A Tale of Resilience: The Periodic Table after Radioactivity and the Discovery of the Neutron

Introduction

Presented in 1869, the periodic system remains an icon in contemporary science, even though the understanding of elements and chemical reactions has evolved tremendously over the last 150 years. At the turn of the twentieth century, the discovery of the phenomenon of natural radioactivity led to the identification of a range of new ‘radioelements’ (radioactive substances believed to be elements). The blank spaces in the periodic system that had been predicted since the 1860s could not accommodate them all. New insights into the composition of the atom revealed the existence of electrons and later protons. The concept of ‘isotopes’ (1913) helped identify most of the radioelements as isotopes of known elements rather than as new elements with a defined space in the periodic system. Eventually, atomic number replaced atomic weight as the unique identifier of an element, and in the 1920s the periodic system was reinterpreted, using atomic theory based on quantum principles to explain the system and its ‘periodic law’ rather than to challenge it.

The 1930s brought further radical insights into the elements and periodic system, including the discoveries of the neutron (1932), of induced (‘artificial’) radioactivity (1934), and eventually, of nuclear fission (1938/39). Yet the perseverance of the periodic system is remarkable. The frame of reference that the periodic system represents has been perpetually renegotiated and stabilized by the scientific community. Today, the periodic law is explained by means of the elements’ underlying atomic structure – in particular its electron configuration – and the nuclear structure furthermore explains the occurrence of isotopes as well as of radioactive disintegration. As a result, it is difficult for students learning chemistry today to comprehend that tables from the nineteenth century, some of which look similar to current ones in their organization, were set up without any knowledge of sub-atomic particles, let alone the belief in atoms. Interestingly, most historical accounts of the development of the periodic system are actually based on explaining the different steps and accommodations the periodic system went through to reach our present view.

Robustness is an attribute of a system able to resist change over the course of time, and the periodic system has indeed been deemed robust.[1] But unlike robust systems that return to their initial configurations without adapting to change – analogous to the physical property of elastic bands – the periodic system has been reorganized through successive steps. One such adaptation is the intrinsically connected conception of an element that was reworked simultaneously with the periodic system.[2] We argue that a more adequate term for the 'robustness' of the periodic system would be resilience, in which the system is able to "absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks."[3]

How can we recognize this resilience of the periodic system? And how did contemporary scientists navigate it in times of reinterpretation? We will address these questions from the historian's perspective by looking at two contributions by women scientists, who were involved in new discoveries and interpretations of the periodic system in different ways. They worked and wrote from the contrasting perspectives of a nuclear physicist and an experimental chemist. By analyzing their writing, which was founded on their experience, scientific background and research interests, we might come to a better understanding of how the meaning and values of the periodic system were perceived at the time.

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[1] Scerri (2007, p. 160). For a definition of robustness taken from management practice, which is in line with the explanation given here, see Wieland and Wallenburg (2012), p. 890.

[2] See essays by Bensaude-Vincent and Kragh in this issue.

[3] This is the definition used for social-ecological systems, see Walker *et al.* (2004), p. 2.

After contrasting the lives and careers of the two women scientists in the first part of this essay, the second part will focus on their work at the intersection of the discoveries of new elements and of nuclear fission. In the third part, we will proceed to an integrated analysis of their contributions to the periodic system, both published in 1934 in the centennial year of the birth of Dmitri Mendeleev (1834–1907), the most famous discoverer of the periodic system. Through this analysis, we will make a case for resilience as the foremost value of the periodic system and discuss what it means for the future of the periodic system and its future representations. We argue that representations should retain their multiplicity and openness to accommodating a variety of understandings that serve the system's users and their needs.

Two women scientists in Berlin

In May and November 1934, respectively, the German chemist Ida Noddack (née Tacke) (1896-1978) and the Austrian physicist Lise Meitner (1878-1968) published independent articles on the periodic system. Noddack's article was entitled 'Das Periodische System der Elemente und seine Lücken' (The Periodic System and its Gaps) and appeared in *Angewandte Chemie* (Applied Chemistry), while Meitner's bore the title 'Atomkern und periodisches System der Elemente' (Nucleus and Periodic System of the Elements) and was published in *Die Naturwissenschaften* (The Science of Nature).[4] Both journals were widely read scientific journals in Germany at the time. While *Angewandte Chemie* was mainly an (applied) chemistry journal, articles on radioactivity appeared as well, e.g. by Lise Meitner in 1923. Likewise, many chemistry-related articles were published in *Die Naturwissenschaften*; Ida Noddack published four papers on chemical elements in this journal between 1925 and 1930.[5]

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[4] Noddack (1934); Meitner (1934).

[5] Some were devoted to the discovery of rhenium, like Noddack and Tacke (1925) and Berg and Tacke (1925). Others continued with the chemistry of rhenium (Noddack and Noddack, 1929) or the natural abundance of

Meitner was 17 years older than Noddack. This factor alone implied some differences in opportunities and challenges for the two women, who were both working in Germany. Universities were still closed to women when Meitner left Vienna for further scientific studies in Berlin in 1907, and she had to ask Max Planck's (1858-1947) permission to attend his lectures. Admitted as Otto Hahn's (1879-1968) collaborator at the chemistry department of the Friedrich-Wilhelm-Universität that same year, at first Meitner was not allowed to set foot inside the main parts of the institute. Instead, she was given permission to work in the basement, using her own entrance.[6] But times were changing. Already the year after, universities in Prussia started to admit women, and the restrictions for Meitner at the chemistry department lessened. In 1912, Meitner took up her first paid position as an assistant to Max Planck, and shortly afterward she was named 'scientific associate' at Otto Hahn's radioactivity section of the newly established Kaiser-Wilhelm Institute (KWI) for Chemistry in Berlin-Dahlem.

In 1917, Hahn's section was divided into two parts, one for physics and one for chemistry. Meitner was made head of the physics section, which brought with it a great increase in salary. A few years later, in 1919, she became a professor at the institute, by all accounts the first woman to achieve such a title in Germany. She received her habilitation in 1922, four years after women in Prussia had been granted this right. This qualified her as the first woman physics lecturer (*Privatdozent)*. She started giving regular colloquia at the university in Berlin in 1923, and in 1926 she was promoted to extraordinary professor – an honour that was even more sensational for a woman than receiving the title of professor at the private KWI. Meitner was at the height of her career when the article in *Die Naturwissenschaften* was published in 1934, at least in terms of her affiliation and formal positions as full

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the elements, another of the Walter and Ida Noddack's joint research topics (Noddack and Noddack,1930). For Lise Meitner's article in *Angewandte Chemie*, see Meitner (1923). On the journals, see Diederich (2013) and Thatje (2009).

[6] Sime (1996, p. 29).

professor and head of her own section. However, members of the Nazi party had been given more influence in the department. Born Jewish, and despite conversion to Lutheran faith, she soon had to flee Germany and chose to shelter in Sweden, where she never again attained the same formal status and work environment.[7] From her exiled position, however, she continued her collaboration with Hahn. Based on his and Fritz Strassman's (1902-1980) experimental findings, Meitner and her nephew, the Austrian-British physicist Otto Frisch (1904-1979), worked out the theoretical basis for nuclear fission in the winter of 1938-39, for which she has become well known.[8]

The year before Meitner became a professor at the KWI in 1918, Ida Tacke completed her exams for the engineering degree at the *Technische Hochschule* in Berlin-Charlottenburg. Indeed, she was among the first generation of female students at higher learning institutions in Berlin, and one of only nine female students enrolled in the program for chemistry and metallurgy at the Hochschule. Three years later, Ida Tacke was awarded a doctoral degree in engineering and was subsequently employed as a chemical engineer at the Allgemeine Elektricitäts Gesellschaft (AEG), as one of the 1.5% women chemists working in the German chemical industry.[9] From that time on, however, her career would develop in the opposite direction of Meitner's, away from paid and high-ranking positions. As we shall see, this was partly due to her status as a married woman – and the rules regulating employment in Germany in the first third of the twentieth century.

Shortly before completing her dissertation, Ida Tacke met the chemist Walter Noddack (1893-1960), whom she fell in love with and later married in 1926. The couple shared an enthusiasm for the periodic system. At that time, more than fifty years after Mendeleev's first

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[7] Indeed, Manne Siegbahn (1886–1978), the director of the Nobel Institute for Experimental Physics in Stockholm, did not include her in his group, nor did he give her the resources to do her own experiments. See Sime (1994) and Friedman (2001).

[8] Sime (1996), pp. 109–110 (on Meitner's titles) and pp. 231–258 (on her exile in Sweden and the discovery of nuclear fission).

[9] Van Tiggelen and Lykknes (2012).

periodic system where many unknown elements had been conjectured, five spaces in the system were still blank.[10] Two of them were positioned beneath manganese and were called the 'eka-manganeses' (for eka- and dvi-manganese), hereafter referred to as the 'manganese homologues.' Together, Ida and Walter set out to find these elements (nos. 43 and 75). When they realized that the necessary literature review needed as background for the analyses demanded full-time work for at least one of them, Ida decided to quit her job at AEG to devote herself fully to the joint project with Walter. In 1924–25, she was an unpaid guest researcher at the physical laboratory of the *Wernewerk Siemens & Halske* in Berlin to conduct X-ray spectral analysis of samples with another German Chemist, Otto Berg (1873-1939). For the rest of her career, Ida Noddack mostly held unpaid positions at her husband's institution wherever he assumed a new position.[11] At the time of the publication in *Angewandte Chemie*, Ida was a guest researcher at the chemical laboratory of the *Physikalisch-Technische Reichsanstalt* (the Imperial Physical Technical Institute, abbreviated as PTR), where Walter was working and had been the director until 1927.

Ida Noddack chose to leave a paid position in chemical industry to work on the literature review in 1923 and later to learn the skills of X-ray spectroscopy. For most married women in Germany, it would soon become impossible to continue working, however. The sufferings of World War I engendered a law that forced women who were supported by their husbands to leave their positions in order to achieve a higher employment rate for men.[12] Married women were expected to direct their energies towards their families, whether they had children or not. Since Lise Meitner was not a married woman, this rule did not affect her

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[10] In his 1871 table, Mendeleev predicted the atomic weight of 100 for what he called the "eka manganese" (element 43) and atomic weight 190 for his "tri-manganese" (element 75, later called dvi-manganese). Mendeleev conjectured many elements but did not predict any properties for all his predictions. Also, some predictions made by Mendeleev were unsuccessful, e.g. that of eka-caesium (atomic weight 175). Clarity as to what elements did indeed exist came with the use of X-ray spectroscopy and the switch from atomic weight to atomic number. See Scerri (2007, pp. 142-173) and Van Spronsen (1969, pp. 220–223).

[11] Van Tiggelen and Lykknes (2012).

[12] Frevert (1989, pp. 197-198).

career. Once married, however, Ida Noddack was fortunate to be part of her husband's research network, having access to the infrastructure of his institute and being able to focus solely on research. Walter always had a collaborator who would follow him from city to city or institution to institution. Ida always regarded herself as an equal coworker, never an assistant.[13] The article by Ida in *Angewandte Chemie*, for example, served as material for two oral presentations, one by Ida and the other one by Walter. Indeed, Van Tiggelen and Lykknes have argued that in all of their joint research, the Noddack couple always acted so as to achieve success for the work unit, their *Arbeitsgemeinschaft*, sometimes at the expense of the individual's credit.[14]

Meitner and Noddack: research on elements and nuclear fission

Lise Meitner and Ida Noddack differed not only in age and generation, but also in terms of formal and informal positions in the scientific community. As noted, Meitner was already an established researcher in 1934, holding an extraordinary professorship at a prestigious university, in charge of a research group at the Kaiser Wilhelm Institute for chemistry and a respected scientist – though indeed facing the threat of the Nazi regime. Ida Noddack, by contrast, was in her ninth year as an unpaid guest researcher at the chemical laboratory of the PTR in Berlin, where she was working with her husband, who was now the head of the photochemical laboratory. With different points of departure and affiliations, however, both Meitner and Noddack worked on elements and their chemistry.

In 1918, sixteen years before the publication in *Die Naturwissenschaften*, Hahn and Meitner discovered element 91, protactinium, the mother substance of actinium, while seeking to

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[13] Ida Noddack's prompt response to a journalist who asked her about the time she was "assistant" to Professor Noddack on the work on rhenium (Noddack, 1969) was that she had never been her husband-to-be's assistant.

[14] Van Tiggelen and Lykknes (2012).

establish the link between uranium and actinium in the radioactive series. The discovery had taken five years of painstaking chemical separations and radiation measurements in their new laboratory in Dahlem and demanded all the expertise they had acquired over the years.[15] As most of the work lay on Meitner's shoulders while Hahn was serving in the army, Meitner the physicist acquired expertise as an analytical chemist as well. The first 0.1 gram of the metallic element was, however, only isolated by the German chemist Aristid von Grosse (1905–1985) in 1934. His method was highly technical and included bombarding protactinium oxide with a stream of electrons in a high vacuum.[16] Such was the power of the science of radioactivity. Already in the 1920s, more than a decade earlier, radioactivity's success had reached a saturation point, suggesting a less promising future for this science field.[17] The theory of radioactive disintegration and the concept of isotopes had been introduced, the radioactive decay series had been established, and the radioelements had become parts of them – what more could be expected from the field? The new discoveries of the 1930s would develop into the new branch of nuclear physics, to which Meitner would contribute the explanation for nuclear fission as her most highly praised achievement. It is against this background that we must understand Meitner's article in *Die Naturwissenschaften*, which displays her interest in and perspectives on the relationships between the new developments in nuclear science and the periodic system.

While Meitner worked in the context of radioelements and the mapping of the radioactive decay series, Ida and Walter Noddack were absorbed by the quest for missing elements in the periodic system. After Ida had spent ten months working full-time in the Berlin State Library ploughing through 100 years of literature in inorganic chemistry, in 1924 the couple took up the practical work of finding the elements 43 and 75 in platinum ores and in the mineral

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[15] Meitner (1918); Sime (1986); Sime (1996, pp. 63–72).

[16] von Grosse (1934).

[17] Badash (1979).

groups columbite and tantalite. These mineral groups contain iron and manganese, as well as niobium (columbite) and tantalum (tantalite), all of which are located near the manganese homologues in the periodic table. The following year, X-ray measurements indicated the presence of both elements in four different minerals and the presence of one of them in three more. In her presentation of the discovery of the manganese homologues, Ida Noddack explicitly referred to Mendeleev's complete predictions for eka-silicon, eka-boron and eka-aluminium.[18] The Noddacks named element 43 masurium, after Masuria (now Polish territory) and element 75 rhenium, after the river Rhine. While Meitner and Hahn had chosen a name connected to the characteristics of the new element (protactinium as the element 'coming before actinium'), the Noddacks resolutely opted for terms with national echoes, by naming their elements after the Western and Eastern borders of the late German empire, a choice which was not appreciated abroad. In 1929, the Noddacks obtained the first gram of rhenium, providing evidence that the element actually existed.

The couple never succeeded in obtaining any quantity of masurium, nor did they ever manage to reproduce the X-ray spectra they had produced initially. Hahn and Meitner, among others, were highly critical of the alleged masurium discovery and characterized the debates that followed as self-promotion without much substantiation by the Noddacks.[19] For their success with rhenium, however, the couple achieved numerous forms of recognition: approval by the German atomic weight commission (1929), the Liebig medal by the German Chemical Society (1931), the Scheele Medal from the Swedish Chemical Society (1934) and nominations for the Nobel prize in chemistry .[20] Ida and Walter Noddack were nominated jointly four times (in 1933, 1935 and 1937), while Walter was nominated alone five times (in 1932, 1933 and 1934). Lise Meitner was nominated for the chemistry prize 19 times between

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[18] For the presence of the eka-manganeses in minerals, see Tacke (1925a, p. 1160). For the reference to predictions, see Tacke (1925b, p. 365).

[19] Sime (1996, pp. 272-273).

[20] Van Tiggelen (2001).

1924 and 1948 and for the physics prize 29 times between 1937 and 1965, both for her discovery of protactinium and for her contribution to the discovery of nuclear fission.[21] Hahn alone was awarded the 1944 Nobel prize in physics.

The two women's careers crossed paths not only when researching and discovering missing elements in the periodic system, but also in the realm of nuclear physics. Commenting on the Italian physicist Enrico Fermi's (1901–1954) claim to have produced transuranic elements (i.e., elements beyond uranium in the periodic system) after having bombarded uranium nuclei with neutrons, Ida Noddack criticized his methods and results in September 1934, some months after the *Angewandte Chemie* article on the periodic system. In fact, Fermi had not compared the produced radioelements with all known elements, focusing only on the neighboring elements and the potential products of decay down to lead. His method was thus not able to rule out all known elements. This led Noddack to propose that the radioelements produced in this reaction might actually be among the known lighter elements, and that heavy nuclei bombarded with neutrons might break up into large fragments and later called nuclear fission. According to Noddack's own reminiscences, Hahn and Meitner characterized her proposal as 'absurd,' while Bohr denied it as an impossible case.[22] Fermi and his collaborators had discussed her input, but they dismissed the proposal. When Hahn and Meitner's work on fission was published more than four years later, Ida accused them of not citing her. In a letter to the German physicist Paul Rosbaud (1896–1963), the editor of *Die Naturwissenschaften*, Meitner even wrote that Ida Noddack had now "made a great fool of herself."[23] Indeed, there seems to have been a bias against the Noddacks in the scientific community, partly because of the priority debates on the discovery of masurium and partly

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[21] Nobel nomination archives database to be consulted online www.nobelprize.org/nomination, choose nomination archives in the submenu. Friedman (2001) discusses the Nobel nominations related to nuclear fission in detail.

[22] Noddack (1966).

[23] Sime (1996, pp. 271–272), quotation on p. 272.

because the Noddacks were suspected to have close connections with, or sympathies towards, the Nazi regime.[24]

Although they shared scientific interests, Meitner and Noddack were thus in opposite camps in many respects: a converted Jew and a suspected Nazi sympathizer, an appointed professor and an unpaid guest researcher, a radiophysicist and a chemist entrenched in the 'wet chemistry' tradition, in addition to the age difference of 17 years between them. Both, however, operated in the German scientific context and were interested in the periodic system and its meaning. In the following, we will analyze the two 1934 contributions to the periodic system by Meitner and Noddack against the two scientists' backgrounds and interests. In particular, we will investigate how the two scientists presented the meaning and values of the periodic system in light of the contemporary developments in chemistry and physics. This will be done by comparing the views of the two scientists on three issues: first, the origin and the evolution of the periodic system, with the notion of isotopes and the concept of atomic number; second, the role ascribed to the "new" building blocks of matter, the subnuclear particles and the neutron in particular; and third, the perspectives on the challenges and the future of the periodic system.

Two texts on the periodic system

Ida Noddack's article appeared in May 1934, six months before Lise Meitner's. For both women, the articles were their first published works about the periodic system itself, although both of them had discussed the placement and properties of their respective discovered element (protactinium and rhenium) in the periodic system. As noted above, the date was no coincidence. Among the many celebratory events organized that year, the international congress in honor of the hundredth anniversary of Mendeleev's birth held in Leningrad (now

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[24] Sime (1996, pp. 272-273).

Saint Petersburg, Russia) constituted a high point. Only 26 foreigners were allowed to participate (compared to 300 official Russian delegates and a further 1400 Russian attendees). The staging of the congress was strongly regarded as Soviet propaganda, and opportunities to visit scientific institutions as well as industrial and agricultural plants were included in the program.[25] Meitner was invited to speak on September 11, the second day of the meeting, and "lectured on atomic nuclei and the periodic system." [26] She was the only woman on the program of the most prestigious and formal part of the program held in Leningrad and one of only three foreigners in an official program of 12 speakers. The congress moved to Moscow after six days, where other foreign scientists were invited to lecture, such as Otto Hahn, the Czech-Austrian chemist Otto Hönigschmid (1878-1945), the Czech chemist Jaroslav Heyrovsky (1890-1967) and the Austrian-American chemist Herman Francis Mark (1895-1992). Among the invited guest speakers in Moscow were Ida and Walter Noddack, who presented aspects related to the finding of new elements and the periodic system. Walter gave a general talk on the organization of the periodic system, while Ida described modern methods for predicting elements. According to the published proceedings that appeared three years later, Walter offered a critical review of the evidence provided for the claimed existence of elements 61, 85 and 87 (conf. Figure 1), while Ida focused on the modern methods of predicting elements.[27] By then Ida had already published her article in *Angewandte Chemie*.

While both Ida Noddack and Lise Meitner's publications took the opportunity of the special occasion to focus on the periodic system in light of contemporary science, their distinct standpoints offer strikingly different perspectives and provide divergent interpretations of the past, the present understanding and the future of the periodic system. The matters they dealt

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[25] Paneth (1934).

[26] Paneth (1934, p. 800).

[27] Noddack, W. (1937) and Noddack, I. (1937).

with are undeniably shared, not just between these two women, but with many a scientist: the system, what defines an element and characterizes its chemical behavior, finding and questing for new elements and accommodating them in the system, the appearance of subatomic particles and the reinterpretation of the elements and their mutual relationship. Not surprisingly, Noddack and Meitner acknowledged the German chemist Lothar Meyer (1830-1895) along with Dmitri Mendeleev as independent discoverers of the system, given that both women were part of the German scientific community. The ways they looked back on the past and evaluated the present and the future of the periodic system, however, were poles apart. The two texts are also organized differently and exhibit different ways of using the periodic system as an investigational tool to arrive at a result – akin to the "paper tool" coined by Ursula Klein that serves a similar purpose to a laboratory.[28] We will discuss their different perspectives in the following sections.

The periodic system, its development and the nature of matter

As is generally known today, Mendeleev and Meyer started thinking about a system for the elements as they were writing a textbook.[29] Ida Noddack hardly concealed her admiration when stating this in her presentation, stressing the chaos that initially reigned when it came to measuring chemical properties. The difficulty was not only a technical one but also operational, as there were two coexisting conceptual systems: the system of atomic weights and that of equivalent weights. The latter expressed the weight of a substance that combined with or displaced a fixed quantity of another substance, while the atomic weight of the same given substance was expressed as a comparison with the atomic weight of another substance chosen as a reference. Though Noddack understood this challenge, in her opinion the real

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[28] Klein (2003). See also Gordin (2018) on the periodic system as a paper tool.

[29] See also Robinson in this issue.

tour de force was the prediction of missing elements. She credited Meyer with constructing a system that included all known elements and for organizing them according to the periodicity of their chemical properties (such as valency or atomicity) and physical properties (for instance atomic weight) – and for persevering over the years to improve and refine that system. Mendeleev's feat was described by Noddack in lyrical terms: by imagining gaps in the system while he was constructing it, Mendeleev also attempted to define the possible features of these elements. Meyer devised an organizational tool; Mendeleev went beyond this and used periodicity as a heuristic principle – a guiding tool which could be used to predict and discover, rather than merely describe the existing relationships between elements.[30] Indeed, Noddack described Mendeleev as a "romantic of chemistry" and went so far as to describe his ability to predict and even compute the expected characteristics of an unknown element from the characteristics of the neighboring elements as "prophesying." Noddack's enthusiasm reflected her own use of the periodic system while she was looking for the manganese homologues.[31] Meitner also mentioned Mendeleev's predictions as brilliant intuition but then immediately explained Mendeleev's luck that the atomic weights were, in the first approximation, increasing at the same pace as the atomic number (not yet used in his time), which allowed his predictions to be met. From such a starting point, therefore, it is clear that the main point of Noddack's discussion of the periodic system would be the gaps in the periodic system, whether they were the elements still missing in the core of the table before uranium or those coming after it, the so-called transuraniums. When dealing with the sub-atomic particles, as we will show in the next section, the question would be whether or where to insert these particles in the system, and ultimately, whether a new system would be necessary.

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[30] Bensaude-Vincent (1986) has made exactly this point, explaining that Mendeleev intended to come up with a natural law that was useful beyond describing the current empirical state of art. See also Bensaude-Vincent in this issue.

[31] Tacke (1925b, p. 365).

In the opening sentence of her presentation, Lise Meitner acknowledged atomic weight as the defining characteristic of the elements from the time the periodic system was set up, but already in the first paragraph she emphasized that the *Platzzahl* (the numbered place in the periodic system) was in fact dependent on the positive charge of the atomic nucleus (and thus also the number of negative electrons surrounding it). She clearly had a presentist view on Mendeleev's achievement. Meitner took the opportunity to explain that atomic weights cannot give unique information about the chemical properties of elements, since isotopes of different elements can have the same atomic weight. To determine the chemical properties, she remarked, only one characteristic constant is needed, and that is the number of electrons orbiting around the nucleus, which is provided by the atomic number. Characterizing the atomic nucleus, however, requires two characteristic constants: the positive nuclear charge and the atomic weight. Atomic number, *Ordnungszahl* (Z), was introduced in the mid-1910s and has been in scientists' consciousness ever since then, but the final approval by the International Committee on Atomic Weights of the International Union of Pure and Applied Chemistry (IUPAC) was given only in 1923. Despite the fact that atomic numbers had long been in use in 1934, Meitner did not place much emphasis on the numbers as such. Instead her focus was on the sub-atomic particles themselves. In the remaining five pages of her article (of the six pages total), Meitner explained the nature of the nuclear particles, what they signify, how one could deduct the number of particles from other constants and the relationship between energy and matter, $E = mc^2$.

After briefly mentioning the atomic weight determinations by the Swedish chemist Jöns Jacob Berzelius (1779-1848) in the nineteenth century, Meitner gave an account of experiments from the twentieth century, providing knowledge about the nuclear particles. The experiments included the discovery of protons by Ernest Rutherford (1871-1937) and the recent (1932) discovery of the neutron by the British physicist James Chadwick (1891–1974).

She paid particular attention to natural (spontaneous) and artificial (induced) nuclear reactions, the energy accounting related to these reactions, and whether or not stable atomic nuclei were formed during these processes. Meitner informed the readers that there were approximately 200 known stable isotopes of the 92 elements, to which must be added a range of radioactive isotopes.

Ida Noddack, as the chemist, included on the very first page of her article a traditionally depicted periodic system in the so-called long form, with 18 columns (Figure 1), and used it to explain periodic trends and the efforts to find new elements. She, too, acknowledged the revolution represented by the developments in atomic physics and the shift from atomic weight to atomic number. She nevertheless dedicated most of her article to the still unconfirmed elements, numbers 61, 85 and 87. Radioactivity was just one of the many means researchers had at their disposal to find, characterize and isolate these elements. The conception of matter exhibited by the two and half pages devoted to the quest for the missing elements was compatible with the longstanding tradition of wet chemistry as a purifying and extracting activity. Noddack's approach was rooted in the "real" sense-perceptible world and included ores, material interactions and enrichment procedures, geochemical theories of the making of the earth, and consequently the local manifestation or existence of the elements according to their appearance in the Earth's crust. Thus situated, Noddack approached matter only through sense-perceptible experiments performed in the laboratory that required a narration of the procedures.

Figure 1. Periodic system presented by Ida Noddack in her article in *Angewandte Chemie* in 1934. It is worth noting that element 43 is named "Ma" for masurium – the name proposed in 1925 by Ida and Walter Noddack for a discovery which they were unable to substantiate or confirm later. Blank spaces included elements 61, 85 and 87 as well as the transuranium elements 93-96. From Noddack (1934), p. 301.

By contrast, Meitner regarded matter as absolute and ubiquitous, and something which could seemingly be produced at will through nuclear processes and manifested with so-called cloud chambers (explained below) and other radioactive measurements. Her take on material reality is illustrated by a few photographs depicting nuclear disintegration, for which she provided captions. The captions always included an element and a subatomic particle, thus telling the story of a nuclear process created in laboratory. This short version of the narrative was developed in the text using two different formats: sentences and equations of nuclear processes. The latter never appear in Noddack's article.

The role of the neutron and elementary particles: what is elemental?

"If we assume that the three gaps we have discussed for the atomic numbers 61, 85 and 87 have been filled," said Ida Noddack, "would the system then be complete?"[32] To answer this question, Noddack started considering the lighter end of the periodic table; that is, what could come before hydrogen. Could the electron be a candidate for one of these lighter elements, for instance? Her treatment of the question reveals an ambiguity about the defining characteristic of elements. By removing an electron from an atom, Noddack argued, a charged atom – an ion – could be created, and in that sense the electron was responsible for causing a change in chemical properties of the element. Furthermore, the electron had mass, although it corresponded to as little as 1/1800 of the mass of hydrogen. In the end, however, Noddack came back to the inseparable association (emphasized by Meitner) between element and positive nuclear charge, of which the electron naturally had none. Consequently, it was dismissed as a chemical element. The fact that Noddack even discussed the electron as a possible element suggests that not all chemists at the time – particularly those entrenched in

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[32] Noddack (1934, p. 304).

the wet chemical and sense-perceptible tradition – unequivocally embraced atomic number as the defining characteristic of elements.

The role of mass appeared even more clearly in Noddack's discussion of the neutron. She found the fact that the neutron had the mass of the hydrogen nucleus a potential argument in favor of seeing the neutron as an element. [33] Indeed, to chemists, neutrons were still unsubstantial and bodyless (*etwas Wesenloses*), and because they did not possess orbiting electrons, they could not possess any chemical properties either. But in Noddack's view, this could only be a transient rule that might change in the future, since understanding of the neutron was still in its infancy. She maintained that one could not exclude the fact that slow neutrons might reorganize chemical bonds as much as cause nuclear "fragmentation" (*Kernzertrümmerungen*). [34] Again, the role of the elementary particle was seen as impacting chemical interactions or the speed of chemical reactions. The nuclear processes, though not ignored, were not considered within traditional chemistry that remained at the core of Noddack's vision of the periodic system.

The discovery of elementary particles was just taking off. When a fast-moving charged particle passes through the supersaturated vapor contained in a cloud chamber, tracks remain visible as the water condenses around the ion trails left behind. By subjecting the chamber to a magnetic field, it is possible to deduce the charge and the mass of the particle. In 1932, the American physicist Carl David Anderson (1905–1991) observed the track of a high-energy particle with a mass about the same as an electron's but with a positive charge, which he later

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[33] Noddack's speculations on the neutron as element 0 were close to the Estonian-born German chemist Andreas von Antropoff's (1878-1956) idea of neutronium, suggested in 1926 (von Antropoff, 1926). Her speculations also bear quite some similarity to Dmitri Mendeleev's table of 1904, in which he added two new elements, named x and y. Placed above helium, x could be the ether which he called newtonium, while y, which was above neon, was placed in the zeroth group and called coronium. Mendeleev's chemistry of ether was an attempt to explain radioactivity in terms that would maintain the untransmutable nature of elements. See Kragh (1989) and Labarca (2016).

[34] Tacke (1925b, p. 304). Note that this refers to fragmentation as a general idea, not yet fission, although it does not exclude it *per se* since there is no restriction as to the size of the fragments.

named the positron. In Noddack's opinion, positrons differed from neutrons, especially since they were so short-lived; they existed for only 10^{-9} seconds before combining with (negative) electrons. But if more long-lived positrons existed, what role could they exercise in their interaction with matter? She thus concluded that a time might come when the chemist would have to deal with "intruders" such as the neutron and even the positron.

To Meitner, these particles were not intruders at all; on the contrary, in her opinion they allowed for a better exploration of the periodic system. Over several pages, she provided a review of the different nuclear processes and used reaction schemes similar to chemical equations, in which alpha particles, neutrons, protons, electrons and positrons were on the same footing as nuclides (not elements). For instance, Meitner described the artificial radioactive process revealed by Irène (1897–1956) and Frédéric Joliot-Curie (1900–1958) in her paper as follows:

[equation image to be inserted here]

(Al –an aluminium nuclide, α – the alpha particle, P – a phosphorus nuclide, n – the neutron, Si – a silicon nuclide, and e^+ – the positron; the subscript number provides the atomic number, while the superscript gives the atomic mass.)

From the use of the two characteristic numbers (atomic weight and atomic number) in the equation (on which she had insisted earlier in her article), it followed quite naturally and without much discussion that the neutron could be the element with atomic number zero.[35] The investigation of these processes as well as their systematization was described with enthusiasm by Meitner as the beginning of a "chemistry of the nuclei."[36] Indeed, the new physics of the atom provided scientists with more than simply a tool to explain the periodic law; it also gave rise to renewed explorations of what an element is and whether, as several chemists had suggested before the 1930s, elements lighter than hydrogen could exist.[37]

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[35] Meitner (1934, p.738).

[36] Meitner (1934, p. 737).

[37] See also Kragh in this issue.

The future of the periodic system in light of the past

While celebrating Mendeleev's 100th anniversary, Noddack and Meitner provided their own views on the periodic system and its role in their quest to understand matter. Meitner had resolutely chosen the subatomic particles to play the pivotal role of explaining nuclear reactions and serving as tools to investigate matter. For Noddack, the appearance of "intruders" added to the problem posed by the multiplication of isotopes. According to the contemporary notions of the day, elements were a mix of isotopes, which she called *Einzelelemente* (individual elements).[38] The field of chemistry was informed by modern physics that the outer shell of electrons inside the atom characterized the elements and provided them with their specific chemical properties, and therefore isotopes were chemically inseparable. However, the (recent) successful separation of hydrogen and deuterium by Edward W. Washburn (1881–1934) and Harold C. Urey (1893–1981) achieved less than two years before her publication, demonstrated in Noddack's eyes that this was a dogma that would soon fall to pieces.[39] The difference in atomic weight between the hydrogen isotopes would inevitably have to translate into slight differences in reaction velocity. Noddack inferred that even though such a 100% difference in atomic weight would not exist between isotopes of any other chemical element than hydrogen, in principle weight differences should impact chemical behavior and eventually open the way for chemical separation.

Noddack's choice of the term "intruder" emphasizes the potential to jeopardize an order that had been achieved through the periodic system. In her popular account of chemistry, published in 1942, both Noddack's historical overview of chemistry and her description of the aim and specialization of chemistry provide a few further clues about her views on the

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[38] *Einzel* may also translate into 'single' which reinforces the idea that isotopes are not a mix compared to elements.

[39] Washburn and Urey (1932).

elements. She proclaimed as her starting point that matter is defined by the fact it can be weighed (*Für den Chemiker ist alles das Stoffe, was der wägen kann*), and that the characterization of that matter has to include not only the properties the substance displays but also those properties the substance does not exhibit.[40] In her historical account, she saw the move towards the basic substances (*Grundstoff*e), which are precisely described substances kept unchanged through chemical reactions, as the turning point of the 18th century. According to Noddack, these chemical elements are the building blocks of the chemical world, many of which were found through chemical analyses of natural substances during the nineteenth century.[41] She did not use the term *Einzelelemente* in her popular booklet, but interestingly, when describing the three (classical) subdisciplines of inorganic, organic and physical chemistry, she insisted on the primacy of analytical chemistry as the operative method for all fields of chemistry. One example of this use is her assessment of purity and the search for even minute impurities.

While there is no expression of political or ideological inclination to be found, the subtext is nevertheless in agreement with the *Deutsche Chemie* program, which had a weaker impact than the better known *Deutsche Physick*. [42] For instance, the framing of chemistry as *Lehre der Stoffe* clearly connects to Conrad Weygand's (1890-1945) book published at the same time.[43] The dawn of nuclear science was unsettling for Noddack within this frame, as it dethroned the individuality of elements in favor of her so-called "intruder" newcomers, which demanded a new order.

The future would be a new natural system in which all *Einzelelemente* would be related to each other in a cogent way. It would be a system, Noddack insisted, that like Mendeleev's

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[40] Noddack (1942, p. 9-10).

[41] Noddack (1942, p. 28).

[42] On the «Deutsche Chemie», see Bechstedt (1980), and Deichmann (2001).

[43] Weygand, Conrad (1942).

would be able to identify gaps and predict the existence of still unknown “elements.” The lyrical reverence expressed at the start of her paper came back as she extrapolated that the periodic system would be replaced by a new system encompassing all the different aggregations of the elemental bricks, including those not yet observed. Noteworthy is her use of the term ‘aggregation’, which left the interpretation of the natural forces at play wide open and obviously not limited to chemical reactions.

Ironically, the result of mapping isotopes as specific species is precisely the chart of nuclides,[44] and the only figure representing the periodic system in Meitner’s paper was constructed as a discrete plot by the German-American biophysicist Max Delbrück (1906-1981), an assistant to Lise Meitner from 1932 on. To illustrate the distribution of known stable and unstable nuclei, he set up a schematic presentation of nuclei of elements 1 (hydrogen) to 20 (calcium) (Figure 2). The atomic number was given on the horizontal axis (Z, also the number of protons), while the number of neutrons in excess of the number of protons was provided on the vertical axis. Since the plot was limited to all isotopes up to calcium, it thus did not cover all 200 stable isotopes that populated the periodic system, to which were added the growing number of unstable isotopes.[45]

Figure 2. Diagram by Max Delbrück used by Lise Meitner in her article in *Die Naturwissenschaften* in 1934. Nuclei up to element no. 20, calcium on the horizontal axis and the number of neutrons exceeding the number of protons in the nuclei on the vertical axis. From Meitner (1934, p. 736).

Isotopes, however, were not all the same, depending on their stability. This is not only discussed in the text but is clearly expressed in Delbrück’s representation of a portion of the

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[44] Guggenheimer (1934), see graph on p. 254 which bears close resemblance to Delbrück’s figure provided by Meitner, except that the horizontal axis simply counts the number of neutrons (not the number of neutrons in excess of the number of protons). Similar tables were published by Fea (1935), with the axes switched. Guggenheimer’s presentation is the one still in use for charts of nuclides today.

[45] Meitner (1934, p.736). The same plot can also be found in Meitner and Delbrück (1935, p. 29).

periodic system that Meitner used, in which the unstable species were represented by an empty circle while the stable isotopes were marked with a filled circle (Figure 2). This representation provided a visual reference of all nuclei of the selected elements and the nuclear processes that allowed scientists to navigate the many possible transmutations from one isotope to another. As such it provided a useful organizational system. However, it did not yet allow for predictions about the existence (or non-existence) of isotopic species, or their stability or lifetime. The representation was nevertheless considered to be a powerful exploratory tool, and at the end of her contribution Meitner mentioned Fermi's experience of bombarding uranium nuclei with neutrons, believing that he was producing elements with atomic numbers higher than 92. Instead of disintegrating Mendeleev's system, the new developments in nuclear physics would come as a consolidation, and to some extent the periodic system would remain a safe foundation to build on.

Conclusion

Though both Meitner and Noddack worked on elements and presented a review of the periodic system for the centennial of one of its founders, one could hardly have picked more contrasting actors to provide us with a glimpse into the way the periodic system has been perceived and used: Austrian-Jewish born versus German suspected Nazi sympathizer, single versus married, professor and research team leader versus unpaid guest researcher, and last but not least, radiophysicist versus chemist grounded in the analytical tradition. What can we learn from these contrasting presentations of the periodic system? One quick interpretation is that, as Meitner expressed it so clearly, Mendeleev left enough space for new discoveries and for further understanding of the nature of matter. In that regard, and also coming back to her initial statement, she was convinced that the true constitution of atoms had at last been elucidated, and that the genius of Mendeleev was to construct a system with enough latitude –

German *Spielraum* – for its successors. To some extent, Meitner's admiration relates to the idea of robustness and the common appreciation that Mendeleev's intuition had been confirmed and even explained by contemporary chemistry and physics.

But *Spielraum* goes beyond robustness and explicitly opens the door to the user's perspective. Despite their differences, both Noddack and Meitner were looking at the same objects (the periodic system, the elements, the particles), but with different programs concerning the understanding of matter and its investigation. Their differing usage demonstrates these distinctions, which were all supported by the same periodic system.

The two women scientists chose to provide their readers with starkly contrasting graphical representations. As emphasized in this article, Noddack used the traditional periodic table. Each element was set in a closed box and defined through its relationship with other elements. In particular, the periodicity allowed Noddack to evaluate and infer the chemical and physical properties from interpolating neighboring elements. But these elements were all distinct individuals, and that is where the existence of isotopes became a problem, despite the official shift from atomic weight to atomic number that had occurred eleven years earlier. Her naming of isotopes as "individual elements" (*Einzelelemente*) is a clear signature of that conception. Noddack did acknowledge the underlying subatomic structure, but how it related to the periodic system and the periodicity were far from obvious. She understood these in terms of the ultimate building blocks, and therefore particles such as the neutron should become part of the periodic system, but accepting this would mean the dissolution of Mendeleev's order. While she did not put it into writing, the crisis echoes a larger preoccupation of order, as well as the definition and the right place of individuals in the order conveyed by Nazism.

That problem did not occur to Meitner, who was the antipodes of Noddack both ideologically and scientifically. Overall, Meitner did not speak much about elements but more about isotopes, and that is probably why her only representation was more similar to the nuclide charts we are familiar with today. However, unlike the nuclide charts, the individual species in Meitner's diagram were dots on a grid, not elements in a box (which would clearly have been Noddack's approach). These individuals were connected through arrows that expressed the respective nuclear processes, allowing for chess-like moves between the dots on the grid. This is in line with Meitner's first acquaintance with the world of elements, as she and Hahn were pursuing the detection and isolation of the "mother substance" of actinium. The methods and the research program of the "radioactivists" did in fact have a more profound impact on what defined the element as an individual: for Hahn and Meitner, individuals could be engendered through nuclear processes and embedded in a series of transmutations, while for Noddack and her co-discoverers Walter Noddack and Otto Berg, the only network in which elements were integrated was the periodic system that organized their properties and created a network of families and neighbors.

This shows that the discrepancy in the use of the periodic system did not emerge first in the 1930s but was already very much in place at the turn of the century, and the two uses coexisted without much problem. The periodic system was thus able to accommodate much more than elements – it made room for different understandings of what elements are and how they relate to each other, which is the *Spielraum* depicted by Meitner.

Similar to the process of resilience, the system was able to face stress and recover by rearranging itself, while previous acceptances were not lost. This has further ramifications for the use of the periodic tables, especially in pedagogical contexts, but also for the history of the periodic system. In fact, if resilience is considered to be the most salient feature of the periodic system, then one can predict not only that it has a future, but also that the multiplicity of its representations will continue to proliferate as new accommodations and understanding require, bearing witness to its endurance.

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