Editors' Introduction

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Abstract

The declaration by UNESCO of 2019 as the International Year of the Periodic Table sparked celebrations and renewed study of this icon of science. Activities included exhibitions, symposia, and publications—including the present volume. A few of those events are reviewed, and the contents of the present volume are previewed.

1.1 International Year of the Periodic Table (IYPT2019)

Late in 2017, the United Nations (UN) General Assembly proclaimed 2019 to be the International Year of the Periodic Table of Chemical Elements. In so doing, it endorsed a resolution that UNESCO (the United Nations Educational, Scientific and Cultural Organization) had adopted earlier in the year. The proclamation was a recognition of the importance of chemistry to the UN's sustainable development agenda in contributing to "solutions to global challenges in energy, education, agriculture and health" [1]. The year 2019 was an appropriate one to celebrate the

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C. J. Giunta et al. (eds.), *150 Years of the Periodic Table*, Perspectives on the History of Chemistry, https://doi.org/10.1007/978-3-030-67910-1_1

Fig. 1.1 Official logo of the International Year of the Periodic Table (https://iypt2019.org)

table because it was the 150th anniversary of the first table by the most influential discoverer of the periodic system, Dmitri Mendeleev.[1]

The idea for IYPT2019 did not originate with the UN, however. The germ of the proclamation appears to have come from a message from Martyn Poliakoff, Professor of Chemistry at Nottingham University in the United Kingdom, to Natalia Tarasova, Professor at the D. I. Mendeleev University of Chemical Technology in Russia in the middle of 2016 [1, p. 14]. Poliakoff is well known to chemists and chemistry students around the world as a presenter in Periodic Videos, a series of short videos about the elements [2]. Tarasova was president of the International Union of Pure and Applied Chemistry (IUPAC) at the time, and she had been on the management committee of the last UNESCO-sponsored year of chemistry, the International Year of Chemistry in 2011. The IUPAC Executive Committee approved exploring the idea, and before long Russian scientific and political support was lined up: the twentieth Mendeleev Congress on General and Applied Chemistry endorsed the idea in 2016, and soon afterward the Mendeleev Russian Chemical Society and the Russian Academy of Sciences followed suit.

IYPT2019 had a logo (Fig. 1.1) and a website [3], and it featured a large number of activities organized and run by local organizations (chemical societies, schools, museums, universities, etc.) around the world from Argentina (a nation named after an element) to Zambia. The opening ceremony was held at UNESCO headquarters in Paris in January 2019, and the closing ceremony at the Tokyo Prince Hotel in December. Both events featured dozens of speakers and attracted hundreds of attendees.

Among the notable conferences and symposia held in 2019 that focused on the periodic table and its history were “Setting their Table: Women and the Periodic Table of Elements” at the University of Murcia, Spain, in February; the Fourth International Conference on the Periodic Table, Mendeleev 150, in St. Petersburg, Russia, in July; and the 21st Mendeleev Congress on General and Applied

[1]As several chapters in this volume will make clear, Mendeleev is the best-known discoverer of the periodic system of the elements and of its chief embodiment, the periodic table, but he was not the first.

Chemistry, also in St. Petersburg, in September. The symposium out of which this volume grew was sponsored by the divisions of the History of Chemistry and Inorganic Chemistry of the American Chemical Society (ACS), held at the Fall 2019 National Meeting of ACS in San Diego, California, in August.

1.2 150 Years of the Periodic Table: Symposium at American Chemical Society San Diego Meeting

Vera Mainz, Gregory Girolami, and Carmen Giunta, the editors of this volume, began planning a symposium to commemorate the 150th anniversary of Mendeleev's table in the summer of 2017. The three of us have long been active in the ACS Division of the History of Chemistry, and we saw 2019 as an ideal time to mount a symposium exploring the origins of the periodic system of the elements, important episodes in its subsequent development, and even its future. Naturally enough, after the proclamation of IYPT2019, we added our symposium to the official list of IYPT2019 events.

The symposium program spanned three half-day sessions. The first session treated classifiers of elements who preceded Mendeleev or were contemporaries of his. Most of the second session dealt with developments in the periodic system in the nineteenth century after the publication of Mendeleev's first table. The final session treated topics mainly from the twentieth century and beyond. A list of symposium authors and the titles of their talks can be found in Table 1.1. We are grateful to all of the speakers who participated in the symposium: their knowledge about and interest in the periodic system made for lively presentations and discussions over the two days of the conference.

Most of the symposium speakers graciously agreed to contribute to the present volume; their chapters will be previewed in the next section. The remaining speakers also added greatly to the success of the symposium, despite being unable to contribute to the book. At our request, Michael Gordin spoke about Mendeleev's career apart from the work for which he is best remembered today. Gordin's biography of Mendeleev, *A Well-Ordered Thing*, was issued in a revised edition in 2019 [4]. Alan Rocke applied his expertise in nineteenth-century German chemistry to outline Lothar Meyer's pathway to periodicity; his research on the subject was published in *Ambix* [5]. Ana de Bettencourt-Dias is an inorganic chemist, specializing in the coordination chemistry and separation chemistry of the lanthanide elements. She spoke about the problems the "rare earth" elements presented to chemists and classifiers in the nineteenth century as well as on the present-day debate over the position of the lanthanides in the periodic table. Brigitte van Tiggelen compared views of the periodic system from Lise Meitner and Ida Noddack. Van Tiggelen spent much of 2019 engaged with the topic of women and the periodic table as co-organizer of the "Setting Their Table" conference mentioned above and as co-editor of a volume on women's contributions to the periodic system, *Women in their Element* [6]. Dawn Shaughnessy, leader of the Nuclear and

Table 1.1 Program for "150 Years of the Periodic Table" symposium held at the Fall 2019 ACS National Meeting in San Diego, CA

William Jensen	Trouble with triads
Carmen Giunta	Vis tellurique of Alexandre-Émile Béguyer de Chancourtois
Julianna Poole-Sawyer	Periodicity in Britain: Periodic tables of Odling and Newlands
Gregory Girolami	Gustavus Detlef Hinrichs and his charts of the elements
Michael Gordin	Mendeleev in St. Petersburg: Marginality of the periodic system
Alan Rocke	Lothar Meyer's path to periodicity
Mary Virginia Orna and Marco Fontani	Discovery of the elements predicted by Dmitri Mendeleev's table: Scandium, gallium, and germanium
Ana de Bettencourt-Dias	Rare earth elements
Jay Labinger	History (and pre-history) of the discovery and chemistry of the noble gases
Gary Patterson	Sir John F.W. Herschel and the concept of periodicity
Virginia Trimble	Hydrogen, helium, and metals: When astronomy met the periodic table
Daniel Rabinovich	Hydrogen to oganesson: Philatelic celebration of the periodic table
Eric Scerri	Impact of twentieth century physics on the periodic table and questions still outstanding in the twenty-first century
Brigitte Van Tiggelen	Uses of the periodic system after radioactivity and the discovery of the neutron: Contrasting views of Lise Meitner and Ida Noddack
Vera Mainz	Mary Elvira Weeks and *The Discovery of the Elements*
Kit Chapman	From neptunium to mendelevium: Element discovery and the birth of the atomic age[a]
Dawn Shaughnessy	Transactinide elements: How the 7th row of the periodic table was discovered
Pekka Pyykkö	Periodic table after period 7

[a]Scheduled but not given due to illness of the author

Chemical Sciences Division at Lawrence Livermore National Laboratory (LLNL) presented on the synthesis of transactinide elements—a topic in which she had firsthand experience as principal investigator in the LLNL Heavy Element Program.

1.3 *150 Years of the Periodic Table:* The Present Volume

1.3.1 Mendeleev and His Predecessors

The present volume begins with Mendeleev, the historical figure most closely associated with the periodic table and with the proclamation of IYPT2019, in a chapter by Ann Robinson titled "Dmitri Mendeleev and the Periodic System: Philosophy, Periodicity, and Predictions." Robinson briefly touches on efforts to classify the chemical elements before Mendeleev—efforts treated in greater detail in the chapters immediately following hers—before exploring how Mendeleev's understanding of elements shaped his periodic system. Mendeleev's distinction between simple substances and elements, and the definiteness and individuality of the latter, led him to eschew continuous representations of the properties of elements, and in particular to disfavor certain spiral representations of his periodic system.

After Robinson's chapter on Mendeleev, the first part of the book is organized roughly chronologically, featuring several chapters on attempts to classify elements before 1869. William Jensen's chapter is called "The Trouble with Triads." As Johann Wolfgang Döbereiner first observed early in the nineteenth century, triads are sequences of three similar elements for which the average of the atomic weights of the heaviest and lightest is approximately equal to that of the middle element. Jensen discusses the use of triads by later classifiers of chemical elements in the nineteenth century and examines the question whether Mendeleev based his well-known successful predictions of undiscovered elements on triads.

In the next chapter, Gary Patterson and Ronald Brashear treat a natural philosopher better known today for his contributions to astronomy than to chemistry, as well as an American who attempted to organize elements to teach chemistry. Their chapter is titled "Josiah Parsons Cooke, the Natural Philosophy of Sir John F. W. Herschel and the Rational Chemistry of the Elements." Herschel's chemical writings in his *Preliminary Discourse on the Study of Natural Philosophy* and his 1858 presidential address to the Chemical Section of the British Association for the Advancement of Science are examined in this chapter. In his address, Herschel pointed to an 1855 paper by Josiah Parsons Cooke Jr. on classifying the elements. Brashear and Patterson discuss that paper as well as Cooke's later classification in his 1868 textbook *First Principles of Chemical Philosophy*.

Carmen Giunta's chapter, "Vis tellurique of Alexandre-Émile Béguyer de Chancourtois" treats the helical arrangement of elements and radicals that the French geologist Béguyer de Chancourtois presented in 1862. Several historians of the periodic system identify the vis tellurique as the first periodic classification, and Giunta concurs. In addition to describing the arrangement itself, the chapter discusses its neglect by chemists until well after periodic classifications by Mendeleev and Meyer were well known.

Giunta joins Vera Mainz and Julianna Poole-Sawyer to present the work of two British classifiers of the elements in a chapter titled "Periodicity in Britain: The Periodic Tables of Odling and Newlands." William Odling and John Newlands, working independently in considerably different circumstances, published periodic arrangements of the elements in the middle 1860s. Neither was influential in the development of the periodic system, but Newlands received belated recognition for his work after pressing his claims.

Gregory Girolami delves into arguably the most obscure and least understood of the periodic systems that predate Mendeleev's in a chapter entitled "Gustavus Hinrichs and his Charts of the Elements." Hinrichs, a Danish-born American polymath included a spiral periodic arrangement (double-spiral, in fact) in an 1867 treatise on the structure of matter. That highly speculative *Programme der Atomechanik* explained similarity among analogous elements by similarity of the arrangements of their fundamental building blocks called pantatoms. Hinrichs also published a slightly different classification of the elements in tabular form in 1869.

Two chapters on the work of Lothar Meyer complete the book's first part. Gisela Boeck's chapter, "The Periodic Table of the Elements and Lothar Meyer," is a translation of a paper she originally had published in *Chemie in unserer Zeit*, a journal of the Gesellschaft Deutscher Chemiker [7]. During his lifetime, Meyer was recognized as a discoverer of the periodic system, sharing the 1882 Davy Medal of the Royal Society (London) with Mendeleev. Boeck discusses Meyer's incomplete periodic system of 1864 published in his short and influential book *Die modernen Theorien der Chemie* as well as his well-known periodic graph of atomic volumes published in 1870.

An introduction and translation by Vera Mainz of key passages from Meyer's *Modernen Theorien*, "Translation of §§ 91–94 of Lothar Meyer's *Modernen Theorien* (1864)," follows Boeck's chapter. The translated sections include several tables, including Meyer's table of 27 elements in a six-column periodic arrangement. They also contain Meyer's cogent discussion of the relationship that chemical theory and experiment ought to have vs. the relationship that they frequently do have.

1.3.2 Discoveries of Elements: Successes and Challenges

The next several chapters treat the discoveries of new elements, particularly after Mendeleev first formulated his periodic system in 1869. These chapters focus on how these new elements challenged Mendeleev's periodic system, forced it to change, and eventually served to convince the world of its merits. This section concludes with a study of the life and work of the foremost chronicler of these discoveries.

Mary Virginia Orna and Marco Fontani describe the discoveries of three elements predicted by Mendeleev and found within two decades of the predictions. Their chapter is called "Discovery of Three Elements Predicted by Mendeleev's Table: Gallium, Scandium, and Germanium." In addition to recounting how compounds of these elements and then the elements themselves were isolated, Orna and Fontani discuss the changing standards by which element discovery has been recognized since the 1870s and 1880s.

Simon Cotton's chapter, "The Rare Earths, A Challenge to Mendeleev, No Less Today," concentrates on the discovery of the rare earth elements: scandium, yttrium, and the lanthanides. He notes that the discoveries spanned about a century and a half from yttrium (or rather its oxide) in 1794 to promethium in 1947. Only five were known when Mendeleev made his first table. The questions of where to put them and even how many there were puzzled chemists until the advent of atomic number, and even now, just what elements are to be considered lanthanides is an unsettled question. Cotton's chapter concludes with a discussion of several aspects of recent lanthanide chemistry, including unusual coordination numbers and oxidation states.

Mendeleev may have known of only five rare earths when he made his first periodic table, but neither he nor anyone else knew of any noble gases at that time—and Mendeleev was reluctant to credit the discovery of the first few when they were found in the 1890s. Jay Labinger recounts how the elements of this group came to be known in "The History (and Pre-History) of the Discovery and Chemistry of the Noble Gases." One of the discoverers of argon, William Ramsay, speculated about the position of argon in the table even before it was isolated. Once characterized, it certainly did not belong in the periodic table where its atomic weight (40) would have placed it, between potassium (39.1) and calcium (40.1). Ramsay eventually solved the dilemma of its place, predicting and then finding most of the elements of the group. Labinger also recounts the flurry of noble gas compounds synthesized by several researchers within a few months in 1962 and 1963.

In "Element Discovery and the Birth of the Atomic Age," Kit Chapman describes the discovery of the first synthetic elements—acknowledging the philosophical question of whether synthesis really qualifies as discovery. Chapman begins by recounting early experiments by Enrico Fermi that were erroneously interpreted as resulting in the synthesis of elements more massive than uranium via the process of neutron capture. As it happens, the neutrons broke apart the uranium nuclei (nuclear fission) rather than sticking to them. Ironically, nuclear fission chain reactions ended up providing the high neutron fluxes that permitted neutron capture and the synthesis of elements 93 and 94 (neptunium and plutonium, respectively). The last elements produced by neutron capture were 99 and 100 (einsteinium and fermium, respectively), formed from the extremely high neutron fluxes in a thermonuclear explosion, the "Ivy Mike" test of the first hydrogen bomb. The discoveries of these elements were closely related to the development of nuclear power and nuclear weapons.

Vera Mainz concludes the focus on the discovery of elements with a chapter, "Mary Elvira Weeks and *Discovery of the Elements*," on a scholar who published accounts of practically all the elements discussed in this section and many more. Weeks was assistant professor of chemistry at the University of Kansas, the same university at which she had earned her Ph.D. in chemistry, when she began writing on how elements came to be recognized. She published 24 (!) papers on the subject in the *Journal of Chemical Education* in 1932–1933. The papers were collected into the classic book *Discovery of the Elements*, which went through seven editions between 1933 and 1968. Henry Marshall Leicester wrote a chapter on the elements of the atomic age for the 6th edition (1956) and was co-author with Weeks of the 7th and final edition (1968).

1.3.3 The Periodic Table from Other Perspectives

The final set of chapters examines aspects of the periodic system and its elements from perspectives of other disciplines—or at least using tools originating in other disciplines such as astronomy, quantum mechanics, and philately.

Virginia Trimble's chapter, "Astronomy Meets the Periodic Table. Or, How Much Is There of What, and Why?" chiefly addresses questions of nucleogenesis and the cosmic abundances of elements. Trimble recounts that early in the twentieth century, hydrogen was thought to account for only a small fraction of the mass of stars, and that estimate rose during the course of the century. The chapter begins, though, with observations of solar spectra leading to the proposal of three new elements in the 1860s—one of which (helium) can still be found on the periodic table.

Eric Scerri had an eventful IYPT2019—as did several other symposium speakers mentioned earlier. He was one of the organizers of the Fourth International Conference on the Periodic Table, Mendeleev 150, in St. Petersburg, and a revised edition of his book *The Periodic Table: its Story and its Significance* was published [8]. His chapter is titled "The Impact of Twentieth Century Physics on the Periodic Table and Some Remaining Questions in the Twenty-first Century." He begins with a brief review of physicists' work on the periodic table from the first half of the twentieth century, including J. J. Thomson's attempt to explain the table based on his electronic model of the atom, Henry Moseley's giving the table a better ordering principle than atomic weight, and quantum aspects of the atom proposed by Bohr, Pauli, and Schrödinger among others. Most of the chapter examines attempts over the years to apply concepts of symmetry and group theory to the periodic table, particularly the empirical Madelung rule for the filling order of atomic orbitals.

Pekka Pyykkö specializes in the theoretical study of the structure and chemistry of very heavy elements, including elements heavier than those that have yet been synthesized. His chapter, "An Essay on Periodic Tables," ranges from historical topics to theoretical limits to the periodic table (predicted for $Z = 172$), to physical effects (such as relativity and quantum electrodynamics) that cannot be neglected in the computational chemistry of heavy elements. Pyykkö's chapter was originally published in *Pure and Applied Chemistry*, the scientific journal of IUPAC [9].

Daniel Rabinovich's chapter, "The Periodic Table at 150: A Philatelic Celebration," returns us to where this introduction started, to IYPT2019. Algeria was the first nation to issue a stamp in honor of IYPT2019, featuring the IYPT logo. Several stamps depict Mendeleev through the IYPT logo, and one from Hungary also shows Mendeleev's handwritten draft of the periodic table. Sri Lanka issued a stamp that displays a full 118-element periodic table with color-coded groups. The stamps Rabinovich shows are visually engaging, celebratory, and often informative.

1.4 The End of the Beginning

The periodic table has been described as an icon of science, one that all scientists and students of science encounter at some point in their careers. The table's profile, its arrangement of orderly but unequal rows and columns of boxes, is a distinctive design that often appears in unexpected places in popular culture. How the periodic table came to be constructed is a fascinating story that rewards serious study and warrants celebration. We think you will find that the following book contains fascinating and occasionally surprising new insights into that story.

Finally, before plunging into the details previewed above, we hope you enjoy this alternative arrangement of the elements, courtesy of Tom Lehrer [10], updated to accommodate elements discovered since nobelium (1958)[2]:

There's antimony, arsenic, aluminum, selenium,
And hydrogen and oxygen and nitrogen and rhenium,
And nickel, neodymium, neptunium, germanium,
And iron, americium, ruthenium, uranium,

Europium, zirconium, lutetium, vanadium,
And lanthanum and osmium and astatine and radium,
And gold and protactinium and indium and gallium,
And iodine and thorium and thulium and thallium.

There's yttrium, ytterbium, actinium, rubidium,
And boron, gadolinium, niobium, iridium,
And strontium and silicon and silver and samarium,
And bismuth, bromine, lithium, beryllium, and barium.

There's holmium and helium and hafnium and erbium,
And phosphorus and francium and fluorine and terbium,
And manganese and mercury, molybdenum, magnesium,
Dysprosium and scandium and cerium and cesium.

And lead, praseodymium and platinum, plutonium,
Palladium, promethium, potassium, polonium,
And tantalum, technetium, titanium, tellurium,
And cadmium and calcium and chromium and curium.

There's sulfur, californium and fermium, berkelium,
And also mendelevium, einsteinium, nobelium,
And argon, krypton, neon, radon, xenon, zinc and rhodium,
And chlorine, carbon, cobalt, copper, tungsten, tin and sodium.

Rutherfordium, lawrencium, seaborgium, flerovium,
Darmstadtium, roentgenium, meitnerium, moscovium,
Copernicium, nihonium, oganesson, livermorium,
And tennessine, and hassium, and dubnium, and bohrium.

These are the only ones of which the news has reached Urbana
And there may be many others—for a chemist, that's Nirvana!

[2]A joint effort of one of the co-editors (GSG) and his University of Illinois colleague Alex Scheeline.

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