Foundations of Chemistry (2020) 22:137–146
https://doi.org/10.1007/s10698-019-09348-1

Reporting the discovery of new chemical elements: working in different worlds, only 25 years apart

K. Brad Wray[1] **· Line Edslev Andersen**[1]

Published online: 3 October 2019

Abstract
In his account of scientific revolutions, Thomas Kuhn suggests that after a revolutionary change of theory, it is as if scientists are working in a different world. In this paper, we aim to show that the notion of world change is insightful. We contrast the reporting of the discovery of neon in 1898 with the discovery of hafnium in 1923. The one discovery was made when elements were identified by their atomic weight; the other discovery was made after scientists came to classify elements by their atomic number. By considering two instances of the reporting of the discovery of a new chemical element 25 years apart, we argue that it becomes clear how chemists can be said to have been responding to different worlds as a result of the change in the concept of a chemical element. They (1) saw, (2) did, and (3) reported different things as they conducted their research on the new chemical elements.

Keywords Chemical element · Discovery · Thomas Kuhn · Neon · Hafnium · World changes · Theory change

In his account of scientific revolutions, Thomas Kuhn suggested that after a revolutionary change of theory, it is as if scientists are working in a different world. Revolutions, Kuhn explained,

> cause scientists to see the world of their research-engagement differently. In so far as their only recourse to that world is through what they *see* and *do*, we may want to say that after a revolution scientists are responding to a different world. (Kuhn 1962/2012, 111; emphases added)

The notion of world change caused problems for Kuhn. As James Marcum notes, "Kuhn's world-change thesis … is … one of his most radical and controversial ideas" (Marcum 2015, 69–70; see also Hacking 1993, 275–276). And Richard Grandy claims that, "of all the controversial elements in *The Structure of Scientific Revolutions* (1962/1970), the

✉ K. Brad Wray
kbwray@css.au.dk

Line Edslev Andersen
lea@css.au.dk

1 Centre for Science Studies, Aarhus University, Ny Munkegade 118, 8000 Aarhus C, Denmark

most controversial and problematic for the majority of readers are Kuhn's claims about the changes in the world that accompany scientific revolutions" (Grandy 2003, 246).[1] Even though Kuhn refined his view of scientific revolutions, replacing the problematic notion of a paradigm change with the notion of a lexical change, he seems to have remained committed to the idea that scientific revolutions involve world changes of some sort. His final unfinished book manuscript, after all, was tentatively titled *Plurality of Worlds: An Evolutionary Theory of Scientific Discovery* (see Nickles 2003, 11; also Hoyningen-Huene 2015, 190).[2]

In this paper, we aim to show that the notion of world change *is* insightful. Specifically, we examine in what sense we may speak of a world change in terms of what scientists see and do through a study of two similar discoveries made on either side of a significant change of theory, specifically, the discovery of new chemical elements before and after chemists came to classify chemical elements by their atomic number.

Recently, K. Brad Wray has argued that there was a Kuhnian revolution in chemistry in the early twentieth century, when chemists came to classify the chemical elements by their atomic number rather than by their atomic weight, as the practice was previously (Wray 2018). Wray acknowledges that the periodic table of chemical elements remained largely unchanged before and after the revolution. Most of the elements retained their same place in the table before and after the revolution. But Wray insists that there was a significant change in the lexicon that chemists used. In this sense, the change constitutes a Kuhnian revolution.

In order to examine in what sense the world changes with a change of theory, we propose to examine the case of the change in the concept of a chemical element in more detail, focusing narrowly on the reporting of the discovery of two new chemical elements. We will contrast the reporting of the discovery of neon in 1898 with the discovery of hafnium in 1923. These discoveries straddle the chemical revolution that Wray claimed happened in early twentieth century chemistry. By considering two instances of the reporting of the discovery of a new chemical element 25 years apart, it becomes clear how chemists can be said to have been responding to different worlds as a result of the change in the concept of a chemical element. They (1) saw, (2) did, and (3) reported different things as they conducted their research on the new chemical elements. So our paper not only aims to provide support for Wray's claim about a revolution in early twentieth century chemistry. It also aims to employ the Kuhnian notion of world changes in a fruitful way.

The discoveries reported

Let us begin by examining how the discoveries were reported. The discovery of neon was announced in 1898 in a short paper published in the *Proceedings of the Royal Society of London*, by Ramsey and Travers (1898). The discovery of hafnium was announced in an

[1] Paul Hoyningen-Huene provides a useful reminder that we need to distinguish between two different meanings of "world" in *Structure*, the world in itself and the phenomenal world (see Hoyningen-Huene 1989/1993, 31). Hoyningen-Huene devotes a whole chapter to the distinction. Ian Hacking also tries to provide a sympathetic gloss on the notion of living and working in a new world after a scientific revolution (see Hacking1993).

[2] In a recent article, Paul Hoyningen-Huene lists the various titles that Kuhn had given his final manuscript over the years as he worked on it. Hoyningen-Huene claims that he (that is, Paul) "liked [*The Plurality of Worlds*] best because it picks out what I called the plurality-of-phenomenological-worlds thesis, which I assessed as a 'fundamental assumption of Kuhn's theory' (Hoyningen-Huene 1993, p. 26)" (see Hoyningen-Huene 2015, 190).

even shorter paper published in the journal *Nature*, by Coster and Hevesy (1923). Only 25 years separate the two discoveries. Yet the way in which the discovery of each element was reported is strikingly different in a number of respects.

Neon is one of the noble gases. Eric Scerri notes that "almost nobody, including Mendeleev, had predicted or even suspected the existence of [this] entire family of new elements" (see Scerri 2007, 151).[3] Hafnium was one of the seven predicted-but-missing elements after the chemical elements came to be identified by their atomic number (see Scerri 2007, 173). Let us look in detail at the reporting of each of these discoveries.

The report of the discovery of neon begins with a concern about the nature of argon, the first of the noble gases to be discovered, only 4 years earlier, in 1894 (see Scerri 2007, 151). The authors report concerns that led them to believe that argon, a recently discovered element, may be a mixture (see Ramsey and Travers 1898, 437). Specifically, they note that "experience with helium taught us that it is a matter of the greatest difficulty to separate a very small portion of a heavy gas from a large admixture of a light gas" (see Ramsey and Travers 1898, 437).

The report also includes an account of the *methods* used to isolate the new element (see Ramsey and Travers 1898, 437–438). It was their concern about the nature of argon that led Ramsey and Travers to the new element. They discovered it in the process of obtaining argon from liquid air by "causing the liquid air to boil under reduced pressure" (Ramsey and Travers 1898, 437). In this process, Ramsey and Travers explain, "the argon separated as a liquid, but at the same time a considerable quantity of solid was observed to separate partially around the sides of the tube, and partially below the surface of the liquid" (Ramsey and Travers 1898, 437). Ramsey and Travers could isolate the solid below the surface of the liquid argon because, as they allowed the air pressure to rise, the liquid argon volatized before the solid. The gas obtained by the volatilisation of the solid needed further purification. Ramsey and Travers explain that the "gas was mixed with oxygen, and sparked over soda. After removal of the oxygen with phosphorus it was introduced into a vacuum-tube" (Ramsey and Travers 1898, 438).

The authors go on to report the tests they conducted on the gas in the vacuum-tube to determine that it was in fact a new gas, and not some other already known gas. The authors begin by reporting some *qualitative* results: the spectrum of the gas "was characterized by a number of bright red lines, among which one was particularly brilliant, and a brilliant yellow lobe, while the green and blue lines were numerous, but comparatively conspicuous" (Ramsey and Travers 1898, 438). There is then a *quantitative* report of the wavelength of the yellow line, including an identification of the person who measured it.[4] The

[3] The discovery of the noble gases was quite significant, even threatening to some extent. Scerri notes that "once [the noble gases] had begun to be discovered, it was immediately understood that the existence of [these] gases might pose a threat to the periodic system. Indeed, a failure to incorporate them might have led to an abandonment of the periodic system, regardless of the earlier successes achieved" (Scerri 2007, 151). Scerri's discussion of "the public announcement of the argon problem" provides insight into the sorts of challenges that argon seemed to raise for chemists (see Scerri 2007, 152–154). For Mendeleev's reaction to the unexpected discovery of argon, see Scerri (2007, 154–155). Mendeleev described the discovery and accommodation of the noble gases into the periodic table as "a 'critical test'" of the periodic system (see Scerri 2007, 156).

[4] Cyril Baly is the person, though he is identified merely as Mr. Baly, except at the end of the article where he is identified as Mr. E. C. C Baly. Interestingly, Baly may have separated isotopes of oxygen before the realization that they existed (see Donnan 1948, 9). Baly is not the only person to be mentioned by name in the report for their contribution to this discovery. William Hampson is also mentioned, having "placed at [Ramsey and Travers'] disposal his resources for preparing large quantities of liquid air" (see Ramsey and Travers 1898, 437).

value was 5849.6 in "a second-order grating spectrum" (see Ramsey and Travers 1898, 438). This enabled Ramsey and Travers to determine that the new element was "not identical with sodium, helium, or krypton" (Ramsey and Travers 1898, 438).

The authors also report other tests they conducted to determine that the new gas was in fact a new gas. For example, they measured the density of the gas to be 14.67 but they note that, "in order to bring neon into its position in the periodic table, a density of 10 or 11 is required" (Ramsey and Travers 1898, 438). Still, since some argon will have remained in the bulb with the new gas, and since argon has a higher density than neon, the result is consistent with the gas being a new noble gas. So the characterization of this new gas, and the securing of its identity, was done through a series of laboratory operations. The various laboratory operations were conducted in an effort to distinguish the new gas from various already known gasses.

Perhaps the most striking fact about the report of the discovery of hafnium is that the report focuses on information about the X-ray spectrum of "extractions of zirconium minerals," the source of the sample of the new element (see Coster and Hevesy 1923, 79). The authors report values for six lines, designated: $L\alpha_1$, α_2, β_1, β_2, β_3, and γ_1. This notation, they note, parenthetically, is Siegbahn's notation, a notation that was developed less than 10 years before, in 1916 (see Siegbahn 1916).[5] The values that they measured for these lines is what enabled the authors to secure the identity of the new element. As they explain, "the values which we obtained for the wave-lengths of the six mentioned lines all agree within one Xu with those found by interpolation" (see Coster and Hevesy 1923, 79). This method of identification, they acknowledge, builds on Moseley's "discovery of the fundamental laws of the X-ray emission" (see Coster and Hevesy 1923). Again, Moseley's discovery was made in 1914, 16 years after Ramsey and Travers discovered neon (see Scerri 2007, 171).[6]

Two chemical worlds

Interestingly, these reports of the discovery of new elements were made only 25 years apart. But chemistry had changed markedly in that time period. Atomic number had become recognized as the essential characteristic of chemical elements instead of atomic weight, thanks to the work of a number of chemists, including, perhaps most importantly, Henry Moseley. And isotopes were recognized to exist. Isotopes are variants of the same element that differ in atomic weight because the samples contain different numbers of neutrons (see van Spronsen 1969, 8). The existence of isotopes is irreconcilable with the idea that chemical elements are defined by their atomic weight (see Scerri 2007, 73; also Wray 2018). As Thornton and Burdette explain, "the idea that different substances could appear to be chemically identical was nearly heretical in the early twentieth century" (see Thornton and Burdette 2017, 125). This fact, that samples of the same element can differ

[5] Incidentally, Karl Manne Siegbahn had also weighed in on an earlier claim by a French team to have discovered the missing element with atomic number 72. Siegbahn was "a leading spectroscopist who had further developed Moseley's methods … [he] examined the [French team's] plates and concluded that no lines were actually present" (see Scerri 2013, 88).

[6] Interestingly, the discovery of hafnium gave rise to a somewhat lengthy and acrimonious priority dispute, first between Coster and Hevesy and the French team, discussed earlier, and then between Coster and Hevesy and Alexander Scott (for the details of this, see Scerri 2013, 91–95).

in atomic weight, escaped the attention of chemists until the concept of isotope was developed by Frederick Soddy in the early twentieth century (see Soddy 1913, 1923; Scerri 2007, 177–178; also Thornton and Burdette 2017, 125).[7]

Hence, Ramsey and Travers worked with a fundamentally different conception of a chemical element in 1898 than Coster and Hevesy worked with in 1923. The conception of chemical element that Ramsey and Travers worked with, which was based on atomic weight, precluded the possibility of isotopes, for example.

The change in the concept of a chemical element is reflected in the reports in the fact that both pairs of chemists produced a spectrum of a chemical element, but they saw very different things when looking at the spectra. Granted, one reason why they saw different things when looking at the spectra was simply that the two spectra *were* in fact of different types. Ramsey and Travers had produced an optical spectrum, while Coster and Hevesy had produced an X-ray spectrum. Whereas "optical spectra result from outer or valence electrons … X-ray spectra involve the excitation of inner electrons" (see Scerri 2007, 314, n. 14). But the principal reason why the two pairs of chemists saw different things when looking at the spectra was that they were working with different conceptions of a chemical element.

Coster and Hevesy saw evidence of electron excitations in the spectral lines, and from the spectral lines they could determine the atomic number of the element. In the very first sentence of the report, they thus mention Moseley's "discovery of the fundamental laws of the X-ray emission" (Coster and Hevesy 1923, 79). These laws determine the atomic number of an element based on the spectrum of the element (see Scerri 2007, 170–172). The scientists interpreted the spectral lines as indicating the atomic number of the element.

Ramsey and Travers did not see evidence of electron excitations when looking at their spectrum. In fact, the electron was only recognized to exist in 1900, 2 years after they reported their discovery (Heilbron 2005, 24). When looking at their spectrum they merely saw the emission of light from the sample of the element they were looking at. They did see in the pattern of the emitted light the "unique spectral fingerprint" of the element, to use Scerri's apt phrase (see Scerri 2007, 67). But the connection between spectral lines and the structure of an atom was not established until later (Heilbron 2005, 24). In fact, at the time of the publication of their report, there was no planetary conception of the atom. Such a conception of the atom was not suggested until 1901 by the French physicist Jean Perrin (see Scerri 2007, 184). While it was known at the time that the spectrum represents a unique fingerprint of a chemical element, none of the atomic models available could explain why. In particular, the spectral lines were not connected in a systematic way with what Ramsey and Travers considered to be the defining feature of an element, the atomic weight.

Hence, we may say that the two pairs of chemists *saw* different things when looking at the spectra, in part, due to the difference in their conception of a chemical element. Coster and Hevesy's concept of a chemical element as determined by atomic number made them see something fundamentally different in their spectrum than Ramsey and Travers saw in their spectrum.

There is another sense in which the two pairs of chemists saw different things when looking at the spectra. With the change in the concept of a chemical element came a

[7] The significance of the discovery of isotopes to chemistry cannot be overestimated. Thornton and Burdette argue that "the natural breakpoint between chemistry and physics is best seen, described, and understood through the discovery and elucidation of isotopy in the early twentieth century" (2017, 120). They suggest that there were possible alternative courses of development that could have unfolded, courses different from the actual course that chemistry took.

change in the conception and understanding of the ordering of the chemical elements in the periodic table. Once the elements that were known were ordered according to atomic number, it became clear what elements still needed to be discovered (see Scerri 2007, 173). This is a very different situation from when Ramsey and Travers discovered neon. As Scerri explains,

> while chemists had been using atomic weights to order the elements there had been a great deal of uncertainty about just how many elements remained to be discovered. This was due to the irregular gaps that occurred between the values of atomic weights of successive elements in the periodic table. This complication disappeared when the switch was made to using atomic number. Now the gaps between successive elements became perfectly regular, namely one unit of atomic number. (Scerri 2011, 80)

Ramsey and Travers knew where they wanted the element to go in the order of the elements. But this did not give them an exact number for how much the element must weigh. Thus, Ramsey and Travers wrote that, "in order to bring neon into its position in the periodic table, a density of 10 or 11 is required" (Ramsey and Travers 1898, 438).

For Coster and Hevesy the spectrum did not only convey the atomic number of the element. For them, the spectrum was also a piece in a 92-piece jigsaw puzzle where it is clear what all the pieces are going to look like and which are missing. Here, of course, the jigsaw puzzle represents the periodic table and the pieces the spectra or chemical elements. At the time, the jigsaw puzzle was almost complete. Only a few pieces were missing. Coster and Hevesy recognized the spectrum they produced as the particular missing piece in the jigsaw puzzle they were looking for. Indeed, that they knew *exactly* what they were looking for is clear from the title of their report, 'On the Missing Element of Atomic Number 72'.

While Coster and Hevesy had discovered *the* missing element of atomic number 72, Ramsey and Travers had merely found *a* new element. Ramsey and Travers could not conceive of their spectrum or element as a missing jigsaw puzzle piece. In fact, they spend much time describing how the element they had discovered is in various ways different from the elements that had already been discovered. Thus, while Coster and Hevesy argued that their element *was* the missing element in place 72 of the periodic table, Ramsey and Travers argued that their element was *different from* the elements that had previously been discovered. These are quite different claims. We return to this difference in the next section.

To conclude, we have described a sense in which we may say, in the words of Kuhn, that "these men really [did] *see* different things when looking at the same sorts of objects" (see Kuhn 1962/2012, 120; emphasis in original). In this particular sense, Ramsey and Travers can be said to have worked in a different world than Coster and Hevesy. There seems to have been the type of shift of perception that, according to Kuhn, accompanies a scientific revolution (see Kuhn 1962/2012, 114–115).

Experimentation in the two chemical worlds

In the previous section, we argued that the two sets of chemists saw different things when looking at their spectra as a result of the change in the concept of a chemical element. In this sense we may speak of the scientists as working in two different worlds. In this section we will examine in detail how the *experiments* they conducted were different, also as a result of the change in the concept of a chemical element. Significantly, not only are the two sets of chemists separated by the instruments they used in their research. They are also separated by the procedures they sought to employ in their efforts to secure the identity of their new discovery. This provides an additional reason for Kuhn's remarks about responding to different worlds before and after a revolutionary change of theory.

Due to their concept of an element as determined by atomic number, Coster and Hevesy knew exactly what missing element they were looking for: the element with atomic number 72. Since they were looking for the element with atomic number 72, they employed a procedure for determining the atomic number of the sample they were looking at. More specifically, they produced an X-ray spectrum of the sample from which they could determine its atomic number. In fact, this was a means of unequivocally showing that the element had exactly number 72 (see Scerri 2013, 84). X-ray technology was invented and developed in the years between the publication of the two reports, and it played an essential role in the more theoretical developments in chemistry, like the discovery of atomic number in the first place. Hence, what enabled Coster and Hevesy to secure their claim to having discovered a new element was the report of measurements of various lines in the X-ray spectrum.[8] Coster and Hevesy produced a spectrum of which they could write that the lines were in "exact agreement with the expectation" both with respect to "their mutual distance and their relative intensity" (Coster and Hevesy 1923, 79).

Coster and Hevesy's concept of an element as determined by atomic number makes it relatively simple, in some respects, to discover a new element, since they have available a very reliable way of determining atomic number. Their concept of an element as determined by atomic number makes their experimental situation simple in the sense that if one combines their concept of an element with the experimental methods available at the time, one gets a straightforward recipe for how to determine whether a given sample is a new element. Even if the experimental work is challenging, the goal is quite precise.

By contrast, Ramsey and Travers' concept of an element as determined by atomic weight does not offer simple, unequivocal guidance for how to determine whether a given sample is a new element. One certainly does not get a recipe for how to discover a new element by combining their concept of an element with the experimental methods that they had available. As described in the previous section, due to their concept of an element as determined by atomic weight, Ramsey and Travers could only give an approximate description of the element they were looking for: an element with a density of 10 or 11. Still, they were guided by their concept of an element as determined by atomic weight in that they employed a procedure for determining the density of the new gas they had isolated. But not only did they not know the exact density of the element they wanted to claim to have discovered, they also had no means for measuring the exact density of the new gas in their sample because the new gas in their sample was mixed with some argon.[9] Hence, they merely estimated that the density of the new gas would match the density of 10 or 11

[8] As Helge Kragh, Eric Scerri, and Thornton and Burdette have all pointed out, chemistry was profoundly shaped by interactions with physicists, and developments in physics, during this period (see Kragh 2000, 448; Scerri 2007, Chapter 7; Thornton and Burdette 2017). For example, the way of reporting the discovery of an element in 1923 would not have been possible without the contributions of physicists to the field of chemistry in the intervening years.

[9] Scerri provides a detailed account for some of the challenges that Lord Rayleigh and William Ramsey encountered as they tried to determine the atomic weight of argon, the first of the noble gases to be discovered (see Scerri 2007, 151–152).

they sought. They wrote that the value they got for the density of the gas mixed with the argon "approaches to what we had hoped to obtain" (1898, 439).

Even they did not regard this as enough to secure their claim to having discovered a new gas. So, unlike Coster and Hevesy, Ramsey and Travers were required to conduct several experiments to support their claim that they had discovered the desired new element. The determining feature of an element on their conception, atomic weight, could not help them further so they were required to also rely on other features of their sample. They had to show that their sample has other features indicating that this is an element different from the elements that had already been discovered. For this reason, as we have already seen, Ramsey and Travers report on other features of their sample than atomic weight, even though they regarded it as the essential feature of a chemical element.

One of these features is the optical spectrum of their sample. In fact, the beginning of Ramsey and Travers' report is devoted to the spectrum they had produced. Although the spectrum represented a *unique fingerprint* of the chemical element even for Ramsey and Travers, the spectrum alone could not prove that they had discovered the element of density 10 or 11 that they were looking for. This is due to the fact that the spectral lines were not systematically connected with what they considered to be the defining feature of an element, the atomic weight. The connection between atomic weight and the optical spectra was more tenuous than the connection between atomic number and the X-ray spectra.

Other than reporting on the atomic weight and optical spectrum of the sample, Ramsey and Travers report on some further qualitative observations that support their claim that they have discovered a new gas. For example, Ramsey and Travers explain that the new gas "is rapidly absorbed by the red-hot electrodes of a vacuum-tube, and the appearance of the tube changes, as pressure falls, from very red to a most brilliant orange, which is seen in no other gas" (see Ramsey and Travers 1898, 439).

Ramsey and Travers themselves acknowledge that they were required to conduct several experiments to secure their claim to having discovered the sought-after new element. Their report explicitly states that it is the experiments combined that prove that they have discovered the new element. They wrote: "that this gas is a new one is sufficiently proved, not merely by the novelty of its spectrum and by its low density, but also by its behaviour in a vacuum-tube" (Ramsey and Travers 1898, 439). Hence, the reporting of the discovery of neon is filled with quantitative and qualitative descriptions that are explicitly related to specific laboratory procedures and operations. And it is the accumulation of such features that enabled the scientists to secure their claim to have discovered a new element, distinguishable in quantitative and qualitative ways from other known elements which may be similar to neon in one way or another.

Finally, we note that part of Ramsey and Travers' argument for having discovered neon is a long and very detailed description in their report of how they carefully isolated the element before conducting the experiments described above. By contrast, Coster and Hevesy hardly give any information on how they isolated hafnium. But this is to be expected. Coster and Hevesy were successful in producing the desired spectrum, and this by itself confirmed that they had been successful in isolating hafnium. Ramsey and Travers' experiments do not in a similar unequivocal way confirm that they have successfully isolated the element. Their detailed description of how they carefully isolated the element provides independent reason for believing that they have successfully isolated the element.

In this section we have examined how *the experiments conducted* by the two sets of chemists were different as a result of the change in the concept of a chemical element. Our findings serve as a nice illustration of what Kuhn writes on "the operations and measurements that a scientist undertakes in the laboratory" (see Kuhn 1962/2012, 125–126). Kuhn writes that,

> far more clearly than the immediate experience from which they in part derive, operations and measurements are paradigm-determined. Science does not deal in all possible laboratory manipulations. Instead, it selects those relevant to the juxtaposition of a paradigm with the immediate experience that that paradigm has partially determined. As a result, scientists with different paradigms engage in different concrete laboratory manipulations. (Kuhn 1962/2012, 126)

Conclusion

In a recent paper, Wray emphasized the significance of the *conceptual* changes in the revolution in chemistry in the early twentieth century, when chemists came to classify the chemical elements by their atomic number rather than by their atomic weight (see Wray 2018). In a similar vein Helge Kragh has emphasised the significant conceptual change that occurred in chemistry between 1900 and 1925 (see Kragh 2000). Most important, Kragh notes, was the reconceptualization of the chemical element (2000, 447). Both Wray and Kragh emphasize the development and acceptance of the notions of an isotope and atomic number (see Kragh 2000, § 3; Wray 2018, 214–216). Both of them acknowledge the fact that the "the periodic system survived the revolution" (see Kragh 2000, 447; and Wray 2018, 216).[10] These studies focus narrowly on the conceptual changes.

Here our focus has been on the changes in scientific practice, in an effort to give some concrete sense to Kuhn's notion of world changes. We acknowledge that some of these changes are strictly a function of developments in instrumentation and methodology. Obviously, scientists working in 1898 cannot use instruments that are developed later. But some of the practices that divide the chemists reporting the discovery of neon and the chemists reporting the discovery of hafnium are a consequence of the conceptual changes that occurred in the 25 years between the two discoveries, the changes that have been highlighted earlier by Wray, Kragh, and Scerri. Thus, the changes in instrumentation and laboratory practices are bound inextricably with the conceptual changes.

By considering two instances of doing the very same task, reporting the discovery of a new chemical element, we have been able to discern some changes in scientific practice that were due to the reconceptualization of the chemical element. We have seen how chemists *saw* and *looked for* different things when looking at spectra of chemical elements, and how they *constructed* and *conducted* experiments differently by virtue of this fact. We have thus provided a detailed example of what it means to see and respond to different worlds by responding to different conceptions. The methods of securing the identity of a chemical element had changed, just as the concept of a chemical element changed. It is in

[10] It is easy to exaggerate the continuity through the revolutionary conceptual change in chemistry. As Thornton and Burdette note, since 2009, the IUPAC "have updated the atomic weights of a [number] of elements from a constant single value to a range. The weight range reflects the variations in element isotopic compositions found in terrestrial materials" (Thornton and Burdette 2017, 133). They add that "it does not appear that … anyone working in the early twentieth century … anticipated atomic weights becoming ranges, rather than specific values" (see Thornton and Burdette 2017, 133).

these respects that the chemists reporting the discovery of hafnium can be rightly said to be working in a different world than the chemists who discovered neon.

Acknowledgements We thank Eric Scerri for feedback on an earlier draft.

Funding Funding was provided by Aarhus Universitets Forskningsfond (Grant No: AUFF-E-2017-FLS-7-3).

References

Coster, D., Hevesy, G.: On the missing element of atomic number 72. Nature **2777**(111), 79 (1923)

Donnan, F.G.: Edward Charles Cyril Baly. 1871–1948. Obit. Not. Fellows R. Soc. **6**(17), 6–21 (1948)

Grandy, R.E.: Kuhn's world changes. In: Nickles, T. (ed.) Thomas Kuhn, pp. 246–260. Cambridge University Press, New York (2003)

Hacking, I.: Working in a new world: the taxanomic solution. In: Horwich, P. (ed.) World Changes: Thomas Kuhn and the Nature of Science, pp. 275–310. MIT Press, Cambridge (1993)

Heilbron, J.L.: Atomic structure. In: Heilbron, J.L. (ed.) The Oxford Guide to the History of Physics and Astronomy, pp. 23–25. Oxford University Press, New York (2005)

Hoyningen-Huene, P.: Reconstructing scientific revolutions. In: Kuhn T.S. (ed.) Philosophy of Science. Translated by A. T. Levine, with a Foreword by T. S. Kuhn. University of Chicago Press, Chicago (1989/1993)

Hoyningen-Huene, P.: Kuhn's development before and after structure. In: Devlin, W.J., Bokulich, A. (eds.) Kuhn's Structure of Scientific Revolutions - 50 Years On, pp. 185–195. Springer, Dordrecht (2015)

Kragh, H.: Conceptual changes in chemistry: the notion of a chemical element, ca. 1900–1925. Stud. Hist. Philos. Mod. Phys. **31**(4), 435–450 (2000)

Kuhn, T.S.: The Structure of Scientific Revolutions, 4th edn. With an introductory essay by I. Hacking. University of Chicago Press, Chicago (1962/2012)

Marcum, J.A.: Thomas Kuhn's revolutions: a historical and an evolutionary philosophy of science. Bloomsbury Academic, London (2015)

Nickles, T.: Introduction. In: Nickles, T. (ed.) Thomas Kuhn, pp. 1–18. Cambridge University Press, Cambridge (2003)

Ramsey, W., Travers, M.W.: On the companions of argon. Proc. R. Soc. Lond. **63**(1), 437–440 (1898)

Scerri, E.: The Periodic Table: A Very Short Introduction. Oxford University Press, Oxford (2011)

Scerri, E.: A Tale of Seven Elements. Oxford University Press, Oxford (2013)

Scerri, E.R.: The Periodic Table: Its Story and Its Significance. Oxford University Press, Oxford (2007)

Siegbahn, M.: Relations between the K and L series of the high-frequency spectra. Nature **96**(2416), 676 (1916)

Soddy, F.: Inter-atomic charge. Nature **2301**(92), 399–400 (1913)

Soddy, F.: The origins of the conception of isotopes. Nature **2806**(112), 208–213 (1923)

Thornton, B.F., Burdette, S.C.: Chemistry's decision point: isotopes. In: Benvenuto, M.A., Willaimson, A., Williamson, T. (eds.) Elements Old and New: Discoveries, Developments, Challenges, and Environmental Implications, pp. 119–140. American Chemical Society, Washington (2017)

Van Spronsen, J.W.: The Periodic System of Chemical Elements: A History of the First Hundred Years. Elsevier, Amsterdam (1969)

Wray, K.B.: The atomic number revolution in chemistry: a Kuhnian analysis. Found Chem Philos Hist Educ Interdiscip Stud **20**(3), 209–217 (2018)