 1932. Immédiatement, la nouvelle particule, le neutron, devint un acteur essentiel de la physique nucléaire et des particules élémentaires et changea complètement l'ensemble du paysage de recherche. Enrico Fermi et son groupe l'utilisèrent pour la radioactivité artificielle, en remplaçant par des neutrons les rayons α utilisés initialement par les Joliot-Curie. Ils découvrirent également que les neutrons lents étaient plus efficaces que les neutrons rapides dans certaines réactions

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nucléaires. Une découverte cruciale d'Otto Hahn, Fritz Straßmann, Lise Meitner et Otto Frisch, après plusieurs mauvaises interprétations de résultats expérimentaux compliqués, fut la fission nucléaire. La multiplication des neutrons due à la fission ouvrait la possibilité d'une réaction en chaîne, suggérée par Léon Szilard et démontrée par Joliot, Halban et Kowarski. La physique nucléaire devint ainsi une science militaire au moment même où la Seconde Guerre mondiale commençait. Plus tard, la fission permit de transformer l'énergie nucléaire en électricité, alors que les neutrons devenaient un instrument de recherche fondamentale grâce à des réacteurs nucléaires puissants. Les *Comptes rendus de l'Académie des sciences* furent les partenaires de plusieurs autres journaux dans un palpitant débat international.

1. The discovery of the neutron

In 1930, at the Physikalisch-Technische Reichsanstalt, in Berlin–Charlottenburg, Walther Bothe and Herbert Becker showed [1] that beryllium (Be), boron (B), fluorine (F), and lithium (Li) atoms, when bombarded by α-particles emitted from polonium (Po), produce a radiation of great penetrating power. They associated it with γ-rays, a type of highly penetrating radiation known at that time. They assumed that these light nuclei capture α-particles, while γ-rays release the excess of energy in these nuclear reactions:

$$\alpha + {}^{A}_{N}X \rightarrow {}^{A+4}_{N+2}Y^{*} \rightarrow {}^{A+4}_{N+2}Y + \gamma \tag{1}$$

A year later, Irène Curie, when studying the absorption of this secondary radiation from Be and Li, found [2] that it penetrates through materials even easier than estimated initially by Bothe. It passed three times thicker layer of lead (Pb) than the most penetrating γ-rays emitted from radioactive elements. Frédéric Joliot studied a radiation emitted by B, bombarded by α-particles from Po [3], and arrived at an analogous conclusion. To explain this effect, they both assumed very high energies of such γ-rays.

Two years later, Irène and Frédéric Joliot-Curie found [4], when measuring together the ionization produced by such secondary "Be radiation" in a chamber with a thin aluminum (Al) window (see Fig. 1), that the ionization in the chamber increased when they placed matter containing hydrogen (H) in front of the window. The effect appeared to be due to the ejection of protons (or "H rays" as sometimes called at that time) with velocities up to a maximum of nearly 10% of the speed of light. The authors accepted without discussion Bothe's hypothesis that "Be radiation" consisted of γ-rays. A more detailed study of their interaction with matter revealed [5,6] internal contradictions of the γ-rays hypothesis, and prompted the authors to assume even "a new mode of interaction of radiation with matter".

On the other side of the Channel, at the Cavendish Laboratory in Cambridge, James Chadwick, who had searched for Rutherford's neutron for a decade, had a different idea to overcome this contradiction. After repeating and improving the experiments, he published, one month later, a very short but particularly clear article [7], in which he demonstrated that the interpretation of the experimental results was incompatible with energy and momentum conservation, if one accepted the γ-quanta hypothesis. One of his arguments was the following: if Be emits γ-rays, then the observed reaction would be:

$$^{9}\mathrm{Be} + \alpha \rightarrow {}^{13}\mathrm{C} + \gamma \tag{2}$$

Chadwick observed "that the mass defect of ^{13}C is known with sufficient accuracy to show that the energy of the [photon] emitted in this process cannot be greater than about $14 \cdot 10^{6}$ volts. It is difficult to make such a quantum responsible for the effects observed." Chadwick concluded: "The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or 'neutrons'". Indeed, if the reaction is

$$^{9}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \mathrm{n} \tag{3}$$

there is plenty of energy left for the neutron (n).

The Joliot-Curies were not convinced at once [8]. They made additional experiments, but rather quickly concluded [9] that these experiments "provide a new support for the neutron hypothesis." In particular, they studied another nuclear reaction producing nitrogen (N):

$$\alpha + {}^{11}\mathrm{B} \rightarrow {}^{14}\mathrm{N} + \mathrm{n} \tag{4}$$

and found that the maximum neutron energy calculated in accordance with this reaction scheme agrees with the measured energy of protons ejected when hit by neutrons. Moreover, the emission of secondary electrons of high energy observed already in [8] was also consistent with the neutron hypothesis.

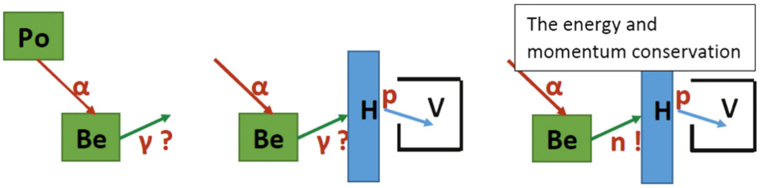

Fig. 1. Left: Bothe's experiment. Be when bombarded by α-particles (in red) of Po emits a radiation (in green) of great penetrating power, which Bothe assumed to be γ-rays. Middle: Joliot-Curie's experiment. H, when hit by the radiation marked in green, emits protons of high energy. Right: Chadwick's experiment. He analyzed the conservation of energy and momentum in these nuclear reactions.

They added, however, that the radiation was complex and that γ-rays were present as well as neutrons. The same was noted by Pierre Auger [10]. Promptly, several experiments studying the properties of new radiation and related techniques were performed in Paris, communicated to the "Académie des sciences" and published in the *Comptes rendus* [11–17].

It is noteworthy to remark that placing H-containing materials, like a piece of polyethylene, in front of a neutron detector is still a usual method of rapidly estimating the energy of incoming neutrons. However, neutrons rather thermalize in the thick H-containing material, thus increasing the probability of their interaction with the detector material, and then eject protons from H; when such thermalized neutrons cause a nuclear reaction in the detector material, they produce protons and other particles. In fact, interpretations of the very first experiments were complex as the list of unknowns was long. We know that neutrons, γ-quanta and protons of different energies, thus with different properties, could be found simultaneously in such experiments. Moreover, different types of detectors used in the experiments of Bothe, the Curies, and Chadwick, appeared to be selectively sensitive to different types of radiation.

Neither Bothe nor Irène and her husband had thought they might have observed neutrons. However, it is likely that before 1932 a few scientists were expecting to see them. Chadwick was. Indeed others. According to Leonardo Sciascia, when Ettore Majorana heard of the Joliot-Curies experiments, he told Segré and Amaldi: "These fools have discovered the neutral proton and are not aware of that" [18].

Immediately after the discovery of the neutron, different scientists reshaped completely the whole research landscape in the field of nuclear and elementary particle physics. Thus, several authors, including James Chadwick [19], assumed neutrons to be constituents of the nucleus [20–22]. Dmitry Iwanenko suggested [23,24] that atomic nuclei consist only of protons and neutrons, not of protons and electrons as in a previous model suggested[1] by Rutherford, which involved "intra-nuclear" electrons. Almost at the same time as Iwanenko, Werner Heisenberg [25–27] and, the next year, Ettore Majorana [28] and Eugene Wigner [29,30] applied quantum mechanics to the nucleus and concluded that this modification enormously simplified the atomic nucleus theory; the strong interaction between protons and neutrons ensures the nuclear structure and stability... Briefly, they reshaped nuclear theory. Heisenberg considered protons and neutrons to be different quantum states of the same particle. Hideki Yukawa analyzed the interaction of neutrons and protons, derived the interaction potential and proposed the theory of mesons [31], which had a major impact on elementary particle physics.

One experimental fact was, however, controversial: the continuous energy spectrum of electrons emitted in β-decay. If the beta decay of a nucleus generates a single particle, as experimentally observed (an electron) energy conservation implies that the electrons should have a well-defined energy. Since the observed energy spectrum is continuous, a few physicists (including Niels Bohr!) thought that energy was perhaps not conserved. The most plausible explanation, however, was the simultaneous emission of another particle, as had been suggested in 1930 by Wolfgang Pauli [32,33]. A major problem was that this particle had not been observed experimentally. Why? The only possible explanation was a very high penetrating power. As this looked nearly incredible, Pauli presented his hypothesis as a joke in a letter addressed to "Dear radioactive Ladies and Gentlemen" in which he wrote that he preferred to publish nothing for the moment about the hypothetical particle. Nevertheless, more and more physicists were believing that Pauli's joke was a serious thing. For instance, in December 1933, Francis Perrin analyzed data on β-decay and suggested [34] that the new particle (which now possessed its modern name, *neutrino*) should have a mass much smaller than the electron mass, and thus a velocity close to the speed of light, and, therefore, a spin 1/2, as proposed by Wolfgang Pauli [32]. The same month, Enrico Fermi published a short note [35], which was quickly followed by a detailed theory of the β-decay [36]. The reaction is identified as the transformation of a neutron (n) into a proton (p), an electron (e) and an antineutrino ($\bar{\nu}$):

$$\mathrm{n} \to \mathrm{p} + \mathrm{e}^{-} + \bar{\nu} \tag{5}$$

As noted by Amaldi [33], this "relationship is not explicitly written in Fermi's paper, but is clearly expressed in words." Fermi was inventing the weak nuclear interaction. The neutrino was only observed in 1956 [37]. It is now believed to have a non-vanishing, but extremely small mass.

[1] Ernest Rutherford, *Nuclear Constitution of Atoms*, Proc. Roy. Soc. A 97 (1920) 374. Rutherford was fully aware of the inconsistencies of his model (in which the very light electron was confined in a very small volume), and this inconsistency was the driving force of Chadwick's discovery. The neutron was implicitly introduced in this article.

Until 1930, only two fundamental interactions (gravitational and electromagnetic) were known. In a very short period after the discovery of the neutron, two new fundamental interactions had been discovered, the strong interaction that binds nucleons together in the nucleus, and the weak interaction responsible for β-decay.

The fundamental properties of the neutron itself were also investigated. As early as 1933, the Joliot-Curies [38] found that the neutron mass is larger than the proton mass, in contrast to the initial statement of James Chadwick [19]. This has important consequences for nuclear stability and nuclear reactions. While forming more than a half of the mass of matter around us, free neutrons have not a very long lifetime: about 15 minutes.[2] One has to break a nucleus in order to reveal the existence of the neutron.

2. Artificial radioactivity

In January 1934, Irène and Frédéric Joliot-Curie found that, when irradiating certain non-radioactive light elements (B, Mg (magnesium), Al) with the α-rays emitted by Po, the irradiated material emits positrons and remains radioactive during a reasonably long time after the exposure [39–41]. They concluded that a new radioactive material had been artificially produced. Now, one could separate a radioactive element simply by measuring with a radiation counter where it is found after every chemical test on this material! The decay was sufficiently slow to allow for chemical separation and identification [42], however fast enough for requiring state-of-the-art techniques for performing chemical analysis, in particular in view of the minor quantities of radioactive materials produced. An important advantage of the "Institut du radium" in Paris was the largest supply of Po in the world, which allowed relatively large intensities of the initial radiation.

For instance, in the case of the transformation of the Al nucleus into a silicon (Si) nucleus, they suggested that the phenomenon takes place in two stages. First, capture of the α-particle and the instantaneous expulsion of the neutron, with the formation of a radioactive atom, which is an isotope of phosphorus (P) of atomic weight 30, while the stable P atom has an atomic weight of 31. Next, this unstable atom, this new radioelement, which they called "radio-phosphorus" in contrast to normal phosphorus, decomposes exponentially with a half-life of three minutes:

$$^{27}\mathrm{Al} + \alpha \to {}^{30}\mathrm{P} + \mathrm{n}, \quad \text{followed by} \quad {}^{30}\mathrm{P} \to {}^{30}\mathrm{Si} + \mathrm{e}^+ + \text{neutrino} \tag{6}$$

They interpreted in the same way the production of radioactive elements in B and Mg; in the first, an unstable N with a half-life of 11 minutes is produced; in the second, unstable isotopes of Si and Al. They also proposed that radioactive elements might be produced "in different nuclear reactions with other bombarding particles: protons, deuterons, neutrons" [41].

For this discovery of the synthesis of radioelements [43], Irène and Frédéric got the Nobel Prize for chemistry [44,45] in 1935; the same year, Chadwick received the Nobel Prize in physics. In the suggested nuclear reactions, the neutron, unknown two years earlier, already appeared as a product of the reaction.

But could it be actually an agent of the reaction as well? This was Enrico Fermi's idea in Rome: to use the new particle, instead of α-rays, to produce new radioactive elements. According to Emilio Segrè, Enrico Fermi "immediately saw that their work could be expanded tremendously by using neutrons as projectiles" [46]. It was more complicated, because neutrons, in contrast with α-rays, are not produced spontaneously. However, neutrons do not need to overcome the nuclear potential barrier; also, their interaction cross-section is large. Fermi and his group (Segré, Amaldi, Rasetti...) were able to obtain more than 20 new radioactive isotopes by this method [47], known today as the powerful and very general method of neutron activation analysis.

Irène and Frédéric re-did the experiments and confirmed his results [48] for Ag, Si, Zn, I, Fe; the decay periods agreed with those obtained by Fermi. Moreover, they verified that the same radioactive element can be obtained using different nuclear reactions:

$$^{25}\mathrm{Mg} + \alpha \to {}^{28}\mathrm{Al} + \mathrm{p}, \qquad {}^{28}\mathrm{Si} + \mathrm{n} \to {}^{28}\mathrm{Al} + \mathrm{p}, \qquad {}^{31}\mathrm{P} + \mathrm{n} \to {}^{28}\mathrm{Al} + \alpha \tag{7}$$

In addition, other artificial transmutations of different types were promptly discovered; some are produced by α-rays, by γ-rays, others by protons or deuterons, others by neutrons. The particles expelled when the nucleus disintegrates are protons, α-rays, or neutrons. Within a short period, a small family of a few dozens of radioactive elements in hands of experimentalists expanded enormously. These isotopes found important applications as "tracers" in physics, chemistry, and biology. Also in medicine, radioactive tracers can be delivered to a particular place in the human body and help treating diseases. This technique had already been developed with natural radioactive elements as early as 1913 by Georg von Hevesy, who obtained the Nobel Prize for chemistry for that achievement in 1943. The discovery of new heavier elements, neutron-rich isotopes and proton-rich isotopes continues nowadays. Today, the heaviest element is oganesson [49], with the atomic number 118, named after Yuri Oganessian, from Dubna.

While studying the neutron-induced nuclear reactions, Fermi's group made another important discovery [50]: in the experiments on radioactivity induced on silver (Ag) by neutrons, a piece of paraffin a few centimeters thick was interposed

[2] The stability of neutrons in atomic nuclei results from Fermi's statistics (which favors the presence of neutrons with a number comparable to the number of protons), strong nuclear interaction (which favors a high number of both neutrons and protons), and Coulomb interaction (which limits the number of protons).

between the source and the Ag sample. While the effect was expected to decrease if the neutron energy does not change, it increased! The conclusion was clear: slow neutrons have a stronger effect than fast neutrons. In particular, the cross-section of neutron absorption in nuclei largely increases when neutron velocity decreases. On the other hand, the coherent scattering of slow neutrons would result in an effective potential for neutrons traveling through matter [51], which appeared to be of major importance for applications of neutrons in research. Slow neutrons turned out to be important in another phenomenon whose discovery was a major event of the middle of the twentieth century: fission.

3. Fission

As well known, the history of fission began in 1938 with articles by Otto Hahn and Fritz Straßmann in Berlin [52,53]. However, the prehistory already started in Rome in March 1934 when Fermi's coworkers "bombarded uranium (U) and thorium (Th) with neutrons. They got complicated results, the interpretation of which was difficult. Nowadays it is obvious that they resulted from the fission of the nucleus, i.e. the division of the heavy nucleus into two fragments of different masses, rather than the formation of transuranian elements, i.e. with an atomic number larger than 92... Fermi, although very cautiously, announced [54] the discovery of transuranian elements" [55]. In line with the logics of the preceding research with light nuclei, irradiation of heavy nuclei with neutrons was expected to lead to the formation of heavy transuranian nuclei.

Fermi's article, however, was criticized by a German chemist, Ida Noddack, the discoverer of rhenium (Re). "It is also conceivable", she wrote in [56], "that when heavy nuclei are bombarded with neutrons these nuclei could break down into several fairly large fragments, which are certainly isotopes of known elements, but not neighbors of the irradiated elements." However, Frau Noddack did not try to check her hypothesis, she did not propose a theoretical basis for this process, and so her suggestion was forgotten until 1938.

Lise Meitner, Otto Hahn, Fritz Straßmann in Germany, and Irène Curie in France performed similar experiments, with the same purpose of producing and investigating new transuranian nuclei [57–60]. The study of the radioelements resulting from the irradiation of U and Th with slow and fast neutrons was particularly complicated because of many nuclei/isotopes/isomers produced as well as the similarity of chemical properties of series of corresponding elements in the periodic table. With the accumulation of new data, internal contradictions of the interpretation were becoming more evident, without clear indication, however, of the origin of the puzzle. In particular, chemical properties of some produced nuclei were different from the properties of any nuclei with an atomic number close to that of U or Th, also the number of isomers to assume for explaining the data was too large.

Things changed when Hahn and Straßmann identified barium (Ba) [52,53] in the reaction products. Does so large a departure from the initial mass of U (Th) mean a nuclear rupture? The authors were unsure about the explanation of their results, as it looked strange that a tiny neutron can break in parts a heavy nucleus. Moreover, prominent scientists around were all discussing the opposite process: the formation of transuranian elements. Hahn was a nuclear chemist and needed the help of a physicist. In several letters, Hahn exposed his latest results and his concerns to his colleague Lise Meitner: "Actually there is something about the 'radium isotopes' that is so remarkable that for now we are telling only you. ... Our Ra isotopes act like Ba. [...] Perhaps you can come up with some sort of fantastic explanation. We do know that it can't actually burst apart into Ba."

Lise Meitner and her nephew Otto Robert Frisch promptly found the correct explanation: nuclear fission [61], named by Frisch in analogy to biological fission of living cells. They assumed a nuclear reaction like

$$_{92}\mathrm{U} + \mathrm{n} \rightarrow {}_{56}\mathrm{Ba} + {}_{36}\mathrm{Kr} + \cdots \tag{8}$$

where the dots (...) represent gamma photons and a number of neutrons that depends on the mass numbers of the three nuclei. Inspired by an article by Niels Bohr and Fritz Kalckar [62], they imagined the process of fission in terms of the nuclear liquid-drop model imagined by George Gamow. "On account of their close packing and strong energy exchange, 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", Meitner and Frisch wrote. When absorbing a neutron, the drop constituted by the U nucleus elongates (Fig. 2). This motion is opposed by the surface tension, but, according to Meitner and Frisch, "the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100." Thus, the drop can split into two smaller drops, which move apart due to their electric repulsion and gain a kinetic energy of some 200 MeV. The released nuclear binding energy is also some 200 MeV and the mass of the fragments is smaller than the initial U mass, as follows from Einstein's formula $E = mc^2$. Otto Frisch [63], and shortly later others [64–68] observed experimentally the great ionizing power of the nuclear fission fragments.

The articles by Hahn and Straßmann, and by Meitner and Frisch, were submitted rather hastily and published very quickly. For instance, it is not quite true to say that the "surface tension is diminished by the charge." Surface tension and Coulomb repulsion are rather antagonistic effects, and the latter wins in heavy nuclei. Also, the kinetic energy might be significantly lower than 200 MeV (say 180 MeV) because of the excitation energy of fission fragments.

The research on fission exploded all over the world. New researchers entered the field; others working on production of transuranian nuclei had to rethink their preceding results. Irène, together with her coauthor Paul Savitch, explained her

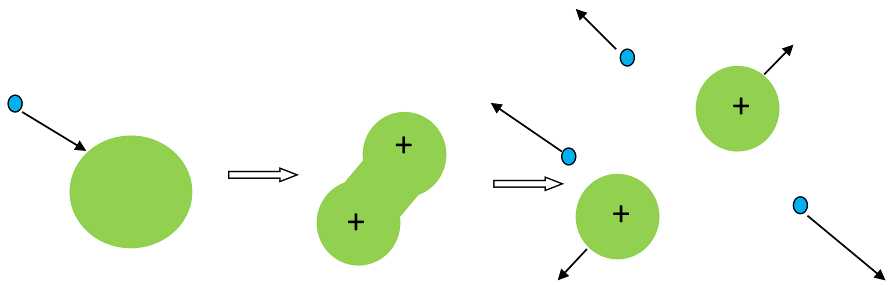

Fig. 2. Nuclear fission in the liquid drop model. When hit by a neutron (blue ball) the nucleus elongates and splits into two parts, creating more neutrons.

hesitations [69]: "We had considered the possibility of a rupture of the uranium atom, but we had rejected this idea [...]", in fact because Hahn, Meitner and Straßmann had, in earlier papers, misinterpreted their experimental results and announced the formation of transuranian elements – the same mistake as Fermi's in 1934 [70]. In fact, transuranian elements were discovered later – neptunium was the first, in 1939, discovered by Edwin McMillan and Philip Abelson in Berkeley [71].

Frédéric Joliot clearly proved the explosive character of fission and separated from U the new nuclei [72,73]. Due to its kinetic energy, a fragment can escape from the U sample surface and traverse an air gap. A complex mixture of radioactive fragments collected at a distance from the U target appeared to be the same as the radioactive products accumulated in the target. An absorption of fragments in thin screens inserted between the U sample and the surface corresponded to kinetic energies estimated from the energy balance in the fission process. Measurements with Th showed the same result.

Already in this article, Frédéric Joliot mentions the production of a few neutrons per fission. Hahn and Straßmann note this possibility in their second publication on fission [74]. As the excess of the number of neutrons over the number of protons in a nucleus increases as a function of atomic weight, it is natural that sufficiently heavy nuclei, like U, can emit not one, but a few neutrons. However, this means that their number can multiply at every step or stay constant if one controls the reaction by means of absorbing extra neutrons or letting them escape out of the reaction zone. Thus, fission can run "in chain"! Immediately, neutrons from fission were observed experimentally [75–84]. "Recent experiments have shown that neutrons are liberated in the nuclear fission of uranium induced by slow neutron bombardment: secondary neutrons have been observed which show spatial, energetic or temporal properties different from those which primary neutrons possess or may acquire" [81]. The complexity of all these features related to neutron diffusion in matter, their thermalization in matter, both as a function of neutron energy, a huge variety of nuclear reactions involved in the process, prompt and delayed neutrons, nuclear isomers [85–87] and so on and so on, was recognized or at least suspected already at that time.

Frédéric Joliot already discussed the possibility of a nuclear chain reaction with important release of energy in his Nobel Prize lecture in 1935. With his colleagues, Hans von Halban, Lev Kowarski, and Francis Perrin, he demonstrated it explicitly [88] in 1939. They placed a source of neutrons in the center of a copper (Cu) sphere immerged into a water bath (which slowed down the neutrons and scattered them, thus increasing the number of fission events because of their back-scattering). They filled the sphere with uranium oxide (U_3O_8), or water, or a mixture of both, and measured the neutron fluxes in the various cases. They observed in this so-called subcritical assembly a large increase in the number of neutrons emitted from the initial neutron source in the middle of the sphere. They even estimated, with a limited knowledge of all relevant cross-sections at that time, the mean number of neutrons produced per fission to be 3.5 ± 0.7. This evaluation took into account the emission of neutrons by fission products. The precise value is 2.41. Without the initial neutron source in the middle of the sphere, the reaction would stop. The authors concluded that they were observing a chain of nuclear reactions. If the size of the reaction zone had been larger and, therefore, a smaller fraction of produced neutrons would have escaped from the sphere surface, the neutron multiplication factor would have increased. For a certain finite size, it would have exploded. Francis Perrin estimated accordingly a so-called critical mass of the active zone without a reflector around it [89].

In these experiments, some external neutron flux provided initial fission events, which resulted in the nuclear chain reaction. Can fission occur in other ways than induced by an external neutron source? Bohr and Wheeler's theory of the fission process [90] based on the "liquid drop" model, predicted that an external "kick" can be given by a γ-quantum. Indeed, photo-fission of uranium and thorium were promptly observed [91] in the Westinghouse Research Laboratories, in Pennsylvania. Moreover, Georgy Flyorov and Konstantin Petrzhak in Leningrad announced [92,93] that a heavy enough nucleus can fission spontaneously, without any initial "kick", thus releasing extra neutrons. Thus, the fission chain reaction will develop itself as soon as the conditions corresponding to the critical mass are met.

The main lines of further developments were clear for those involved in the fission research. Low absorbing neutron moderators and reflectors, like heavy water (D_2O) or pure graphite, if placed around the reaction zone, would increase the efficiency of the reaction. Neutron absorbers, like cadmium (Cd), would decrease the efficiency, and thus allow controlling the reaction at some chosen intensity. Provided in such a way, a controlled steady chain fission reaction would not need any more an external neutron source to keep it running. Such a so-called critical assembly provides an "infinite" multiplication factor for the initial neutron intensity. Due to such multiplication, it would dramatically improve the intensity of usually weak neutron sources, thus providing useful tools for research. Due to larger neutron fluxes, it would allow producing much larger amounts of artificial radioactive elements, which make them a real instrument in medicine, biology, and other domains. Due to 200 MeV of energy released per one fission event, it would produce a quantity of energy that one can hardly imagine in advance. The list of thought applications was increasing. However, one still had to do significant steps towards the practical realization of these ideas.

Until 1939, nuclear science had been the object of a tight international competition in several languages (English, German, French, Russian, occasionally Italian and others). It was rather friendly, since young researchers occasionally moved from one laboratory to another. For instance, Ettore Majorana spent some time in Germany with Heisenberg, Bruno Pontecorvo in France with Joliot-Curie. Two events were going to change the situation drastically. On the one hand, the extreme right became very powerful in continental Europe, and was victorious in the beginning of the Second World War, so that many major scientists from Italy, Germany, Austria, Denmark, and France fled to the United States of America (as Fermi did) or to the United Kingdom (as Otto Frisch did, while his aunt Lise Meitner, in July 1938, fled to Sweden). On the other hand, nuclear fission and chain reactions gave nuclear physics a military importance. In 1939, Francis Perrin [89] could still discuss the critical mass of a radioactive material (a very new topic!) in the *Comptes rendus de l'Académie des sciences*. In the first days of May 1939, Joliot, Halban, and Kowarski filed patents on power production from a nuclear chain reaction as well as on nuclear explosion. The next year, this subject had become highly confidential. It was treated in detail and quantitatively by the German Rudolf Peierls and the Austrian Otto Frisch in a memorandum written in English for the use of the British Government.

4. Conclusion

In the friendly, but tight competition between European scientists before the Second World War, the *Comptes rendus de l'Académie des sciences* informed the competitors in a very short time about the latest discoveries of the French scientists, but also about their hesitations and mistakes. This publication style may be compared with the current one, which involves peer reviewing, an often very long process. Both styles have an advantage. The interest of rapid publication is responsible for the wild multiplication of on-line journals. Publication in the *Comptes rendus* was not completely open to anybody. Every communication, when the author was not an Academician, was presented by an Academician, who could control the quality of the note. This control was however rather loose. It was not too bad in that time, since the proportion of scientists in the human population was much smaller than nowadays (and the human population smaller too). Presently, a careful control is generally necessary, in particular to ensure the innovative nature of the articles. Nevertheless, a decentralized system of publication, allowing for a more direct contact between the author and the editor, may still have an interest.

Detailed overviews of the discovery of neutron and fission can be found in Refs. [33,94]. At a more elementary level, excellent accounts can be found on Wikipedia: https://en.wikipedia.org/wiki/Discovery_of_the_neutron, https://en.wikipedia.org/wiki/Nuclear_chain_reaction, https://en.wikipedia.org/wiki/Spontaneous_fission#History.

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Appendix A. Supplementary material

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