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Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur

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ISSN 2191-5407 ISSN 2191-5415 (electronic)
SpringerBriefs in Molecular Science
ISSN 2212-991X
SpringerBriefs in History of Chemistry
ISBN 978-3-319-77904-1 ISBN 978-3-319-77905-8 (eBook)
https://doi.org/10.1007/978-3-319-77905-8

Library of Congress Control Number: 2018934947

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Printed on acid-free paper

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The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

When we look at the lives of our political leaders, their deeds, skills, successes, in war and in peace, the course of their lives, and their personalities, their achievements inspire us so much that their faults and failings are often obscured. On the contrary, how often are the great personalities of science and invention overlooked, working as they often do in the shadows far removed from the paths of power and influence. At the same time, their work, slowly permeating, or suddenly expanding into our consciousness, begins to define our culture. Rarely does a picture, or a street name, or even more rarely, a brief mention at school, remind us of someone whose genius and diligence actually changed our very way of life.[1]

This observation aptly describes the life and work of Carl Auer von Welsbach. A chemist, entrepreneur, and inventor who pioneered the fields of modern lighting technology, discovered as many as four chemical elements, and founded industrial complexes that are still in operation today with thousands of employees worldwide, is hardly known outside of his home country of Austria. This situation is probably due to the fact that he has been described as one of the last "private scientists" who worked virtually alone without a large team of collaborators, that he published little, and that his works are all in the German language.[2] It is hoped that this volume, in recounting the course of his life and his achievements, may demonstrate his impact on our modern world. In doing so, we also hope to show how the circumstances of his life and the lives of those who surrounded him influenced events, sometimes for better, and sometimes for worse. There are so many various facets to Carl Auer von Welsbach's personality that just one volume cannot do him justice. Therefore,

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[1] Paraphrased from D'Ans J (1931) Carl Freiherr Auer von Welsbach. Ber Dtsch Chem Ges A 64(5):59–92.

[2] He is listed as a "private scholar" in Wehefritz V (1994) Bibliography on the history of chemistry and chemical technology. 17th to the 19th century. Walter de Gruyter, Berlin, p. 532.

many references to his own writings and those of his contemporaries, along with essays that have been written about him, will round out this portrait of a truly great scientist.

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Acknowledgements

Thanks to the objects and documents from the personal effects of Dr. Auer von Welsbach, his life's work could, for the first time, be gathered together and recorded in its full scope. These personal effects were contributed by the Auer von Welsbach family as well as by Treibacher Industrie AG, the Auer von Welsbach Museum, and the Auer von Welsbach Forschungsinstitut (both of the latter founded in 1998), and by the faculty of chemistry at the University of Vienna.

For additional supporting materials, we wish to thank the Stadtgemeinde Althofen, the Kärntner Landesarchiv, the Alpen-Adria-Universität Klagenfurt, the Institute for Radium Research, Vienna, the Austrian Academy of Sciences, the Atominstitut at the Technische Universität Wien, the Isotope Research and Nuclear Physics Group at the University of Vienna, the Ignaz-Lieben-Gesellschaft, the Technisches Museum Wien as well as many additional private and public lenders, researchers, and supporters.

We also want to thank Gerfried Klinger, Rudolf Werner Soukup, and Gernot Sturm, the editors of the libraries of Robert Wilhelm Bunsen, Carl Auer von Welsbach, and Ludwig Haitinger, respectively, which are invaluable for ongoing research.

Our great thanks also go to Marco Fontani of the University of Florence for his immense help in obtaining some difficultly accessible references and to the series editor, Seth Rasmussen, for his helpful questions and suggestions.

Everyone who contributed to this publication deserves our thanks and recognition.

Contents

Chapter 1
Family Heritage

1.1 Antecedents

Though Carl Auer von Welsbach (1858–1929) was himself born in Vienna, his family seat, so to speak, was Wels, a little town about 25 km from Linz, the provincial capital of Upper Austria. Lying on the Traun River, it was an important hub in Roman times and eventually became the county seat of Wels-Land with a population of about 11,000 at the time of Auer's birth.

The direct Auer line can be traced back to the end of the 17th century beginning with one Hanns (1650–1710), who with his wife Katharina (1658–1718), gave to the world another Hanns Auer, who became a raftsman on the River Traun. This Hanns, in turn, with his wife Magdalena, had five children, the fourth of whom, born in 1732, was named Johann Georg, who became a carpenter. Johann Georg and his wife, Maria, had in their turn five children, among them Mathias (1760–1836). Like his grandfather, Mathias took up being a raftsman for his livelihood. After being twice widowed, he married one Maria Anna Mayr (1773–1855), and the sixth of their seven children, Alois Auer, made his appearance on May 11, 1813.[1] Figure 1.1 shows the family tree right down to the arrival of Alois' own four children, the youngest of whom was Carl, born on September 1, 1858.[2]

1.2 His Father: Alois (Ritter) Auer Von Welsbach (1813–69)

Considering his relatively humble ancestry, Alois Auer was indeed an extraordinary man. Apprenticed as a typesetter at the age of 11 at the small book printery of Michael Haas, in Wels, he pursued his "higher education" on his own, reading and

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[1] von Hueck [1].

[2] Auer von Welsbach [2].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_1

Demnach ſtellt ſich heraus:

a) **Ur-Urgroßvater:** (wahrſcheinlich) **Hanns Auer. Ur-Urgroßmutter: Katharina.**

b) **Urgroßvater: Hanns Auer. Urgroßmutter: Magdalena.**
Gevatter: Michael Mittermayer. Gevatterin: Suſanna Winterin.
Kinder: Eva Maria, Suſanna, Hanns Michael, Johann Georg, Johann Paul.

c) **Großvater: Johann Georg Auer. Großmutter: Maria.**
Gevatter(in): Adam und Maria Binder.
Kinder: Johann Adam, Maria Anna, Mathias, Thereſia, Eliſabeth.

d) **Vater: Mathias Auer. Mutter: Maria Anna Mayr.**
Kinder: Maria Anna, Mathias, Eliſabeth, Thereſia, Michael, Alois, Joſepha.

e) **Söhne, verehelicht:**	**Kinder:**
Michael Auer mit Katharina Derflinger.	Joſepha, Philomena, Amalia, Alois, Andreas, Thereſe.
Alois Auer *) mit Thereſe Reuditſchka.	Leopoldine, Alois, Amalie, Carl.

Fig. 1.1 Entry showing family origins of the Wels branch of the Auer family

studying into the wee hours. He was passionate about learning languages, and mastered Italian, French, and English so well that he passed the public examination in those three languages at the University of Vienna. This achievement opened new career paths for him, and so a short time later, in 1837, he moved to Linz as a private language instructor, and later as Italian teacher at the Lyceum there.

While in Linz, he got the idea of linking his typesetting and language expertise to compose and publish a French-Italian grammar book in which he exploited the similarities between the two languages—he placed each grammatical point side by side in parallel columns so that the reader could see, understand, and learn each point, as well as their deviations, at a glance. To accomplish this, he devised a typometric system in which print characters were exactly measured with respect to the space they occupied,[3] allowing the columns to be synchronously printed. This innovation, which created a sensation, did not escape the notice of the Imperial Chancellor and the Lord Minister, under whose patronage he came.

With official recognition came the confidence to entertain new ideas: from his own typesetting experience, Alois Auer realized that the contemporary methods of printing were quite primitive, and he wanted to see what was going on in the rest of the world. He also felt that Austria had the capabilities of housing an exemplary graphics institution. So, in 1839, at his own expense,[4] he arranged for a dedicated comprehensive study tour of the most important and famous printing houses, art institutions, and libraries of Europe. On his return, he recorded his observations, laid out his plan to set up a typographical institute for the execution of linguistics and dictionaries, and submitted them to his powerful Viennese sponsors. It did not take long for Prince Metternich (1773–1859) to realize Auer's ambition and genius: soon afterward, at the age of 27, in 1841, he was named Director of the *Hof- und Staatsdruckerei* (Imperial and State Printing House) in Vienna. During the first six years of his directorship, he turned a floundering establishment with about 45 employees into a world-class institution with about 700 on its technical staff.

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[3] Auer von Welsbach [3].

[4] It was customary for young craftsmen from the various professions, after completing an apprenticeship or an examination, to go on study tours to neighboring cities and countries to learn about innovations in the field and to share knowledge.

1.3 Alois Auer's Career at the *Staatsdruckerei*

Founded in 1804, the *Staatsdruckerei* had been in decline for many years and when Auer took over, it was not much more than an appendage to the finance ministry's shipping office, with the charge to print the documents required by the government authorities and offices. However, because of its obsolete printing methods, these very offices were actually in the habit of outsourcing their needs to private establishments, resulting in a highly unprofitable situation.

Using the knowledge he had gained from his own research, Auer took the *Staatsdruckerei* in a new direction by obtaining new presses and modern auxiliary machinery, by training or re-training efficient workers, and above all, by replacing the obsolete typesetting method with his own typometric system. Once these measures began to place the press on an upward path, he could then begin to think about making more ambitious typographical plans.

Auer redesigned the entire character of the *Staatsdruckerei* according to his own typographical system, eventually making printing possible in 500 indigenous[5] and 100 foreign alphabets, a formidable and forward-looking achievement, but hardly scratching the surface. Auer gave a detailed account of this work in one of his many publications.[6] In his history of the *Staatsdruckerei*,[7] he claims that "this treasure of types forms the most numerous collection of alphabets in the whole world." Auer also took care to make sure that the type-cutters for the various foreign alphabets were given lectures in those languages in order to insure stylistic accuracy—they were very soon listening to lectures in Turkish, Arabic, Chinese, Japanese, and Sanskrit.

Just when things seemed to be going so very well for Alois Auer, political thunder struck. All of Europe became embroiled in what is now called the Revolution of 1848. Metternich fell from power; the Royal family fled Vienna; and businesses, like the *Staatsdruckerei*, now lacked a ready market for their services due to the anticipated social and political upheavals associated with such events. While unemployment rose, Austrian currency plummeted.[8] During this difficult period, Auer himself had to personally face conflicting orders regarding the publication of public announcements, doing so at one point under the watchful eyes of an armed delegation. Dramatic concessions by the Habsburg government finally brought a semblance of stability at the price of a tattered and fractured central

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[5] According to the Wikipedia webpage on European languages [https://en.wikipedia.org/wiki/Languages_of_Europe, (last accessed 15 January 2018)] there are presently 72 official and semi-official languages used in the European Union, 306 languages in danger of extinction throughout the European continent, and 120 extinct languages, so Auer's "capture" of 500 indigenous languages was virtually complete at the time.

[6] Auer von Welsbach [4].

[7] Auer von Welsbach [5].

[8] http://www.age-of-the-sage.org/history/1848/revolution_of_1848.html (last accessed 15 January 2018)

Europe. Nevertheless, such concessions allowed for more freedom of movement, secure property ownership, and freedom of choice for everyone with respect to occupation.[9]

1.4 Innovation and Creativity

In the period following the stormy year of 1848, the *Staatsdruckerei* was occupied with the production of paper money, stamps, and other state securities, and by the printing of many publications relating to the reform of the state. Auer was able to significantly increase the efficiency of the institute by means of increasing mechanical equipment as well as by structural extensions. Auer also found time to take on the promotion and perfection of new graphic methods, such as electroplating, chromolithography, and photography.

Perhaps the method of which Auer is most proud and which gave him the most joy was his "discovery" of the *Naturselbstdruck*, or nature-self-printing process. This technique, in a word, involved making an impression of a natural object, such as a plant or a leaf, on a lead plate which could then be inked so as to print multiple copies. Auer always acknowledged his co-worker, Andreas Worring, as co-inventor and credited him with suggesting the use of lead for the impressions.

In Auer's essay describing the process, he first asks the question: How do you get a printing plate in a few seconds almost free of charge and deceptively similar to every original, without a draftsman or engraver? The solution: If one briefly places a plant, flower or an insect, cloth or fabric, or a lifeless object between a copper and a lead plate, and passes the assembly through two tightly screwed rollers, the original leaves its image with all its proper details, as it were, on the surface of the lead sheet. If one applies colors to the embossed lead plate, as in the printing of a copper engraving, one obtains, by a one-time pressure from a plate, a deceptively similar copy with the most diverse colors.[10] The New York Botanical Garden has two pristine exemplars of Auer's original prints (Fig. 1.2).[11]

In his book,[12] which he wrote in four languages, Auer shows the use of plants, lace samples, fossil fish, and other objects impressed by rollers onto lead plates and then hand-colored before making the final print. Of course, there are many variations and refinements to this method. Furthermore, despite his claim, Auer did not invent nature-printing, but only his particular form of it. There are reports of efforts to produce images of natural objects dating back to at least 1570.

Alois Auer, in spite of his ambitions, had a collaborative spirit and always wanted to share credit with his co-workers. He energetically encouraged them in

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[9] Judson [6].

[10] Sedlacek [7].

[11] http://sciweb.nybg.org/Science2/Onlinexhibits/exhbtcata.html (last accessed 14 July 2018).

[12] Auer von Welsbach [8].

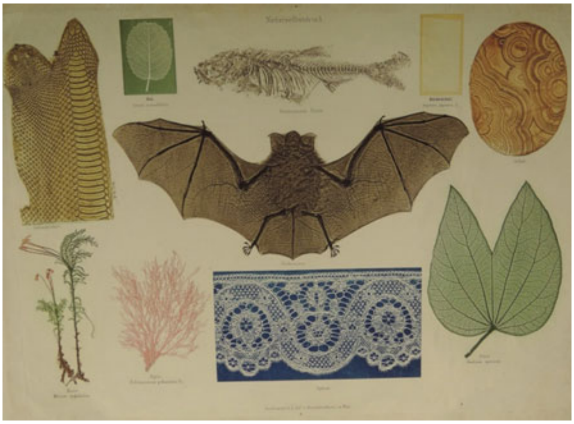

Fig. 1.2 Samples of the Naturselbstdruck process perfected by Alois Auer von Welsbach. Among them are plants, animals, minerals, and lace. Advertisement from "Pflanzen, Blümen und Blätter." k.k. Hof- und Staatsdruckerei, Wien. Archives of The New York Botanical Garden. *Photograph* Mary Virginia Orna

their own inventiveness. One example is the invention, under his directorate, of new types of jigsaw machines by Josef Kliegl and L. E. Tschulik. These accomplishments earned not only praise, but also more funding, from two Habsburg emperors. Another groundbreaking invention by Paul Pretsch (1808–73) of the *Staatsdruckerei* was photogalvanography, patented in 1854. In the 1850s, while photography was still in its infancy, many photographers wanted to find a way to make their work permanent by using printers' ink rather than rely upon the albumen silver prints that were produced by the direct photographic process, but subject to fading. One of these methods was the photogalvanic process, a technique that "combined photography and electroplating to produce an etched metal plate that could be printed, like a traditional engraving, on an intaglio press…Although more permanent than traditional photographic prints, photogalvanographs lacked the finesse and tonal subtlety of chemically produced prints and often required intervention by hand".[13] It is almost breathtaking to realize that Paul Pretsch's invention was mentioned, in a report of 1864, almost in the same breath as that of the father of modern photography, William Henry Fox Talbot (1800–77).[14] This surely indicates how very close to state-of-the-art the *Staatsdruckerei* was, not only in printing, but in the use of the infant science of photography to accomplish it.

In order to keep its paper supply available to meet its demands at all times as well as to be independent of fluctuating, and often sensitive, paper prices, the *Staatsdruckerei* established its own Papierfabrik (paper factory). Although this idea was motivated by economics and organization, Auer had another idea: efficiency. He wanted to connect the high-speed presses directly to the paper-producing machines

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[13] Baldwin et al. [9].

[14] Diamond [10]. "We now approach, for very brief notice, a variety of contributions illustrating several very important applications of photography. First among these may be mentioned the photolithographic process of Mr. Osborne, the photozincographic process of Col. Sir H. James, the photographic process of Mr. Fox Talbot, and the processes of Mr. Paul Pretsch, for producing, by the combined aid of photography and electricity, plates for printing in either intaglio or relief."

and drive them simultaneously with the same force so that the newly manufactured paper is printed upon while still moist and removed at the far end of the train. While this idea was not immediately feasible, what Auer did accomplish was setting up a number of the high-speed presses so that they could directly print on rolls of paper which were then cut to their appropriate sizes after printing—thus becoming the forerunner of the modern rotary presses that, with gigantic rotating cylinders and very high speed made the giant copies of modern newspapers possible.

Another idea coming from Auer's ever-creative mind was more cultural in its intent. He wanted the products of the graphic arts to transmit historical, geographical, artistic and linguistic knowledge to all classes of people to a far greater extent than had been possible before, that is, he wanted to engage in popular education in the most general sense. He was actually able to see this accomplished by introducing cost-effective measures and at the same time perfecting reproduction methods, thus allowing for greater multiplication of illustrated materials.

1.5 Marriage, Honors, and Retirement

In 1849, at a time when he had been a Privy Councilor (with the title Hofrat) and a recognized personality for some time, Auer (Fig. 1.3 is a portrait of Alois Auer in his middle years) married Therese Neuditschka (1831–1910), the daughter of a respected merchant of Wels. The marriage produced four children: Leopoldine, Alois, Amalie, and Carl. Therese, who outlived her husband for many years, was an excellent mother to her children, but especially to her youngest.

Auer received many awards in his lifetime. In the founding year of the Imperial Academy of Sciences in Vienna, 1847, he was appointed a full member of this body. In 1860 he was ennobled with the title of Ritter.[15] Since his family originally came from Wels, in which there was a brook (Bach, in German) that emptied into the River Traun, it was highly fitting that "von Welsbach" become his knightly name. From thenceforward, Alois Auer was known as Alois Ritter Auer von Welsbach. The recognition which he received from nearly all the ruling princes of Europe, as well as the memberships of countless learned societies, cannot be enumerated here.[16]

But for as many honors he received, there were equal numbers of grievances which Auer experienced during his working life, and the downgrading and humiliation of his own authority, brought about by intrigue even by his superior, forced him to go on leave, an embittered man, in 1864. The severe restrictions on the operation of the *Staatsdruckerei*, which was very dear to him, also led him to this decision. Fortunately, as a government employee, Auer was entitled to a considerable pension, and his wife could expect a widow's pension after his death,

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[15] The title of *Ritter* is equivalent to the British baronet.

[16] Sedlacek [11].

Fig. 1.3 Alois Ritter Auer von Welsbach

so the family was not in any way lacking support. Auer did not live long after his retirement, which became official in 1866. He died in Vienna on 10 July 1869.

It is remarkable that a young man to whom a formal education was denied was able to surmount this difficulty by assiduous study, exercise of his creative powers, untiring hard work, and collaboration with his peers to rise to world prominence and noble status. Auer thought globally in a world that was still enmeshed in its own local concerns. His legacy, in whatever manner it was transmitted, led his younger son along the path of fame and fortune.

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Chapter 2
Childhood, Early Education, and Beyond

2.1 Beginnings

Alois Auer von Welsbach's youngest child was born in his twilight years, and for six of those years, until his death, Alois spent them either on leave from his demanding work or in actual retirement. This afforded him leisure time to pass with young Carl, encouraging his interest in nature and modeling his own work ethic: creativity, energy, tenacity, and endurance. Alois recognized early on that Carl's strengths did not lie in learning many languages, but in working adroitly with his hands to fashion tools and various pieces of apparatus. In the brief period of time that remained to him, Alois was able to transmit to Carl the deeper meaning of nature, the necessity of careful observation, and fearlessness in following through on new ideas.

After Alois' death in 1869, the care of the four children fell to Therese (Fig. 2.1), who, according to some reports[1,2] was totally devoted to them, so much so that Carl later said that he would be eternally grateful to her for her solicitude and love. Carl had many delightful memories of school vacations spent with his siblings at their maternal grandparents' home in Wels; he described these days as among the happiest of his life.

Carl, after completing elementary school, went away to boarding school for two years, returning to Vienna to attend the Gymnasium, basically a high school for university-bound students. However, proficiency in both Latin and Ancient Greek was strictly required at the Gymnasium, and Carl's difficulty with languages caused him to transfer to the Realschule, a type of school in the German-Austrian system which placed an emphasis on the practical and on laboratory work. It was here that Carl showed great talent for chemistry, descriptive geometry, freehand drawing, and sports, receiving his diploma in 1877 (Fig. 2.2).

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[1] D'Ans [1].
[2] Auer von Welsbach [2].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_2

Fig. 2.1 Therese (Neuditschka) Auer von Welsbach

Under the Compromise of 1867, a new law was passed that decreed three-year conscription followed by ten years in the reserve. In practice, many conscriptees were discharged after service of only one year. It was in this mode that Carl entered military service, choosing to serve in the Festungs Artillery Brigade Number 4. He completed his term in 1878, having earned the rank of Lieutenant (Fig. 2.3). While in the service, his chemical expertise was put to good use: his job description included the designation of chemist and electrical engineer for lighting purposes, being responsible for electric lighting, possibly for searchlights, since there were electrical arc lamps at that time. During this time, he already had designed an arc-lamp with a clockwork control for which he applied, and obtained, a patent. However, the constant noise of the shooting of guns and cannons damaged his hearing, which possibly affected his subsequent habitual behavior. He was not a sociable person to begin with, but withdrew more and more into an isolation that, more than likely, had its roots in his inability to hear well. This affliction, moreover, grew worse over the years, and by the time he was in his 60s, he was almost totally deaf.

2.2 Higher Education

By the end of 1878, Carl was ready for university. Some books, biographies, and obituaries about Carl Auer von Welsbach state that he began his higher studies at the University of Vienna under the mentorship of Adolf Lieben (1836–1914). However, documentation held at the archives of the Technische Hochschule Wien (presently Technische Universität Wien, or TU-Wien) definitively places him as a matriculated student at that institution from the time he completed his military service in 1878 until 1880[3,4]. And given Carl's natural bent toward the practical, this choice makes much more sense.

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[3] Peters [3].

[4] Soukup and Schober [4].

Fig. 2.2 Carl Auer von Welsbach as a Realschule Student, 1877

A little history might help to rationalize the situation. In the early decades of the 19th century, chemistry, as well as the other sciences, were in a sorry state in Austria. However, after the Revolution of 1848, the Austrian educational system was completely revamped on both the secondary and the post-secondary levels. In the universities, the so-called hard sciences were moved out of the faculty of medicine into the faculty of philosophy since they were seen to have "no use in practical life".[5] One can surmise that this attitude did not sit well with young Carl Auer von Welsbach, a youth mainly interested in what he could accomplish and apply with the work of his hands. At the Technische Hochschule, on the other hand, chemistry was one of the major curricular offerings—and the emphasis was on developing hands-on, practical proficiency.

While there, as a Lieutenant in the reserve, Carl studied inorganic chemistry in the winter semester with Alexander Bauer (1836–1921) and continued to study organic chemistry with him in the summer semester. Bauer, together with his friend, Adolf Lieben, had himself studied at the Technische Hochschule when it was called the k. k. Polytechnic Institute, as a student of Anton Schrötter von Kristelli (1802–75), one of the founding members of the Austrian Academy of Sciences and a talented technical chemist whose research led to the invention of the safety match. Once Bauer was named full professor at the Polytechnic Institute, he played a major role in transforming it into the technical university we know today.

It is well-known that Alexander Bauer was an inspiring teacher, a cutting-edge scientist, a first-rate lecturer, and a passionate pioneer in the history of chemistry. But Bauer was not only a distinguished chemistry professor in his own right: he was also the grandfather of one of the most famous physicists who ever lived. Bauer's middle daughter, Georgine, married one of his former chemistry students, Rudolf Schrödinger. Their only child, Erwin Schrödinger (1887–1961), shared the physics

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[5] Kernbauer [5].

Fig. 2.3 Carl Auer von Welsbach in Military Uniform, 1878

Nobel prize of 1933 and gave to the world his eponymous equation, studied, but doubtfully understood, by virtually every freshman chemistry student ever since.[6]

In 1879 and 1880, Carl also attended lectures on "General and Applied Physics" with Prof. Victor Pierre (1819–86) and "Mathematics II" with Prof. Anton Winckler (1821–92), but only until 16 March 1880.

2.3 Formative Years in Bunsen's Laboratory

In order to make progress in any scientific area, and, in fact, to do something special, and advance his family, which was Carl's ambition, research with a well-known scientist in a prestigious German university was a *sine qua non*. So, Carl, possibly influenced by his chemistry professor's great friend and former Bunsen student, Adolf Lieben, matriculated in the laboratory of Robert Wilhelm Bunsen (1811–99), at the Ruprecht-Carls University, Heidelberg on 24 April 1880, and remained there for four semesters.

It was a great privilege for any young student to be welcomed into Professor Bunsen's august circle. Students arrived from all over the European continent and beyond. Some of the more famous ones were, in addition to Adolf Lieben, Carl's future host at the University of Vienna, Edward Frankland (1825–95; theory of valency and father of organometallic chemistry), Viktor Meyer (1848–97; benzene compounds pioneer and discoverer of thiophene), Hermann Kolbe (1818–84; organic synthesis), Friedrich Kekulé (1829–96; structural organic chemistry), Dmitri Mendeleev (1834–1907; periodicity of the elements), and Fritz Haber (1868–1934; ammonia synthesis).

Born in Göttingen where his father was on the faculty of the university there, Bunsen received his doctorate at the age of 20. From 1830 to 1833, he continued his education at Paris with Joseph Louis Gay-Lussac (1778–1850), Berlin-Oranienburg

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[6] Soukup [6].

with F. Ferdinand Runge (1795–1867) and Vienna (Sèvres Royal Porcelain Works), along with visits with other famous chemists such as Justus von Liebig (1803–73) in Giessen and Eilhard Mitscherlich (1794–1863) in Bonn. These travels, which were partially financed by the German government, were pivotal regarding his intellectual creativity, but also built a network of contacts that would stand him in good stead throughout his incredibly productive career.

Bunsen returned to Göttingen where he began a marvelous half-century long career that made him a household word to the public and a beloved father-figure for many of his students. The years between 1836 and 1851 were spent at Cassel and Marburg[7] with a brief period at Breslau (today's Wrocław, in Poland), where he met Gustav Robert Kirchhoff (1824–87), who was to become his lifelong friend and collaborator.

Although his name is most closely associated with a burner that he did not invent, but greatly improved,[8] his research contributions were much more diverse and significant: he discovered the first member of an organometallic chemical series described as cacodyl,[9] he invented the galvanic battery, and together with Kirchhoff developed the field of spectroscopy[10] by building a prototype spectroscope and discovering with it two elements, cesium[11] and rubidium. Some of the joyfully quirky anecdotes about Bunsen that make up a collection that came to be known as "Bunseniana" is humorously documented in W. B. Jensen's tale, "Robert Bunsen's sweet tooth".[12]

After his retirement in 1889 at the age of 78, Bunsen did not engage in active teaching. But "learned societies sought to honor themselves by heaping upon him memberships, degrees, and orders. These, however, ought hardly to be mentioned on the same page with the genuine admiration which his marvelous skill of hand, his wonderful clearness of thought and his marked originality called forth from the scholars and students of two continents. And even this praise can hardly have a place beside the loving esteem which his simple-mindedness and his warm-heartedness gained for him among all his personal friends".[13] It was into this atmosphere that the young Carl Auer von Welsbach entered that fateful April day in 1880.

Carl studied inorganic experimental chemistry and physical chemistry, along with their accompanying laboratory exercises, with Bunsen and Professor Hermann Kopp (1817–92), physics with Professor Georg Hermann Quincke (1834–1924), and mineralogy with Professor Karl Heinrich Rosenbusch (1836–1914). Not only

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[7] Lockemann and Oesper [7].

[8] Jensen [8].

[9] Bunsen's only foray into organic chemistry.

[10] The laurels for inventing spectroscopy must go to Joseph von Frauenhofer (1787–1826). In 1817, he analyzed the solar spectrum with a diffraction grating of his invention.

[11] Orna [9]. Although the process of discovery by spectroscope sounds simple, it required laborious purification of samples, and in the case of cesium's discovery, distillation of 44 tons of spa water before the two telltale blue lines could be identified as those of a new element.

[12] Jensen [10].

[13] Crew [11].

was Bunsen the inventor and state-of-the-art practitioner of spectroscopy, he had also been using this method for the previous 20 years before Auer's arrival, constantly refining it and finding new areas of application. All this Auer absorbed, but he also learned about electrochemistry (electrolysis, electrical potential differences for analytics and electrochemical current sources, etc.), and this was to become his great strength in devising his future inventions in the electrometallurgy of the rare earth elements. He also studied the history of chemistry, mineralogy, and physics.

At the end of his stay, on 2 May 1882, he passed the doctoral examination of the Faculty of Philosophy with a "cum laude" in chemistry[14] and satisfactory grades in physics and mineralogy. However, Carl did not submit a doctoral thesis: Bunsen, recognizing and appreciating Auer's great scientific capabilities, allowed his accession to the Ph.D. by saying the "the scientific capabilities of the young man were beyond any doubt and not requiring further written proof".[15] It is said that he had asked Bunsen to give him a project on the rare earths, dominated by the idea that in this field of chemistry he would have to seek his fortune, that is, in one of the most difficult areas of inorganic chemistry.

Carl Auer von Welsbach's two-year sojourn in Bunsen's laboratory is legendary. A quiet, hardworking, not very sociable, serious young man, intent on learning as much as he could, he was always the first to arrive in the lab in the morning and the last to leave at night. He shunned the regular outings that the other students indulged in, preferring to work alone—untiring, diligent, persistent, industrious, but also creative, thoughtful, quick to learn, and curious. His great strength lay not in theory, but in practice, and this fact alone endeared him to Bunsen. His experimental skills, practical sense, and powers of observation were extraordinary (and we might also remark that these were precisely the qualities fostered in him by his long-departed father).

Bunsen, himself, never wrote a textbook, so Carl had to rely on the notebooks of his fellow students, as well as on some hand-written, unpublished notes lent to him by other professors. His admiration for Bunsen was so great that Carl made it his business to acquire his personal library after his death in 1899.

Perhaps sensing that his own career was slowly winding down, Bunsen worked extensively with him in the laboratory. It was here that Carl learned how to exploit the differential solubilities of double salts to separate compounds of the rare earth elements by fractional precipitation. Here, at the very source of the new science of spectroscopy, he learned that science from the master. Here he learned the great value of the Bunsen flame as an excitation source, but he also became skilled in producing arc and spark spectra as well. In the late 19th century, there were four principal ways of producing spectra: the Bunsen flame, the electric spark, the vacuum tube, and the electric arc. Spark and arc spectra are produced by an

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[14] Carl had to improve his knowledge of Latin in "crash courses," and on 1 May 1882, he took a preliminary examination in Latin with Dr. Wachsmuth, he likely passed; otherwise the examination for the doctorate on 2 May 1882 would not have been permitted.

[15] Gutmann [12].

induction coil to generate a spark between two metal rods and by discharge across two carbon rods connected to a high voltage battery.[16] Three of these methods, flame, spark, and arc had been regular features of the experimental work in Bunsen's laboratory for almost 20 years before Carl's arrival.[17] These skills were to later earn him the fame and the fortune that marked his burgeoning career.

Toward the end of Carl's second year at Heidelberg, Bunsen offered him a position as assistant in his laboratory, and it is difficult to ascertain why he turned it down. He may have wished to be closer to home and to his family. He may have wished to be autonomous and independent, as suited his nature. For whatever reason, Carl Auer von Welsbach departed definitively for Vienna shortly after completing his examinations in early May, 1882. In addition to Bunsen's letter of introduction to Adolf Lieben, he took with him three treasures: (1) a small collection of rare earth minerals gifted to him by his beloved professor; (2) a laboratory skill-set that would enable him to succeed in untangling one of the most difficult problems in inorganic chemistry, one that occupied countless scientists over the course of a century; (3) a back-burner idea that rare earth salts, when subjected to intense energy such as a burner flame, were highly luminous. These treasures were to become the foundation of his career and the direction of his life.

2.4 Auer's Arrival in Adolf Lieben's Laboratory

Carl Auer von Welbach's choice of a postdoctoral mentor at the University of Vienna, as recommended by Robert Bunsen, could not have been more auspicious. Adolf Lieben, a native Viennese, had studied with Bunsen at Heidelberg, receiving his doctorate there at the age of 20, in 1856.[18] Thence he did further study in Paris with Charles Adolphe Wurtz (1817–84) and, in 1860, had the opportunity to attend the famous Karlsruhe Chemical Congress where he was introduced to, and deeply affected by, Friedrich August Kekulé's (1829–96) ideas on structural chemistry and Stanislao Cannizzaro's (1826–1910) clarifying paper on atoms, molecules, and atomic weights.[19] Following his tenure at several prestigious posts (Palermo, Turin,

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[16] Houstoun [13].

[17] The vacuum tube was almost the first instrument to establish the field of spectroscopy. In 1859, Julius Plücker (1801–68), University of Halle, observed that gas discharge contained in a sealed tube was characteristic of that gas. The tube, made by his assistant, H. Geissler (1814–79) snatched the fame from Plücker: no one ever hears of him anymore, but Geissler is a household word to science history aficionados. Szabadváry [14].

[18] When Lieben was a student in Bunsen's laboratory, the spectroscope had not yet been invented. Bunsen's major research at the time was the isolation of metals like chromium, magnesium, aluminum, and manganese by electrolysis.

[19] Kohn [15].

and Prague),[20] Lieben finally came "home" to Vienna in 1875, a welcome that overlooked his heritage in favor of his skills in organic chemistry, among which was the famous iodoform test. He lost no time in introducing the modern doctrine of "structural chemistry," a term first introduced by Russian chemist Alexander Butlerov (1828–86)[21,22] and used it effectively in both his teaching and research. Among his many honors were his election, at an early age, to the Vienna Academy of Sciences, and his elevation by the Emperor Franz Josef (1830–1916) to the Austrian Upper Chamber, a rank equivalent to being a member of the British peerage. Although he was an organic chemist, Lieben invited and accepted many students to work with him, "but he never prevented those who had independent ideas from carrying them out… [He] thus contributed to the development of fields which he personally did not till".[23] And so it was that organic chemist Adolf Lieben gave wide latitude to the talented young inorganic chemist who took up residence in his laboratory as an unpaid research associate. The next few years were to prove very fruitful to all involved.

Lieben's lasting homage to the nurturing of independent ideas was the co-founding, with Ludwig Barth (1839–90) in 1880, of the "Monatshefte für Chemie." Originally conceived as an Austrian journal of chemistry, it was gradually transformed into an international journal, the "Monatshefte für Chemie/Chemical Monthly," including all branches of chemistry. Unbroken in its publication record since its founding, it features the most recent research in analytical, inorganic, medicinal, organic, physical structural, and theoretical chemistry, including the chemically oriented areas of biochemistry. Adolf Lieben's personal and family life was colorful, high society of the time.

Ignaz Lieben (1804–92), Adolf's father, married into the very wealthy Lewinger family: Elise Lieben, née Lewinger (1809–77), was the source of all the funding for his many philanthropic projects, including the so-called Austrian Nobel, the Ignaz Lieben Prize, awarded to young researchers in the molecular sciences and physics. It was given annually until the Austrian *Anschluss* of 1938 to such luminaries as Lise Meitner (1878–1968) and Karl Przibram (1878–1973). The prize was revived in 2004 by Alfred Bader (b. 1924), himself a 14-year-old refugee from the Holocaust, and is now awarded yearly to young scientists working in one of the countries formerly part of the Austro-Hungarian Empire.

In 1887, at the age of 51, while Carl Auer von Welsbach was still working in his laboratory, Adolf Lieben married the Baroness Mathilde Schey von Koromla (1861–1940). This event turned out to be very important for Carl's future as well. Mathilde came from a highly-respected Jewish banking family whose music teacher was none other than the composer Hugo Wolf (1860–1903). After her marriage, she

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[20] Because of his Jewish background, it was very difficult to obtain major professorial posts in Austria, which had a centuries-long history of anti-Semitism that found its climax with the rise of National Socialism in the 20th century. See http://www.austrianinformation.org/fall-2015/dark-history (last accessed 15 January 2018).

[21] Rocke [16].

[22] Hunsberger [17].

[23] Kohn [18].

moved out of the Palais Schey, an imposing structure on the Vienna Ringstrasse, into the more cramped quarters of the official residence of the Chemical Institute. Nevertheless, aware of her unique heritage as a member of the Jewish cultural élite, she began to hold what became a hub of intellectual and artistic exchange with her famous salon that lasted for decades. It was from atmospheres such as hers that revolutionary breakthroughs in science, literature, psychology, art, and music spread out to the rest of the world. It was at these salons, that Carl is known to have frequented, that he met some of the most important contacts of his life, men who were to support and enhance his inventive and entrepreneurial skills in later years. Not the least of these was Adolf Lieben himself: although Lieben's major interests were in organic chemistry and pharmacology, he provided a professional home for Auer for many years, including those of failure and retrenchment.

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Chapter 3
Discoveries Among the Rare Earths

3.1 Ytterby and Beyond

When Johan Gadolin (1760–1852) took up the challenge of examining a small sample of a strange mineral found in the feldspar mine near the little Swedish village of Ytterby in 1788, little did he realize that he would set in motion a search that would last for over a century. The sample, named “ytterbite” by Lieutenant Carl Axel Arrhenius (1757–1824), its discoverer, could not have fallen into more skilled hands. Gadolin, at that point in his career climbing the academic ladder at the Royal Academy in Åbo (present day Turku), Finland, had studied chemistry under Torbern Bergman (1735–84) at Uppsala and excelled in analytical chemistry.

His detailed analysis of this “Ytterby earth” turned out to contain 38% of what he felt was a new earth[1] although he spoke of it “not without great trepidation”.[2] The first confirmation of Gadolin’s analysis, and conclusion, came from the Swedish chemist Anders Gustaf Ekeberg (1767–1813), remembered for his discovery of tantalum in 1802. He had obtained a larger sample of ytterbite which had been partially purified of feldspar. Hence, his analysis, agreed with Gadolin’s in every aspect but one: he found that it contained 47.5% of the “new earth”,[3]

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[1] “A clear-cut definition of an earth did not exist in the 18th century. Earth denoted a mineralogical substance which lacked taste, was insoluble in water, was incombustible and which was the basis of the minerals. Silica and alumina, for instance, could be regarded as oxides or hydrated oxides. Lime, magnesia and barytes denoted at first the carbonates, but later the oxides. At the end of the century an earth was described as an oxide which was difficult to reduce, difficult to dissolve and difficult to volatilize. At the end of the century there was a clear-cut difference between an earth and a metallic oxide.” Trofast [1].

[2] Gadolin [2]. This paper, claiming the discovery of what was thought to be the earth, or oxide, of a single new element, was also submitted to *Crell’s Annalen* in a submission letter dated 3 July 1794 but received by Crell on 26 March 1796, almost two years later!

[3] Pyykkö and Orama [3].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_3

subsequently called “yttria,” although isolation of the element, yttrium, would come much later.[4]

3.2 150 Years of Searching

This initial foray into rare earth chemistry was to become the first of almost a hundred over the course of the next 150 years, ending with the announcement of the discovery of promethium, element 61, in 1947.[5] At first, when chemists began to pull apart the complex ores from Ytterby, they thought they had completed their separations into two or three new elemental bodies that were immediately recognized as new “earths.” When later chemists took up the task, they began to realize that substances that were thought to be elemental bodies actually contained more than one. It soon became evident that these rare earths were very stubborn in yielding up their secrets—they were almost like those Russian dolls that contain a seemingly endless parade of more little dolls hidden within. There were four problems regarding the rare earths that gradually emerged:

- Chemists had no idea of how many of these new elements might be hidden in the ores; some thought that the number might be limitless, and this idea led to the proclamation of many false discoveries.
- Their chemical similarity was such that they were very difficult to separate and distinguish from one another. Their earths were found to be mixtures of very closely related substances, among which there were generally only very slight differences in properties, for example, in the solubility or thermal decomposition of their salts. The separation steps, therefore, had to be carried out step by step, fractionated and frequently repeated in order to arrive at pure substances. The chemists, who were generally also mineralogists at that time, had never before encountered such a state of affairs.
- Once the periodic table was proposed, they had no idea of how to accommodate the growing number of these rare earths in it; they seemed to defy the idea of periodicity.
- There was no viable theory of atomic structure until the first decades of the 20th century, thus precluding any idea of how these rare earths might be related to one another and to all the other elements, and why their properties differed, but were also uncannily similar.

Given the confusion that existed because of these difficulties, volumes can be written (and have been) documenting the errors, false starts, and the priority disputes based upon complications with publication dates and recognition. An excellent, though dated, account is given by Mary Elvira Weeks[6] and a more contemporary description can be found in Chaps. 2, 3, 4, and 5 of C. H. Evans’ 1996 collection,

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[4] It was isolated by Friedrich Wöhler in 1828. Wöhler [4].

[5] Marinsky [5].

[6] Weeks [6].

Episodes from the History of the Rare Earth Elements.[7] Both of these sources include correspondence among some of the puzzled discoverers, translated from the original Swedish, that gives the reader a real flavor of the conundrum that they were dealing with. We will look in more detail at the disputes that involved Carl Auer von Welsbach's separation of didymium into neodymium and praseodymium, as well as the separation of ytterbium into lutetium and what was initially called néo-ytterbium (named *cassiopeium* and *aldebaranium* by Auer von Welsbach).

Meanwhile, the complicated discovery history can be summarized in the form of the two charts that follow (Figs. 3.1 and 3.2). They are based upon the fact that early in rare earth research, chemists discovered that they fell into two main groups, a geochemical divide, so to speak: the so- called yttric earths and the ceric earths, due to the fact that, in the process of the separation method of fractional precipitation, the former group forms soluble double sulfates and the latter sparingly soluble double sulfates.[8] The two flow charts illustrate a simplified discovery trajectory of both groups and include the dates of discovery and the principal discoverers involved, although simplification often leads to passing over delicate details.[9,10] For example, in Fig. 3.2, erbium and terbium were initially confused and the names were switched. Most of these data were taken from John Emsley's books.[11,12]

Before the advent of the periodic table in 1869, there was a dawning concept of accommodating new elements in some kind of order, but the known rare earths in Dmitri Mendeleev's time did not fit into his idea of periodicity. In fact, even later, when the ordering principle of atomic number became clear, they still did not fit.

It was actually a Czech chemist, Bohuslav Brauner (1855–1935), who suggested that all of the rare earths, with the exception of scandium and yttrium, be placed in the same box in the peridodic table.[13] This "same box" has since been expanded into the familiar offset at the bottom of the modern classroom periodic table.

3.3 What Is a Rare Earth?

Any treatise on the rare earth elements will insert a disclaimer that they are not by any means rare! In fact, they are ubiquitous,[14] but so scattered around the earth, so embedded in their mineral substrates, and so similar to one another that it took over

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[7] Evans [7].

[8] Krishnamurthy and Gupta [8].

[9] A similar chart labeled "Genealogical table of the rare earth elements" can be found in Szabadvary F. Discovery and separation of the rare earths. In Gschneider and Eyring [9]. This reference is also a very rich account of the discovery of the rare earths and includes a comprehensive bibliography.

[10] Another pair of charts also shows the role of the rare earth salts' colors in effecting their separation. Habashi [10].

[11] Emsley [11].

[12] Emsley [12].

[13] Brauner [13].

[14] Some rare earth elements, like yttrium, are more abundant than cadmium and mercury.

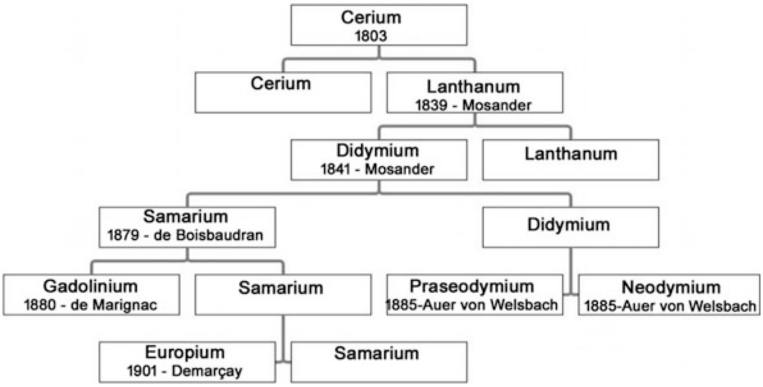

Fig. 3.1 Discovery chronology of the ceric rare earths

a century to separate and identify each one. They are so difficult to process even today that, in these senses, they are indeed rare. They are also referred to as "earths" since they occur in nature as their oxides; "earth" was an old term for an oxide. Furthermore, one must be careful to define what is meant by a rare earth element (often simply abbreviated REE) and specify how many exist. Strictly speaking, there are 17 REEs if one includes not only the lanthanides (elements 57–71), but also scandium (21) and yttrium (39) because of their similar chemical behavior and their placement in Group 3 of the periodic table. However, when discussing REEs, the topic is usually limited to the lanthanides. Table 3.1 presents a complete list in order of atomic number to clarify the discovery chronology of Figs. 3.1 and 3.2.

The chemical similarities of all seventeen rare earths arise from their trivalent nature as members of Group 3 in the periodic table. The first rare earth makes its appearance as scandium with an electron configuration of $[Ar]3d^1 4s^2$ in period 4, followed by yttrium in period 5 with a configuration of $[Kr]4d^1 5s^2$. So far all seems to be in order. However, moving into period 6, where 4f orbitals become energetically available, it seems that all the newly extracted rare earths must fit into the same box as suggested by Brauner. It was only after 1913[15] that chemists came to realize that there were just fourteen elements between lanthanum and hafnium, and only after 1918, when Niels Bohr (1885–1962) interpreted this number as an expansion of the fourth quantum group from 18 to 32 electrons,[16] that it became generally agreed that the lanthanides shared, with three exceptions partially to accommodate half-filled and completely filled subshells, the electronic configuration of $[Xe]4f^n 5d^0 6s^2$. Such a situation conferred unique properties on the group as

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[15] H. G. J. Moseley's X-ray work that resulted in the atomic number as the defining feature of an element.

[16] Greenwood and Earnshaw [14].

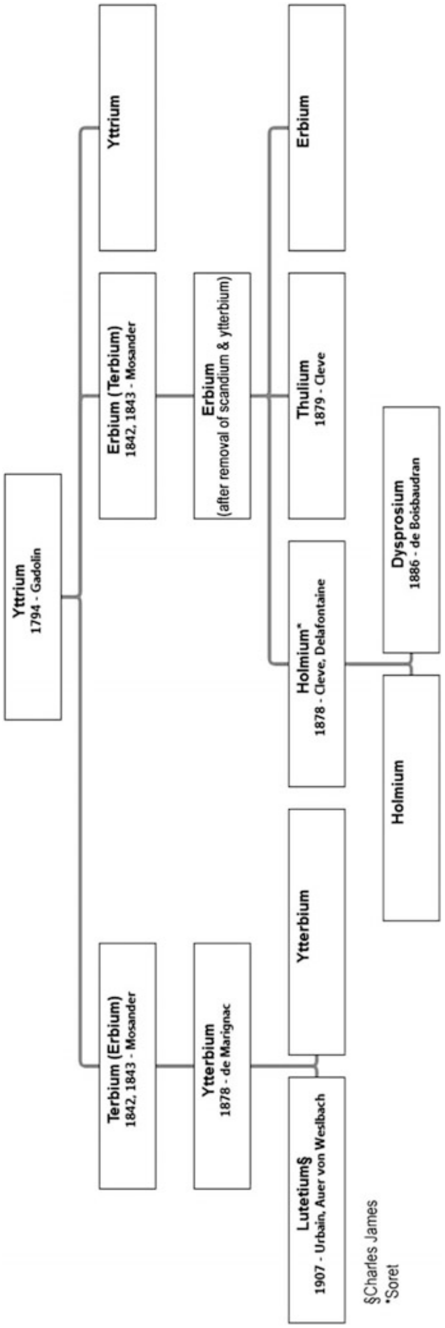

Fig. 3.2 Discovery chronology of the yttric rare earths

Table 3.1 The rare earth Elements

Z	Element	Date	Location	Discoverer
21	Scandium (Sc)	1879	Uppsala, Sweden	Lars Fredrik Nilson
39	Yttrium (Y)	1794	Åbo, Finland	Johan Gadolin
57	Lanthanum (La)	1839	Stockholm, Sweden	Carl Gustaf Mosander
58	Cerium (Ce)	1803	Bastnäs, Sweden, Berlin, Germany	J. J. Berzelius, W. Hisinger, M. H. Klaproth
59	Praseodymium (Pr)	1885	Vienna, Austria	Carl Auer von Welsbach
60	Neodymium (Nd)	1885	Vienna, Austria	Carl Auer von Welsbach
61	Promethium (Pm)	1945	Tennessee, USA	J. A. Marinsky, C. D. Coryell, L. E. Glendenin,
62	Samarium (Sm)	1879	Cognac, France	P. E. Lecoq de Boisbaudran
63	Europium (Eu)	1896, 1901	Paris, France	E. -A. Demarçay
64	Gadolinium (Gd)	1880	Geneva, Switzerland	J. C. Galissard de Marignac
65	Terbium (Tb)	1842, 1843	Stockholm, Sweden	Carl Gustaf Mosander
66	Dysprosium (Dy)	1886	Cognac, France	P. E. Lecoq de Boisbaudran
67	Holmium (Ho)	1878	Uppsala, Sweden Geneva, Switzerland	P. T. Cleve, J. L. Soret, M. A. Delafontaine
68	Erbium (Er)	1842,1843	Stockholm, Sweden	C. G. Mosander
69	Thulium (Tm)	1879	Uppsala, Sweden	Per-Teodor Cleve
70	Ytterbium (Yb)	1878	Geneva, Switzerland	J. C. Galissard de Marignac[a]
71	Lutetium (Lu)	1906, 1907	Vienna, Austria, New Hampshire, USA; Paris, France	Carl Auer von Welsbach, Charles James, Georges Urbain

[a] Marignac actually did not realize that his ytterbium was impure; it was later separated into two elements by both Carl Auer von Welsbach and Georges Urbain, giving rise to a sustained priority dispute

a whole, most keenly realized by the earlier researchers in the difficulty of their separation one from the other because of similar solubilities.

A glance at Table 3.1 indicates that half of the rare earth elements were discovered in Scandinavia, a total of eight, and if we count didymium, which was later separated by Carl Auer von Welsbach into neodymium and praseodymium, the total comes to ten. And since naming rights went unquestioningly to the discoverers in those days, absent the subsequent ruling international commissions, many of these are named for Scandinavian locations: Ytterby mine, Sweden (yttrium, ytterbium, erbium, terbium),[17] other parts of Scandinavia (holmium, for Stockholm; thulium, for Thule, and the ancient Greek place name associated with Scandinavia; scandium, for

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[17] It has been said that when it comes to naming elements, there is Ytterby and everywhere else.

Scandinavia). The Ytterby mine is unique in that these three latter elements were also found in that mine.[18] Figure 3.3 shows the commemorative plaque at the Ytterby mine. Two other rare earths are named after places: europium, obviously for the European continent, and lutetium, an ancient name for the city of Paris. Three are named for their behavior or some other property: lanthanum (from the Greek, "lying hidden," since it first showed up as an impurity in a cerium sample), dysprosium from the Greek, "hard to get," which it certainly was!), and praseodymium (from the Greek, "green twin," due to the color of its salts and its derivation from didymium). Neodymium derives its name from didymium as well, being newly found in that mixture. Samarium was named after the mineral in which it was found, samarskite, which by extension, was named after Vasili Samarsky-Bykhovets (1803–70) for the role he played in granting access to mineral samples to the mineralogist brothers, Gustav (1798–1873) and Heinrich Rose (1795–1864). For this gracious act, he became the first person to have an element named after him, though indirectly. The second person, however, was Johan Gadolin, after whom gadolinium is named.[19] Cerium was named after the dwarf planet Ceres which had been discovered two years earlier (and by extension, after Ceres, the Roman goddess of agriculture, from whom we derive the word "cereal.") And finally we come to promethium, the element born out of due time, a kind of Caesarian arrival from the womb of a cyclotron, appropriately named after Prometheus, who brought fire from the gods to earth.

It is no accident that the first of the rare earth elements was discovered in Scandinavia. The region has a history of mining that extends back a thousand years. The economic well-being of the area depended upon the mines, virtually the only natrual resource until the advent of hydroelectric power in modern times. The chief rare earth mineral sources are the phosphate minerals, monazite and xenotime, and the carbonate mineral, bastnasite.[20] Of these, monazite is by far the most important and most abundant, although it occurs mainly in four different varieties depending upon the predominance of the particular rare earth element: cerium, lanthanum, neodymium, or samarium. Table 3.2 illustrates the variances in terms of percentages of occurrence of each of these elements.[21]

Monazite and bastnasite are the principal sources of the so-called "light" rare earths, La, Ce, Pr, and Nd, comprising 93 and 99% of their weights, respectively. Xenotime, on the other hand, is approximately 92% "heavy" rare earths, namely, Sm, Eu, Gd, Tb, Dy, Ho, Er, and Tm.[22] Carl Auer von Welsbach returned to Vienna from Heidelberg with some rare earth samples in his possession. Any further acquisition of the rare earth minerals, especially in any considerable amount,

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[18] Muhammed and Habashi [15].

[19] There are now fifteen other persons who have achieved this honor in the present periodic table, if we count curium twice for Marie and Pierre, and if we count flerovium, named after the laboratory which bears the name of its founder, Georgy Flerov.

[20] Voncken [16].

[21] http://www.webmineral.com/ (last accessed 15 January 2018).

[22] Habashi [17].

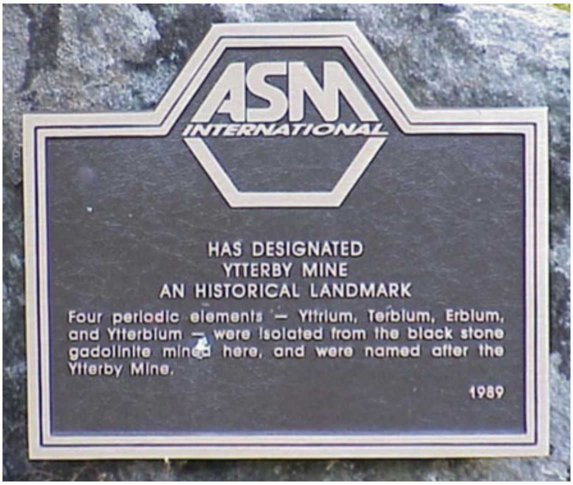

Fig. 3.3 Plaque erected by ASM International (formerly American Society for Metals) in 1989 to designate the Ytterby Mine as an Historic Landmark. Photograph courtesy of J. L. and V. R. Marshall, "Rediscovery of the Elements," ISBN 978-0-615-30793-0

Table 3.2 Average compositions (%) of the various monazite minerals

	Ce	La	Nd	Sm
Monazite-Ce	28.17	14.46	12.01	
Monazite-La	14.60	28.95	12.02	
Monazite-Nd	11.64	14.43	29.96	
Monazite-Sm	9.50		6.52	13.59

required great expenditures since they would have to be imported from a distance (Scandinavia, and later Brazil).

3.4 Progress in the Separation of Rare Earth Ores

In this overview of rare earths—their identities and their discoveries—much has been left out since the steps along the way were many and varied. We must now review some of these steps to understand why and how Carl Auer von Welsbach took up his work in Adolf Lieben's laboratory in 1882.

About forty years previously, in 1843, the great pioneer of rare earth research, Carl Gustaf Mosander (1797–1858), professor of chemistry and pharmacology at the Karolinska Institute in Stockholm, announced, after a discovery hiatus of forty years,[23] his discoveries of lanthanum and didymium (and in an addendum, of erbium and terbium) at the 13th meeting of the British Association for the Advancement of Science. The actual discoveries took place over a period of five years and were well-known to the chemistry community of the continent through letters, word of mouth, and brief notices published in scientific journals.

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[23] If we discount Gabriel Sefström's announcement of vanadium, not a rare earth, in 1830.

Early in his career, Mosander had become convinced that the curious ores from Ytterby, and elsewhere in Scandinavia, contained more than met the eye, and certainly more than the yttrium earth announced by Gadolin in 1794 and the cerium earth discovered in 1803 by Martin Heinrich Klaproth (1743–1817) and independently by Jöns Jakob Berzelius (1779–1848) and Wilhelm Hisinger (1766–1852). In 1838, in his examination of cerium earth, Mosander reasoned that if it were a mixture of more than one "earth," that the second one might be more basic than cerium and therefore separable with dilute strong acid—a guess that turned out to yield an oxide completely different from that of cerium and not corresponding to any other known oxide. He named this new substance *lanthan* (after the Greek word meaning "hidden," since it was "hiding" in the cerium). Not long afterwards, he succeeded in wresting another new earth from the mix, and since it followed so closely upon lanthanum's "birth," he named it "didym," meaning "twin," to lanthanum, of course. This name did not sit well with certain prestigious members of the community and they sought to change it to something less "childish," but Mosander persisted. And even in the flush of a new discovery, Mosander was not satisfied with the purity of his didymium—perhaps being prescient about what was to come decades later.

In 1843, convinced that yttrium earth also contained more unknown oxides, Mosander tackled it by fractionally precipitating basic salts from a solution of yttria in nitric acid and subsequently treating the precipitates with strong heat. He found three oxides, each different from the other, and corresponding to no other oxides then known. He named them, in order of decreasing basicity, yttria (keeping the original name), terbia, and erbia, thus setting a precedent for naming elements coming from the Ytterby mine eponymously.[24]

Mosander's work expanded the number of recognized rare earths from just two (cerium and yttrium) to six, adding lanthanum, didymium, terbium, and erbium to the list. Although one would expect that this achievement would have spurred feverish research to find even more of these elusive elements, curiously enough, quite the opposite happened. Perhaps because of the death of some of the early enthusiasts, like Berzelius, or more likely, perhaps because organic structural chemistry claimed the attention and efforts of the majority of chemists, inorganic chemistry was no longer "fashionable." But perhaps a field driven by scientific curiosity alone was not viable: there was no known use for these strange and elusive elements. Furthermore, the demands of the tried and true methods of fractional precipitation and crystallization had taken chemists about as far as they could go and the development of new techniques were necessary to give an impetus to this field of research again—in any event, there was a virtual hiatus of about thirty years before rare earth research picked up steam again, thanks in part to Bunsen and Kirchhoff's introduction of spectral analysis, and Mendeleev's ordering tool, the periodic table.[25]

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[24] Tansjö [18].

[25] Szabadvary and Evans [19].

3.5 1882–84: A Research-Based Private Scholar

Equipped with experimental knowledge of the analysis of the yttric earths along with his experiences of separation chemistry and spectroscopic analysis from Robert Bunsen's laboratory, Carl Auer von Welsbach was ready to write his "doctoral dissertation." By this is meant that he was preparing to conduct the experimentation that led to the two key papers that he wrote following his reception of the doctoral degree. They were, respectively, "Über die Erden des Gadolinits von Ytterby" (Auer von Welsbach C. (1883) Über die Erden des Gadolinits von Ytterby. Sitzungsber—Oesterr Akad Wiss Math-Naturwis. Kl Abt 2 88:332–344) and "Über die seltenen Erden." (Auer von Welsbach C. (1884) Über die seltenen Erden. Monatsh Chem 5:508–522). In the first of these two papers, he sets out his purpose[26]:

> The present work is the first publication on investigations which have the purpose of contributing to the knowledge of the earths of this interesting mineral, and, finally, should afford the possibility of obtaining, in a profitable manner, the elements contained therein in pure compounds and in abundant quantity in order to finally be able to accomplish the production of the elements themselves.

This initial declaration is very important since Auer now intends to accomplish what no other research chemist has yet managed to do: obtain pure rare earth compounds, produce them in large quantities, and eventually succeed in reducing the rare earth compounds to obtain the pure elements. That he more than succeeded is a matter of history, but this threefold purpose was almost prescient: he knows that he is going to succeed. In the following paragraph, he clearly sets out his program[27]:

> For the time being, I shall confine myself to the exposition of those methods which have been applied to separation in general in order to render the elements into distinct groups. I shall report later on their preparation in pure states, the determination of their equivalent weights, and the spectral methods applied as the basis of the investigations.

This brief paragraph conceals a very ambitious program. Rare earths can be separated from one another by a variety of physical means: selective oxidation, selective reduction, fractional crystallization, fractional precipitation, ion exchange,

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[26] Authors' translation from the German: Die vorliegende Arbeit ist die erste Publication über Untersuchungen, die den Zweck verfolgen, einen Beitrag zur Kenntniss der Erden dieses so interessanten Minerals zu liefern und schliesslich die Möglichkeit bieten sollen, in einer vortheilhaften Weise die darin enthaltenen Elemente in reinen Verbindungen und in reichlicher Menge zu gewinnen, um zuletzt die Darstellung der Elemente selbst realisiren zu können.

[27] Authors' translation from the German: Für diesmal beschränke ich mich auf die Darlegung derjenigen Methoden, welche zur Trennung im Allgemeinen angewendet wurden, um die Elemente in bestimmte Gruppen zu bringen. über die Reindarstellung dieser, die Bestimmung ihrer Aquivalentgewichte and das als Grundlage der Untersuchungen angewendete Spectralverfahren werde ich später berichten.

and solvent extraction.[28] Though it is now obsolete, fractional crystallization was the preferred method in the late 19th and early 20th centuries, and one used with painstaking care by Carl Auer von Welsbach. The method depends upon the variation in solubility of a mixture of salts in solution, the least soluble being the first to precipitate. Each successive fraction is treated in the same way, with purer (and smaller) amounts of the desired salt coming out of solution. The process is slow and tedious, and the choice of salts is crucial. Auer von Welsbach pioneered the technique with the double nitrates of ammonium salts in concentrated nitric acid.

So, separating rare earth compounds is the fruit of enormous labor: precipitation, calcination, dissolution, re-precipitation, filtration, washing, combining fractions, crystallization, grouping into series and then keeping track of the series, and each time analyzing each fraction spectroscopically in order to determine the purity of the substance, or lack thereof. In this regard, Auer was also very fortunate. A doting aunt had gifted him with a very thoughtful and precious graduation present: a pocket spectroscope from one of the best scientific instrument makers of the time, John Browning, & Co. of London, best known for precision spectroscopes.[29] She may not have known how he intended to use this expensive object, but she trusted in his talents, as did his loving mother who agreed to support him in his unpaid position—not knowing where all this might lead. Figure 3.4 is an image of Auer's original spectroscope; some time later he was able to upgrade to a Steinheil of Munich instrument.[30]

Auer followed the method of Bahr and Bunsen[31] and acknowledges his indebtedness to his mentor. It is worthwhile looking at this method since Auer himself acknowledges that it was a breakthrough in this work. Bahr and Bunsen dissolved the mineral gadolinite with hydrochloric acid, filtered off the insoluble siliceous material, and precipitated the salts from the boiling solution with oxalic acid. The precipitate, after being allowed to settle, was washed with water by decantation. The precipitate contained, aside from yttria and erbia, lime and the oxides of cerium, lanthanum, and didymium. The latter (ceric earths) were re-precipitated with potassium sulfate and separated from the double sulfates of the yttric earths, which remained in solution. The sulfate precipitate was calcined in an open platinum crucible, washed with boiling water, dissolved in nitric acid, and the salts were precipitated again with oxalic acid. This process was repeated until a concentrated solution of these earths in nitric acid no longer exhibited the didymium spectrum.

Bahr and Bunsen went on. In order to separate the erbia from the yttria, they proceeded as follows. They evaporated the two nitrates in a platinum capsule, waiting until the first red vapor bubbles appeared, indicative of an incipient

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[28] Voncken [20].

[29] https://en.wikipedia.org/wiki/John_Browning_%28scientific_instrument_maker%29 (last accessed 15 January 2018).

[30] https://de.wikipedia.org/wiki/C._A._Steinheil_%26_S%C3%B6hne (last accessed 15 January 2018).

[31] Bahr and Bunsen [21].

Fig. 3.4 Carl Auer von Welsbach's original pocket spectroscope. *Courtesy* Carl Auer von Welsbach Museum, Althofen, Carinthia, Austria

decomposition. They then immersed the capsule in cold water, and the pasty mass was transformed into a transparent, reddish glass, so friable, that the substance would often burst into pieces when touched with a stirring rod. They then dissolved the mass in just enough boiling water to do so and allowed the solution to cool, whereupon needles of dibasic erbium nitrate crystallized out. They repeated the same treatment for the mother liquor, effecting a second crystallization and a second mother liquor, which was subjected again to the same treatment, etc. The crystals most rich in erbium from these processes were combined, and after adding a small quantity of nitric acid, a new series of operations was begun (fusions, dissolutions in water, crystallizations), and a second series of crystallized products richer in erbium than the former was thus obtained. They represented the products derived from these various series of operations in a very simple way by coefficients 1, 2, 3, and the crystallizations of each series by exponents; $3a^4$ therefore designated a product obtained by the fourth crystallization in the third series of operations. In order to ascertain the progress of the purification, they carried out atomic weight determinations on the products.

At the time that Auer began his work, no rare earth preparations in a pure state existed. Since the separation of the yttric earths had been brought quite far by other investigators, Auer turned to the ceric earths, from which no additional element had been wrested in the previous thirty years with the exception of Paul-Émile Lecoq de Boisbaudran's (1838–1912) discovery of samarium in the didymium fraction in 1879 and Jean Charles Galissard de Marignac's (1817–94) further separation of samarium into gadolinium in the following year (See Fig. 3.1).

Both of these rare earth element discoverers arrived at their chemical fame via very different pathways. Lecoq de Boisbaudran, coming from a family of French wine merchants from Cognac, had little formal education in chemistry. This lack was more than compensated for by his burning interest in the rare earths, which he stumbled upon by seeing a display of their minerals in a university display case. He set up his “laboratory” in one room of his two-room apartment and spent his days and nights precipitating, washing, re-dissolving, and re-crystallizing his very small samples, all that he could afford. His hard work paid off by his discoveries: first, gallium in 1875 from zinc ore, then samarium in 1879 and dysprosium in 1886 from typical rare earth ores.[32]

Swiss chemist Jean Charles Galissard de Marignac came by his chemistry in a quite straightforward way: from the École Polytechnique of Paris he gravitated first to the École des Mines and thence to Giessen. He returned to his native Geneva to take up teaching in what would become the University of Geneva, distinguishing himself for his great precision and exactitude in his experimental work, particularly in determination of atomic weights and crystal structures. He also succeeded in extracting ytterbium from terbium in 1878 and gadolinium from “pure” samarium in 1880.[33]

3.6 In the Footsteps of Bunsen: Separations and Spectra

Following Bunsen’s classic separation method, Auer first used the fractional decomposition of the nitrates for separation, but soon found an improvement by carrying out a fractional basic precipitation by the addition of earth oxides, his oxide process. As starting material, he used 7 kg of ceric earth that he had obtained from the Bastnäsgrube mine near the town of Riddarhyttan, Sweden. The raw mineral contained large amounts of silicates, beryllium, and iron which had to be digested and separated out—a very laborious process. As his work progressed, he realized that the method of fractional crystallization could be more advantageously used than fractional precipitation. Although the time expenditure is greater, the results make up for it by greater separation efficiency. Furthermore, the preferred solvent is almost always water, certainly more pleasant to use than noxious strong acid solutions.[34]

In this method, the mixture to be separated is converted into a well-crystallized salt, conveniently soluble in hot rather than cold solutions. During the crystallization of closely related earths, mixed crystals are formed. They are dissolved by heating and several fractions are allowed to crystallize successively. After complete cooling, the solutions are separated from the crystals, and the solution of a fraction is combined with the crystals of the next, dissolved by heating, and allowed to crystallize again. The crystals of the first fraction are dissolved in water; the solution of the last fraction is evaporated to dryness. By frequent repetition, the

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[32] Marché [22].

[33] Figuier [23].

[34] Auer started out working with concentrated nitric acid as the solvent, but later found he could just as effectively carry out the required separations in water.

crystallization series becomes more and more drawn out, i.e., the separation effect becomes more evident. The most difficultly soluble constituents become more and more abundant in the earlier fractions, especially in the main fraction, the most readily soluble in the latter fractions and the residual solution. If the respective fractions were sufficiently pure, they could then be removed.

Auer made various improvements allowing him to scale up to 20 kg of oxide in the form of the corresponding salt. He also found that double salts were particularly suitable, for example, the double ammonium nitrates, recommended in 1873 by Dmitri Mendeleev,[35] $M(NO_3)_3{\cdot}2NH_4NO_3{\cdot}4H_2O$, where M represents the rare earth metal. When the starting amount is sufficient, in principle all components of a mixture can be separated out in the pure state. A disadvantage, as mentioned before, is the high total time expenditure, since one can usually only carry out one series per day and depending upon the purity of the starting material, several hundred series may be necessary. After the removal of the principal quantities of cerium by thermal decomposition of the nitrates, these methods were applied to the mixture of the other cerium earths.[36] The quantitative tracking and mathematical calculation was only carried out in the mid-20th century. It gave a confirmation of the scheme and a more precise characterization of the separation effect.[37]

While he was in Bunsen's laboratory, Auer was asked to study the different spectra of the rare earths that had been extracted from gadolinite. He realized that spectral analysis was the key to determining the degree of purity of an element or its earth because certain spectral lines disappeared during chemical purification by fractional crystallization.[38] When Auer returned to Vienna to work in Lieben's laboratory, this experience of spectroscopic analysis was a major skill that would stand him in good stead.

Much has been made of the Bunsen-Kirchhoff prototype spectroscope and the use of the Bunsen burner to discover new elements such as rubidium and cesium. What is sometimes overlooked is the fact that Bunsen was quite forward looking in terms of always looking for new techniques; it was not long before he dropped "his" burner in favor of the far more powerful method of elemental excitation, the spark generator. This method consists of placing near one another two metal rods connected to the ends of the secondary of an induction coil. When the coil is activated, a stream of sparks passes between them.

Michael Faraday (1791–1867) discovered the induction principle in 1831 and carried out the first experiments using induction coils.[39,40] The utility of such coils was

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[35] Mendelejeff [24].

[36] Rossmanith [25].

[37] Joy and Payne [26].

[38] Habashi [27].

[39] The structure and use of an induction coil is described in detail in Houston [28]. Available as a Google book: https://archive.org/details/atreatiseonligh00housgoog (last accessed 15 January 2018).

[40] See https://en.wikipedia.org/wiki/Induction_coil (last accessed 15 January 2018).

quickly understood and within a short time, they became much improved and commercially available. The Ruhmkorff[41,42] (Fig. 3.5) coil was a favorite model and the one used by Robert Bunsen in his spectroscopic experiments as a means of quickly and powerfully exciting elements in order to observe their characteristic spectra.

Kirchhoff and Bunsen describe their use of the Ruhmkorff apparatus thus[43]:

> Small pieces of potassium, sodium, lithium, strontium, and calcium were bound to fine platinum wires and fused into glass tubes in pairs so that they were separated from each other by a space of 1 to 2 mm, and the wires penetrated the glass wall. Each of these tubes was placed before the slit of the spectral instrument: with the aid of a Ruhmkorff induction apparatus, we let electric sparks pass between the above-mentioned metal pieces, and compared their spectrum with the spectrum of a gas flame into which the chloride of the corresponding metal was brought. The flame was behind the glass tube. When the Ruhmkorff apparatus was alternately placed in and out of action, it was easy to see without even measuring them that the bright lines of the flame spectrum were unobstructed and quite visible despite the brilliant spectrum of the spark.

Auer was quite familiar with this method and applied it to his fractions of recrystallized rare earth salts assiduously. However, over the course of his work, he made improvements to the design and voltage generation. In a major paper written much later in the course of his career, “Spektroskopische Methoden der analytischen Chemie”,[44] he provides diagrams of the various pieces of apparatus that he designed and used.

His spectroscopes improved with time as well. Figure 3.6a shows one of his typical spectroscopes, manufactured by the Munich firm of C. A. Steinheil Söhne, with the sparking apparatus set to one side on the right, and Fig. 3.6b depicts the sparking apparatus in place and ready to be used. His own personal design and improvements of the auxiliary equipment, which he made himself and were state-of-the-art, were of decisive importance because they enabled him to follow with greater certainty and precision the spectra generated in the course of his work. One writer, J. D’Ans, remarks that it is astonishing, in spite of its simplicity, its greater advantages, and Auer’s great success in its use, this type of apparatus remained ignored for decades.[45] D’Ans goes on to say that his work habits were somewhat peculiar: he often came into the laboratory late in the afternoon, and worked through the night into the early morning. He observed this timetable until the day of his death.

In Auer’s second paper (1884), he engages in a more general separation of the rare earths from minerals other than gadolinite. He remarks that he hit upon a very simple method of accomplishing this, namely, addition of finely divided oxides of

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[41] Heinrich Daniel Ruhmkorff (1803–77) is often credited with the invention of the induction coil, but it was actually invented by the Irish Roman Catholic priest, Nicholas Callan (1799–1864) in 1836. Ruhmkorff was the first to commercialize and popularize his product so that his name quickly became associated with the induction coil.

[42] https://en.wikipedia.org/wiki/Heinrich_Daniel_Ruhmkorff (last accessed 15 January 2018).

[43] Kirchhoff and Bunsen [29].

[44] Auer von Welsbach [30].

[45] D’Ans [31].

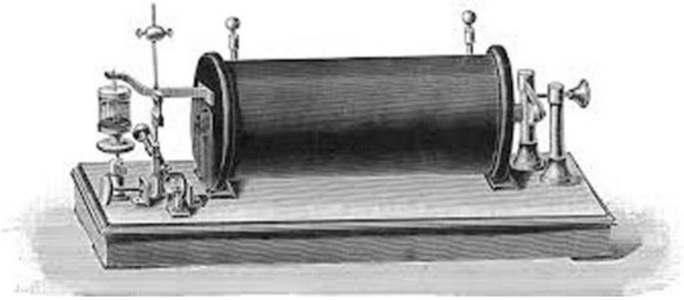

Fig. 3.5 A Heinrich Ruhmkorff induction coil, 1851

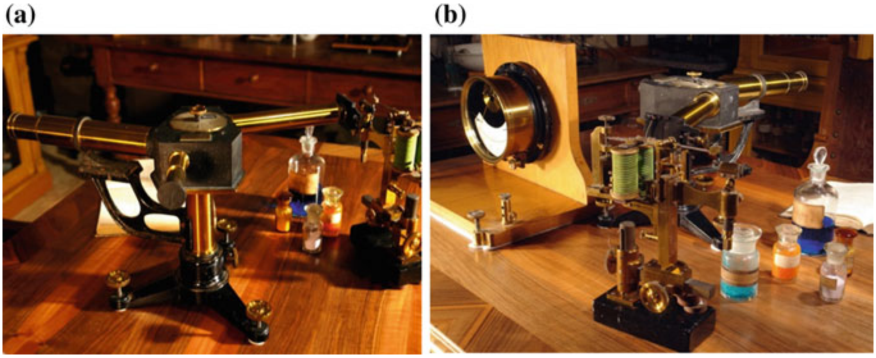

Fig. 3.6 **a**, (left) Steinheil spectroscope used by Auer von Welsbach with spark apparatus on the right; **b**, (right) Spectroscope with spark apparatus in place

certain rare earths to the solution, making the entire mixture uniformly basic. Then, during the procedure the circumstances may vary, but[46]:

> the end result is the same in all cases, the different degree of basicity always remains the guiding principle of the principal separations.

The ideas and descriptions in Auer's papers are never easy to follow. But they betray to us aspects of how excellent his powers of observation and his experimental techniques were. He took tried and true methods of fractional precipitation, and later of fractional crystallization of the double ammonium nitrates, and implemented them systematically according to a fixed scheme which became the gold standard for later work. It should be noted that these methods were extremely

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[46] Auer von Welsbach [32].

painstaking and demanded unrelenting persistence: more than 100 fractionations were often necessary to produce observable differences, and each individual crystallization involved a waiting period of 24–48 h.[47]

In his descriptions, we can recognize his gift of seeing the possibilities for improvements, and in seeing the quickest, most efficient way to reach a goal. In his publications, there are numerous indications of important observations he made, and which he promised to return to at another time. His keen and unparalleled observational skills revealed to him many things that he could not cope with all at once since he always worked alone. His passion and ambition were the separation of the rare earths, and the possible discovery of new elements in their ores. He pursued this interesting and important field of endeavor with inexorable genius, ever building on the work that went before. It was the combination of his skills in separation, spectroscopy, and atomic weight determination that were to catapult him into the limelight of the scientific stage in the following year.

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Chapter 4
Didymium's Twilight and Two New "Stars"

4.1 Suspicions Regarding Didymium

Long experience in dealing with the rare earth elements and the difficulty of separating them one from the other made chemists aware of the pitfalls of claiming that they had succeeded in producing an unequivocally pure compound. Furthermore, the claimed discoveries turned out to be a tangled web of errors mixed with grains of truth as investigators tried to go over old ground, that is, to take another look at minerals once pronounced to be completely separated and analyzed. They uncovered layer after layer of new information that often led to the discovery of a new element that lay hidden all along.

The analytical expertise of Carl Gustaf Mosander was a match (almost) for the chemical elusiveness of the rare earths. He managed to extract six of them from the yttrite and cerite minerals at his disposal, more than any chemist before or since had managed to do. Among the "children" in this prodigious series was the element he named "didymium" in 1841, derived from the Greek word *didymos*, meaning twins, since it occurred twinned with lanthanum and cerium in its minerals. This choice stirred up some controversy and harsh objections in the chemistry community; some people, among them Friedrich Wöhler (1800–82), claimed the name sounded like baby talk.[1] Mosander stood firm against all comers with respect to the name; he claimed that it was simply to utilize the letter D to name an element since that letter had never been used before, and he wanted to have something different.

It did not take long before didymium's credentials as an element were called into question. In 1848, Jean-Charles Galissard de Marignac found that it had an atomic weight, calculated by today's methods, of 73.36, a value too low for a rare earth element. A few years later, he repeated this analysis and determined an atomic weight of 96, again far too light to be compatible with an assignment among the rare earths.[2]

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[1] Wöhler asserted that Mosander had chosen the name because he had two sets of twins.

[2] Marignac [1].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_4

More doubts about the nature of didymium arose as time went on, this time on the basis of spectroscopic evidence.[3, 4] One of the most vociferous doubters was Marc Abraham Delafontaine (1837–1911), an indefatigable worker who published prolifically, convinced that he had discovered new rare earth elements that he named *mosandrium*,[5] *philippium*, and *decipium*.[6] Not one of these remains today—though he receives joint credit for the discovery of holmium (Delafontaine's *philippium*) and perhaps should for gadolinium, more than likely his own *decipium*. He was very much involved with the terbium-erbium dispute and eventually was able to confirm the existence of terbium as well as yttrium and erbium in 1864.[7]

Despite his errors, Delafontaine was a very good and observant chemist. The rare earths ended up confounding the brightest of chemists over a period of 150 years. He had learned his lessons well from his old teacher, Marignac: he was well versed in theoretical chemistry and a superb analyst. By the time he took up a complete study of samarskite in 1878, he had set up his own analytical laboratory in Chicago, USA, having emigrated from Switzerland in 1870. He published a note that raised some questions about the homogeniety of didymium. Didymium had been under suspicion for years: who knew what hitherto undiscovered elements lurked under its shadow? Delafontaine remarked[8]:

> Ever since Mosander did his fine work, the results of which have been confirmed and extended by Messrs. Marignac, Bunsen, Cleve, and others, it is agreed that didymium be considered a simple body. It must be remarked, however, that all these chemists have worked on products taken from Bastnoes cerite; I do not know if a comparative study of the didymium contained in other mineral species has been made. My old experiments on didymium from gadolinite had led me to suspect that didymium is not a simple body; some recent observations on samarskite from the United States have greatly strengthened these suspicions.

He goes on to cite some experimental evidence to support his suspicions:

> As is well known, solutions of didymium salts give a beautiful absorption spectrum characterized by numerous lines and bands, of which MM. Bunsen and Lecoq de Boisbaudran carefully determined the position. Now, I have found that, at an equal or even greater amount, the didymium nitrate obtained from samarskite gives a less complete spectrum than that from cerite. In the least refrangible blue, that is, near the green, the didymium from cerite exhibits spectroscopically a group of four narrow bands (the first three at least), which are substantially equidistant; The first and third ($\gamma = 482$ and $\zeta = 469$ of M. Lecoq) are much sharper and darker than the other two; They are still very visible even in dilute solution…I have not been able to observe this group under the same conditions in solutions of didymium from samarskite, no matter how varied the experiments have been, this negative result has always been the same.

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[3] Bunsen [2].

[4] Bunsen [3].

[5] Note: With the exception of didymium, the names of elements that are not now present nor ever were present in the periodic table are rendered in italics.

[6] This could mean either "deceived" or "disappointed." Delafontaine was both.

[7] Delafontaine [4].

[8] Delafontaine [5].

The two sharp bands, the blue at 482 nm and the green one at 469 nm convinced Delafontaine that his sample contained a new element, characterized by the more energetic blue band. Who knows if he had pursued this line of research further if he would have beat Carl Auer von Welsbach to the punch and have been the first to separate didymium into its constituent elements?[9]

Probably the most cogent piece of experimental evidence to be offered to date was that of Per-Teodor Cleve (1840–1905), professor of chemistry at Uppsala University.[10] A very competent rare earth chemist, he is credited with the discoveries of holmium and thulium. It would be worthwhile to reproduce his communication in its entirety because it first recalls some historic information about didymium, then describes his own experiments, and then, by his report, reserves the right to continue his work along these lines, and finally states that he does not wish to stand in the way of other investigators, expressing the hope that this article will be of some help to them. It is this last bit of equivocation that gives the impression that the author is still assailed with doubts.

> In 1874, I determined the atomic weight of didymium by means of an oxide in which the spectroscope did not detect the presence of lanthanum, nor of yttria. As an average, I found the number 147. Later, Mr. Brauner fixed the atomic weight at 146.6, which differs very little from the number found by myself. The chemists who, before me, proposed to determine the atomic weight of didymium found numbers approaching 144. Most recently I received a letter from Mr. Brauner in which he informs me that he later found the number 145.4. I have always suspected the presence of a new element accompanying didymium during the last few years, and have made several efforts to find it. At the beginning of the year I subjected about 200 g of didymium oxide, extracted from gadolinite, and separated from the earth of yttria with sulphate of potash by repeated precipitations, to fractional precipitation.
>
> The atomic weight of the fraction which precipitated first was 146; the last fraction had an atomic weight 142. Examination of the spark spectrum showed, in the last fraction, fairly strong lines of didymium and lanthanum, but also of new lines, of which one is very strong and possesses the wavelength $\lambda = 4333.5$, after an exact determination of Mr. Thalén. This line does not belong to didymium or lanthanum, nor to yttrium, erbium, terbium, or to the $Y\alpha$ of M. Marignac.
>
> The first atomic weight fraction 146 gave only a small trace of this line. It is therefore obvious that the metal which exhibits this line is more basic than didymium, and less [basic] than lanthanum. Samarium is less basic than didymium. Having subjected the chloride of didymium to a series of decompositions fractionated by heat, I have found the same line in the fractions which are most resistant to decomposition, but I have not been able to trace it in the first fractions. I have found the line in the spectrum of the fractions which have been precipitated with formic acid, whence it appears that the formate must be sparingly soluble, such as didymium formates and oxides of cerite. The double salt with sulphate of potash must also be less soluble.
>
> The line 4333.5 had already been observed in 1868 by M. Thalén in a mixture of lanthanum and didymium obtained by M. Bahr. He could not find it in 1874, by examining didymium and lanthanum prepared by myself. Consequently, I had eliminated it by the repeated

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[9] Although in the separation later carried out by Auer, he does not mention a blue band as indicative of either praseodymium and neodymium.

[10] Cleve [6].

> fractionations to which I subjected the lanthanum and the didymium. The metal which produces this line appears to accompany didymium in most minerals. It has been found in impure didymium extracted from hjelmite, monazite, eucolite, orthite from Arendal, cerite and gadolinite.
>
> I have reported these facts to reserve the right to continue my research on didymium, for which I made considerable preparations. I do not want to prevent chemists who, fortunately for science, are occupied at the same time with me in the chemistry of the rare earths, to continue their research. On the contrary, I will be satisfied if the facts mentioned above can help them in their research. It follows, it seems to me, from the above, that there is still an unknown element accompanying didymium, and, in order not to give it a name, I propose to designate it provisionally by the symbol Di-β, characterized by the strong line λ = 4333.5.

With a speed competitive with lightning, a communication from the Czech chemist, Bohuslav Brauner,[11] appeared in the same journal, probably composed the very day that he read Cleve's note (or perhaps submitted prior to Cleve). Again, it is important to look at this article in its entirely to catch its tone: is it really trying to establish priority for the splitting of didymium?

> M. Cleve has published a Note on a new metal of cerite, which he designates by Di beta… This metal, less basic than lanthanum, is more so than didymium. I dealt with the same subject in a Memoir which was read before the Vienna Imperial Academy on October 6, 1881, but I deferred publication of the part dealing with a new element from cerite until my experiments were more advanced. M. Clève's communication enables me to present to the Academy the first results of my experiments, of which I have been engaged for the last three years. I have found that lanthanum sulphate, purified by repeated crystallizations, may be decomposed, if the oxide is treated with a solution of ammonium nitrate, into two earths: the atomic weight of the most basic (lanthanum oxide) being 138.3–138.8, and the weight of the less basic 140.2.
>
> By treating the oxide of didymium, containing no lanthanum, by the nitrate of ammonia, I was able to extract from it an earth that formed colorless salts, the atomic weight of which was 140.6. The atomic weight of the remaining didymium was 142.5; but, by repeated precipitation, a product with an atomic weight of 146.6 was finally obtained. In the spark spectrum of the different fractions obtained by decomposing the impure didymium, I found lines belonging to none of the earths from cerite whose spectrum is well known.
>
> I have explained all these phenomena by the presence of a fourth element in cerite, which is doubtless identical with the Di beta of M. Cleve. By carefully purifying fresh quantities of didymium, and especially after removing the more basic and less basic fractions than didymium, I have found for the atomic weight of didymium the number Di = 145.4 (O = 16, S = 32,074).
>
> By employing the same process, in order to purify the didymium, which had previously given me the atomic weight 146.6, I succeeded in separating another earth with an atomic weight greater than 145.4: the residue remaining after this purification gave me an atomic weight equal to 145.4. It is, I believe, the number that most closely approximates the true atomic weight of this element.
>
> In the most basic liquids obtained after the precipitation of pure didymium containing no lanthanum, a mixture of didymium and an earth lowering the atomic weight of the didymium was found up to 143.3. We see from the foregoing that ordinary didymium is a

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[11] Brauner [7].

> mixture of at least three elements. One is the real didymium (Di = 145.4); the other (M. Cleve's Di beta) is more basic than didymium, and its atomic weight is about 141; the third, with a higher atomic weight, is less basic than didymium (*samarium*?). The preceding communication is not intended to dispute the priority of the Swedish scientist, whose fine researches on rare earths signal a new epoch in science. I only wish to show that I have made observations on a new earth of cerite independently of M. Cleve.

It is interesting to unravel the timing of these notes against Brauner's professional timeline. Cleve's note appeared on 3 July, 1882[12]; Brauner's, in which he states he was engaged in this research for the last three years, i.e., since 1879, in the laboratory of Sir Henry Enfield Roscoe (1833–1915),[13] followed later in that same year but with a publication date of 26 June, 1882.

Although Brauner's publication is dated BEFORE Cleve's, according to the *Journal of the American Chemical Society*, it is clear that it was actually published AFTER Cleve's because he refers to Cleve's paper in his note—unless the correspondence between the two was so close and so frequent that it is difficult to say who preceded whom. Cleve states in his paper that he received correspondence from Brauner in which he reports an atomic weight for didymium of 145.4, the value published by Brauner[14] in his own paper.

Nothing more seems to have appeared in the chemical literature on this subject in the subsequent three years, and things quieted down.

4.2 Didymium Is Subjected to the Test

Carl Auer von Welsbach returned to Vienna from Robert Bunsen's laboratory shortly after 2 May, 1882 and set up shop under the patronage of Adolf Lieben. Here he worked for two years on rare earth separations that resulted in two important papers, documented in Chap. 3. All the while, the question of didymium's true nature was simmering, it seeming odd that this didymium, obtained from different rare earth minerals, also had different atomic weights.

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[12] Abstracts in J Am Chem Soc (1882), 4:240. Remarks on Didymium. By P. T. Cleve. (No. 1, July 3d, 1882.) In a preliminary note the author suggested the existence of a new element which he named Beta-Didymium, but further experiments have shown the non-existence of this new element.

[13] Abstracts in J Am Chem Soc (1882), 4:240. On Didymium. By B. Brauner. No. 26. (June 26, 1882). Ordinary didymium is a mixture of three elements-didymium, beta-didymium and perhaps samarium.

[14] Bohuslav Brauner was a Bohemian chemist who spent almost his entire career at Charles University in Prague. A student in Robert Bunsen's laboratory from 1878 to 1879, he conceived there a lifelong interest in the rare earth elements. He was particularly observant regarding missing elements and proposed that one lay hidden between neodymium and samarium. He also was the first to propose that all of the rare earths should be placed in the same box in the periodic table since there did not seem to be any other room for them given their chemical similarities.

Having tested his own mettle and developed uncanny expertise in fractional precipitation,[15] he took advantage of subtle differences in the solubilities of the constituent elements in the rare earth mixture to separate it into its constituent elements, with each step producing only an incremental change in composition. For Auer this procedure constituted a simple and fruitful plan of work. His methods were to be imitated and carried to a stupendous conclusion in the work of Marie Curie who, using this method perseveringly, fractionating tons of pitchblende, eventually succeeded in unearthing new elements such as polonium and radium.

In 1885, the results of his work appeared in the little known session reports of the Austrian Academy of Mathematics and Science.[16] For the sake of comparison with the earlier work of Cleve and Brauner, it is wise to examine this work in detail. The paper is paraphrased below.

Auer first refers to his earlier works on the separation of the rare earths as described in Chap. 3. He then begins to describe a new method of separation: the fractional crystallization of the ammonium double nitrates of lanthanum and didymium in a nitric acid solution. He found it possible to completely separate the lanthanum from the didymium in only a few operations, obtaining very pure lanthanum. When he speaks of the element, he really means compounds of the element as methods to reduce the rare earths to their elemental forms were not developed until much later. Any amount, he says, can be processed with the same degree of effort, not only to separate the lanthanum from the didymium, but also the constituent elements in the didymium one from the other. Then came the daunting sentence:

> After several hundred repetitions of the separation process, the elements obtained were abundant and pure.

He then goes on to say that the absorption spectra of the compounds of these elements are parts of the absorption spectrum that had hitherto been regarded as characteristic of what had been presumed to be a pure element, didymium itself. And if one combines these elements in a certain ratio, one can obtain the original spectrum of didymium as well as its characteristic color. Thus, he says, the didymium spectrum is, in a sense, the sum of the absorption spectra of the new elements.

The spark spectra of the new elements are splendid, he says, and these are, in a similar manner, parts of the didymium spectrum. The compounds of the two new elements have different colors. Those of the first, (which fractionates) nearest to lanthanum, are a pure and intense green; those of the latter, which appear in later fractions, are pure pink or amethyst. This latter element forms the major part of the elements split out from didymium.

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[15] Goldschmidt [8]. Fractional crystallization is a method of separating two or more substances whose properties are so similar that the classical chemical methods are useless. The evaporation of a solution containing their compounds gives rise to mixed crystals; however, the proportion of the two elements in these crystals is different from those in the mother liquor, so that it is possible to separate one from the other by successive operations.

[16] Auer von Welsbach [9].

He goes on to say that the abovementioned separation process is based on the lower solubility of lanthanum salts and on the significantly greater solubilities of the ammonium double nitrates of didymium-containing elements in nitric acid. The raw material he used was a mixture of didymium and lanthanum nitrate, as obtained, for example, by processing cerite. The presence of the lanthanum facilitates separation. You have to start with very rich material. He started with 2.5 kg of the blended nitrates. The solution of the nitrate mixture is treated with the corresponding quantity of ammonium nitrate, acidified with nitric acid (concentrated nitric acid making up about one tenth of the total solution), and evaporated in a large porcelain dish until small crystals begin to precipitate on the surface (Some care must be taken not to evaporate the mix too strongly.) Then some water is added. Crystals begin to reform and the solutions are always allowed to crystallize for about 24 h.

He goes on: After the mother liquor has been poured off, the crystals are placed in a large funnel and washed with a little concentrated nitric acid. The wash liquor is added to the mother liquor, and this is now evaporated. It is advisable to add to the almost cold solution the crystals of an earlier or later fraction, in order to prevent supersaturation. The evaporation of the residual mother liquor is repeated about 6–8 times, thus obtaining 6–8 fractions, forming the first series. The first fractions contain nearly all the lanthanum and the last almost all the didymium. The first fraction is pale pink; the latter are successively more intensely colored. But the absorption spectra still show no appreciable change.

He then combined the first few fractions and did the same thing as with the last few fractions; this is how an intermediate series develops. Then one begins to recrystallize the combined fractions. The last fractions of the series contain no lanthanum, but only didymium and the very interesting elements of the yttria group that accompany didymium.

During the next series of recrystallizations, the first portions of the lanthanum fraction begin to show a yellowish-green color. The didymium fractions become somewhat paler. These last portions are always combined again and again, until finally a small quantity is obtained which no longer crystallizes.

The absorption spectra of the outermost fractions of the above-mentioned series have already become distinctly different. The fractions at the beginning (146–148) show extraordinarily intense absorption bands in the blue, fractions 156–159 are close to the color of the sun's F-line (486.1 nm on the Fraunhofer scale) and fractions 179–185 have a violet shade. The absorption bands in the yellow and green have become much weaker. He then observes that addition of concentrated nitric acid to these solutions bleaches the spectrum, whereas dilute nitric acid has no effect. So, he advises that nitric acid be removed from the solutions or that they be diluted with water.

Here is his summary of the separation process up to number 15, including the numerous intermediate series:

> The quantity of pure lanthanum fractions is diminishing; almost all of the lanthanum contained in the raw material has been obtained. The green coloration of the first fractions of these series, which follow the lanthanum fractions, becomes ever more intense and purer: in spite of numerous operations, it becomes increasingly difficult to obtain colorless

> products from it. The early fractions of the last series exhibit no color, the intermediate fractions have a mixed color, and the later fractions are tinged with light green and violet, but the green is fast disappearing.

We can see here the beginnings of a complete separation of the two elements.

Interestingly enough, in dealing with the syrupy mother liquor that remains, Auer says that the absorption bands of decipium are clearly recognizable. We have to recall that decipium was Marc Delefontaine's name for gadolinium. Further recrystallizations of the later fractions, which are very soluble in dilute nitric acid, produce magnificent rose-red crystals which, prior to this work, would have been identified as pure didymium.

Auer goes on to describe the colors of the separated salts when transformed into oxalates, when weakly and then strongly ignited in an oxidizing flame, and also how, along the way, he recognizes the occurrence of other rare earths such as samarium. He also notes a correlation with their absorption, emission, and spark spectra, describing how the latter were obtained with a new instrument.

He notes that the chemical resemblance of the two elements is, in most cases, exceedingly great, and in fact the greatest one known between elements. If a separation of the two bodies were to be effected (as nitrates), the precipitations would have to be repeated several thousand times. See Fig. 4.1 for a typical storage bottle for one of these fractions. The one element forms green salts and green solutions, while the other gives pure pink crystals and splendid amethyst salts. He also notes the properties of their oxides, produced by vigorous ignition of the nitrates or oxalates. The first, dark, almost blackish-brown, dissolves in dilute sulfuric acid and is easily reducible to a greenish-white sesquioxide with a formula of M_4O_7. The other element does not show these changes in its oxidation states.

Finally, after all this descriptive evidence about the two new elements, accompanied by figures of their spectra, Auer declares:

Fig. 4.1 A fraction of praseodymium, 1st series, fraction 160. Label written by Carl Auer von Welsbach

> In view of the fact that the resolution of didymium into multiple elements has been accomplished, I suggest that the term didymium be now completely eliminated, and that the first element, corresponding to the green coloration of its salts be called praseodymium with the symbol Pr and that the second, as "new didymium," have the designation neodymium with the symbol Nd.

Auer then gives the results of his atomic weight determinations, which, he states, were carried out according to Bunsen's method: Praseodymium = 143.6, neodymium = 140.8, and the corresponding oxide being given by the general formula M_2O_3. He says, "The properties of the two elements presented here clarify many of the contradictory results of the chemical investigations carried out to date." And further:

> In the course of my exposition I have spoken of more than these two elements. This was partly due to remarkable correlation of the absorption spectra of the preparations of the neodymium series. These phenomena can only be followed further by means of large, high-dispersion spectrometers. If further investigation in this field proves the existence of new bodies, these are present only in minute quantities in didymium.

4.3 Results and the Disappearance of Didymium

There is no mistaking the fact that this report is evidence of careful, painstaking, persistent work over a long period of time and represents far more than a casual interest in didymium and the other rare earth elements. It was work undertaken with a purpose and with the secure knowledge of success. It was also an original work, eschewing even the tried and true fractional precipitation method for a new one developed by himself in 1884,[17] fractional crystallization of ammonium double nitrates. The choice of the salt was serendipitous: since the method relied on the differential solubilities of the salts, it was more effective and required fewer fractionations if the solubility differential was large, which in this case, it was! Separation nonetheless required hundreds of fractionations, each one of which required a wait time of 24–48 h. The reader is treated to a gradually unfolding discovery told as a colorful tale as each new fraction begins to fall on the side of the green or of the rose-red. Finally, at the end, almost with a flourish, the author definitively states that the old name of didymium be discarded and replaced with two new names: praseodymium, meaning "green twin," and neodymium, meaning "new twin." He buttresses his conclusion with spectroscopic data and atomic weights. The latter are given as 143.6 for praseodymium and 140.8 for neodymium respectively. In a later paper,[18] Auer corrects himself, having mixed up the two elements. Praseodymium, the lighter of the two, is given as 140.57 (140.908 today) and neodymium is given as 144.54 (144.24 today). The accuracy of these figures speaks volumes for the purity of the salts that Auer obtained. Brauner's reported weights were 141 and 145.4 respectively, a solid indication that he too had

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[17] Auer von Welsbach [10].

[18] Auer von Welsbach [11].

separated didymium into its elements, but never proposed names and actually, in his paper reproduced above, he never claimed any kind of priority.

It is interesting to note that in the secondary literature immediately following Auer's publication, the names of the two new elements are given as praseodidymium and neodidymium, noting that the "extra –di-syllable" was dropped about ten years later. However, in neither of Auer's two papers announcing his discovery does he ever use the –di. So, the correct question might be: why was the –di- added after the discovery?

After Mosander's discovery of didymium in 1841, it is possible to trace its history via the chronology of ceric rare earth discoveries (Fig. 3.1). In 1879, when Lecoq de Boisbaudran split out samarium from didymium, he preserved the latter's name. Likewise, when Marignac separated out gadolinium from samarium a year later, he preserved the name samarium even though initially it, too, was a mixture. A growing tradition, carried out even as late as 1901 by Eugène Anatole Demarçay (1852–1903), seemed to be that the original name of one of the elements was kept even after resolution of other elements contained in the mixture.

Carl Auer von Welsbach chose to break with that "tradition" and while he preserved the final syllables of didymium, he attached his own prefixes to signify a color (praseodymium) and the novelty of the new element (neodymium). And so it was that the venerable name of didymium disappeared from the official roll call of the elements. But the name lives on in the literature as a historic artifact that can easily be accessed on line.[19]

4.4 *Aldebaranium* and *Cassiopeium*

On the heels of Auer von Welsbach's successful separation of didymium into its two constituent elements[20] came a series of other successes that will be detailed in the chapters that follow. For this reason, Auer discontinued his work on rare earth separations from yttrite and cerite minerals, though this type of chemical research always remained close to his heart. So from 1884 until the close of the 19th century, he was occupied with other aspects of the rare earths, transforming "useless" laboratory curiosities into some of the most sought-after commodities on earth.

At the beginning of 1900, he took up his separation work again in his purpose-built laboratory (Fig. 4.2) in his home in the province of Carinthia (German: Kärnten) in southern Austria due to two new circumstances: he found some leisure time to pursue these studies, and he also had become almost completely deaf, thus causing him to withdraw from the industrial communities that he himself had established. Preferring to do his first work on the problem of didymium, he left his suspicions about the homogeniety of ytterbium unexplored. Auer was not the first chemist to have these reservations about ytterbium. Ever since Marignac

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[19] Langmuir [12].

[20] No additional elements were ever found even though thoroughly searched for by Auer himself.

Fig. 4.2 Auer von Welsbach's home laboratory in Schloss Welsbach, Carinthia

separated ytterbium from raw yttric earth in 1878, a long line of questioners emerged: Sir William Crookes (1832–1919) in 1888, Franz Exner (1849–1926) and Eduard Haschek (1875–1947) in 1899, Eugène Anatole Demarçay in 1900 and Georges Urbain (1872–1938) in 1905, among others.

Since Auer had a large amount of rare earth minerals available to him from the work of the previous decade, he was in a good position to begin again. Starting with about 500 kg of raw yttrite earth, he began to use his tried-and-true fractional crystallization of the ammonium double nitrate salts but found the method less effective with this different raw material. Resorting to another handy method, use of the ammonium double oxalates, he was soon successful in separating out erbium and thulium, but also noticed something new: a change in the relative intensity in the spark spectrum of the region normally assigned to ytterbium. Patiently working out a series of fractional crystallizations over a period of some years, he was finally able to read in his report to the Vienna Academy on 30 March 1905, that he had irrefutable proof of "two" ytterbiums because what he had in hand were two parts of the complete ytterbium spectrum.[21]

In the following year, having perfected the oxalate method and given accolades to his former mentor, Robert Bunsen, for all his help, he was able to say that not only was ytterbium a composite mixture, but that he was on the cusp of isolating the components.[22] However, as was his habit in other publications, he promised to

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[21] Auer von Welsbach [13].

[22] Auer von Welsbach [14].

provide more details later: no quantitative information was contained in either of his two preliminary reports: no atomic weights and no observed wavelengths. To distinguish between his two components, he referred to them as Yb I and Yb II, but declined at this point to confer names on them.

Late the following year, on 19 December 1907, Auer presented his definitive paper on the resolution of ytterbium into two different elements.[23] In it, he again described his use of the double ammonium oxalates for his fractional crystallizations, remarked that things got more difficult after about 50 fractionations, and he described the separation process in detail along with the spark and absorption spectral measurements that he made for each separation. In the end, he was able to obtain about 0.5 kg ytterbium oxide when he combined his fractions.

This time he named the elements *aldebaranium*, with the symbol Ad, and *cassiopeium*, with the symbol Cp.[24] Their atomic weights were determined as 172.90 (today 173.04) for Ad and 174.23 (today 174.97) for Cp. The paper also contained 21 pages of wavelength tables. Auer's ace-in-the-hole were the spark spectra of the two elements which he noted almost completely agreed with those measured by spectroscopic experts in both Sweden and Austria.[25, 26, 27]

Auer almost waxes poetic in his descriptions of what he observed. He says that the spark spectra of the two new elements are among the most glorious he has seen, and that this is especially true of *cassiopeium*, reminiscent of the splendid spectrum of barium distinguished by two bright lines in the green and the blue. He made photographs of the spectra avoiding high contrast in order to have true images with no retouching and no corrections, using a 200 s exposure time for all the plates.

Finally, he states that he discovered these elements at the beginning of 1905 and gives the date and session in that same year in which he reported his findings.

Reading his paper, one wants to weep at the tremendous effort that went into this work, and virtually to no avail. Forty-four days before, Georges Urbain "scooped" him with an announcement with not much more detail than Auer's 1905 and 1906 papers, and with atomic weights that were approximate, at best, and certainly nowhere near the accuracy of Auer's own.

What was to follow was a priority dispute folded within another priority dispute that made the Auer-Urbain controversy almost a footnote in the polemics that marked what one might call the *celtium*-hafnium dispute.[28,29]

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[23] Auer von Welsbach [15].

[24] Aldebaran is a near-first magnitude star located in the constellation Taurus, about 65 light years from the sun; Cassiopeia is a constellation in the northern sky.

[25] Exner and Haschek [16].

[26] Thalén [17].

[27] Eder and Valenta [18].

[28] Kragh [19].

[29] Kragh [20]. This reference, and the preceding one, are invaluable for following the intricacies of the priority disputes to be discussed in summary below. The authors owe a great deal to the scholarship evidenced by Prof. Kragh in telling this complicated tale.

4.4.1 Controversy with Georges Urbain

Georges Urbain was a young Parisian chemist who had built his career on the rare earth elements. He wrote his dissertation on the subject of the rare earths and quickly became well-known in the field. He was able to refute some claims of other chemists with such precision that he soon gained a reputation for being the gatekeeper of the discovery roster of the rare earths. In 1898 he took up the question of the yttric earths, but folded this work into a larger research project that included his earlier work on dysprosium, terbium, gadolinium, and europium. His method of separation was quite close to that of Auer's except that instead of using the oxalate salts, he preferred the nitrates. It was estimated that in a 15-year span of his career that he had performed over 20,000 fractional crystallizations.

It would be well to review Urbain's work as paraphrased from his first paper[30]: Urbain first comments on the fact that he had observed that ytterbium had the most soluble salts, a factor in the separations he was carrying out on the yttric group. He crystallized the nitrates in order to free ytterbium from yttria, erbium, and thulium, thus obtaining about 50 grams of raw ytterbium in 1905. He subjected this material to systematic fractionations, 22 in all. He then determined their absorption spectra and found that fractions 9–16 contained only thulium, which he discarded. Considering the other fractions as containing pure ytterbium, he converted the material to the sulfate salts and determined the atomic weights. Far from being constant, he noted a gradual increase from 169.9 for fraction 17 and 173.8 for the last fraction, no. 31. He notes that such a considerable variation would suffice to establish the complexity of ytterbium as it was then available.

In determining the absorption spectra, he noticed that there were numerous, strong lines for the most part in the last fraction (no. 31) which could not be observed in the lead fraction (no. 17). Conversely, fraction 17 had some weak intense lines, absent in fraction 31 and presumably attributable to thulium. Omitting these lines from consideration, the two spectra showed a large number of common lines and intensities of the same order. Urbain felt that these lines were those which characterized the main mass of the starting material, the impurities (thulium and the new element) accumulated, one at the beginning and the other at the end of the fractionation series.

He then reported in tablular form the lines that he claimed were characteristic of the new element (see Table 4.1), denoting which lines were determined by the arc or the spark method. He then declares: "Within the limits of my measurements, these 34 lines constitute the relatively complete spark spectrum of the new element. I propose for this element the name *lutecium*, Lu, derived from the ancient name of Paris." He went on to say that the other lines listed in the spark spectrum of ytterbium recently described by Sir W. Crookes, with one of my old preparations, characterize the main mass of the former ytterbium. He proposed to give this earth the name of *neo-ytterbium* in order to avoid confusion with Marignac's old element,

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[30] Urbain [21].

Table 4.1 Lines characteristic of Georges Urbain's new element, lutecium

Line	Description	Line	Description	Line	Description	Line	Description
*2701.8A	Very strong	*2963.5A	Very strong	3118.6 N	Medium	*3376.7A	Strong
*2754.2A	Very strong	2970.0A	Very strong	3171.5 N	Quite strong	*3385.6A	Quite strong
*2798.3 2796.75A	Very strong	*2989.4 N	Medium	*3183.5 N	Medium	*3397.2A	Very strong
*2847.6A	Very strong	3020.7A	Very strong	3191.9 N	Medium	*3472.6A	Very strong
2895.0A	Very strong	*3056.8A	Very strong	*3198.2 N	Strong	*3506.8 3507.56A	Very strong
*2900.4A	Very strong	3058.0A	Very strong	*3254.5A	Very strong	3554.6A	Very strong
*2911.5A	Very strong	*3077.7A	Very strong	3275.5 N	Quite strong	3568.0A	Strong
*2951.8A	Very strong	*3080.3 N	Medium	*3312.4A	Strong	3624.1A	Strong
				*3359.8A	Strong	3647.9A	Strong

but also to conserve the name ytterbium. Regarding atomic weights, he says that the atomic weight of neo-ytterbium should not be far removed from 170 and the atomic weight of lutetium should not be much greater than 174.[31]

And finally, he alludes to the ongoing work of Auer von Welsbach, of which he was not ignorant.

> Mr. Auer von Welsbach recently announced that the fractionation of the double ammonium oxalate of ytterbium had given him the opportunity to observe variations which he has not specified. He gave no measurements of the lines between λ 7000 and λ 5000, nor did he indicate the elements which he supposes might exist in the former ytterbium.

Urbain's second paper, which appeared in 1908, reasserts his claim to the discovery of *lutecium*.[32] He says:

> In the session of 19 December, 1907, that is to say, 44 days after my communication at the Paris Academy of Sciences, M. Auer von Welsbach published, without alluding to my research, a short Note to the Academy of Science of Vienna (Sitzung der Mathematisch-Naturwissenschaftlich Klasse, vom 19 Dezember 1907, no. 27, p. 468), in which he considers, like me, ytterbium as a mixture of two elements. He characterized them only by their atomic weights, 174.5 and 172.9, and limited himself to saying that there are differences between their spectra, which he does not give. He named the first *aldebaranium* and the second *cassiopeium*. *Aldebaranium* is obviously identical to lutecium and neoytterbium is *cassiopeium*…If it is true that we have been studying, Mr. Auer von Welsbach and I, independently from each other, the same question for several years, as I have already mentioned in my first Note, it is not less true that I have been the first to give numerical

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[31] In actual fact, today's value for ytterbium is 173.04 and the value for lutetium is 174.967; Urbain's error factor for ytterbium almost exceeded three atomic weight units!.

[32] Urbain [22].

> results that clearly specify the new elements, not only as to their atomic weights, but also to their different spectra. The communication from Mr. Auer von Welsbach only confirms previously published research that he is not yet in a position to report in a more precise manner. There was no need to propose new names for lutecium and neoytterbium already named.

Commentary

1. Urbain refers to his own first paper as a Preliminary Note—in which he names two new elements.
2. Urbain refers to Auer's 1907 paper as a Note, when as a matter of fact, it was 45 pages long and included 21 pages of spectral tables.
3. Urbain gives the atomic weights determined by Auer as 174.5 and 172.9, (whereas they were actually given as 174.23 and 172.90), both inaccurate in terms of the number of significant figures, and one inaccurate also in terms of the measured atomic weight.
4. Urbain accuses Auer of citing differences in spectra, but does not give the differences. Reading the published tables makes the differences very clear.
5. Urbain says that *aldebaranium* is actually his *lutecium*, and *cassiopeium* is *neoytterbium*. They are actually the other way around.
6. Examination of Urbain's 34 spectral lines[33] that confirm the identity of *lutecium* compared with Auer's measured spectral lines from the 21 pages of tables in his 1907 "Note" is telling. In the table above, the spectral lines given by Urbain are annotated: * means that these are, in Urbain's own words, characteristic of the arc spectral measurements. "A" following the line's value means that this was a measurement also noted by Auer in his 1907 paper. "N" following the line's value means that these were lines measured by Urbain, but not observed by Auer (Authors' notation).

In Auer's 1907 paper, the published tables note many more lines that Auer observed but that are not included by Urbain. These are, for the most part, weaker lines, which means that Urbain's instrument may not have been sensitive enough to pick them up. However, what is even more telling is that there are many lines in the 3080–3198 range in the table that Auer did not observe. One can conclude from this that Urbain's sample may have been very impure and that these lines belonged to other chemical species. In fact, Auer himself commented on this table[34]: "Some of these lines are attributable to scandium, thorium, erbium, thulium, yttrium, to any common element, and to any rare earth, except the old ytterbium." This is an important observation in terms of the priority dispute over *celtium* and hafnium that followed in 1923. In the same paper, he makes this caustic comment: Urbain "says that *aldebaranium* is certainly identical with *lutecium* and *cassiopeium* with *neo-*

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[33] Units were never given either for atomic weights nor for spectral lines and bands. One assumes that in the table presented the units are in Ängstroms.

[34] Auer von Welsbach [23].

ytterbium. To be correct, it should be: *Cassiopeium* doesn't have much to do with *Lutecium*, and *Aldebaranium* has almost nothing to do with Neo-Ytterbium."

4.4.2 The Controversy Escalates: The Discovery of Celtium

Eventually the question of priority was placed in the hands of the International Committee on Atomic Weights. Up until 1907, the membership on the committee consisted of: Frank Wigglesworth Clark (1847–1931) from the United States, Wilhelm Ostwald (1853–1932) from Germany, Thomas E. Thorpe (1845–1925) from England, and Henri Moissan (1852–1907). Upon the death of Moissan on 20 February, 1907, Georges Urbain was chosen to replace him, placing Urbain in a key position to advance his own arguments—which he did. There is no mention of Urbain's recusing himself because of vested interests. On the contrary, he exerted a great deal of influence on the committee, which accepted his arguments that he was the first to publish spectral data and atomic weights. The Committee's verdict was published in January, 1909[35]:

> That the old ytterbium is a mixture of two elements has been proved by Urbain in Paris and Auer von Welsbach in Vienna, working almost simultaneously and independently. In his earlier paper, Urbain names the two components "neoytterbium" and "lutecium," with approximate atomic weights of 170 and 174 respectively. In his second memoir, Urbain gives atomic weights for a series of ytterbium fractionations, ranging from 170.6 to 174.02. Welsbach, whose work appeared later than Urbain's, names the two elements "aldebaranium," atomic weight 172.90, and "cassiopeium," atomic weight 174.23. Since Urbain has clear priority, his nomenclature should be preferred, but the atomic weights need to be more sharply determined.

Although Auer von Welsbach had maintained a discreet public reserve throughout 1908, when this verdict was announced, he broke his silence, claiming that this decision was a grave injustice. Although Auer had shared his quantitative data on *aldebaranium* and *cassiopeium* privately, that fact was discounted: to claim scientific priority, it was publication that counts. In his review of the situation, Helge Kragh[36] states:

> There is no doubt that Auer was the first to separate Marignac's ytterbium into reasonably pure components. Urbain and the International Committee granted him that much, but for them the crucial point was the lack of publicly available numerical data to confirm the claim. Urbain was the first to supply such data, although his atomic weight determinations were imprecise and of little value. Auer's determinations were earlier and more precise, but he failed to make them public in due time…With the International Committee's emphasis on publicly available, numerical documentation it is understandable that Urbain's priority claim was recognized. Yet the Committee's decision was far from objective, but based on an interpretation of the available data which predetermined the outcome of the controversy.

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[35] Clark et al. [24].

[36] Kragh [25].

So Urbain's *lutecium*, later changed to lutetium, and *neo-ytterbium*, later changed back to ytterbium, entered the official list of elements. *Aldebaranium* and *cassiopeium* had to take a back seat in the history of the discovery of the elements.

Meanwhile, Auer continued his search for more elements, and in particular a third one in the ytterbium mix. After exhaustive work, he finally admitted that only two elements, lutetium and ytterbium, were present. However, he continued his work and in 1912, gun shy from the lutetium-*cassiopeium* affair, prematurely reported the discovery of three new elements derived from impure terbium. He named these elements terbium-I, terbium-II, and terbium-III. Georges Urbain lost no time in demolishing Auer's discovery. Undeterred, he continued his fractionations, this time on what he considered to be impure thulium, but with the same results. Having identified thulium-I, thulium-II, and thulium-III in arc and spark spectra, he reported his findings but confessed that he had failed to isolate these three new elements. Auer had fallen victim to a common error among spectroscopists: the phosphorescence spectra of pure substances could be greatly altered by the presence of trace amounts of impurities.[37]

Some years after the end of World War I, Auer became interested in the element "missing" between neodymium and samarium. He worked up a large amount of samarium salts with his customary care and, by now, inimitable expertise – to no avail. He finally came to the conclusion[38]:

> There was no trace of this strange body to be detected. Even the X-ray examinations that were done by Dr. Ortner in Vienna and Professor Prandtl in Munich showed no trace of 61. Thus, it is unquestionable that element no. 61 is not present in the mixture of Nd and Sm derived from cerite, or it is only present in an amount hardly detectable with our present methods.

With this pronouncement, Auer put to rest, at least for himself, that looking for element 61 using the usual methods was in vain. This lesson was learned the hard way for the many chemists who claimed to have found it, and named it,[39] only to have their aspirations dashed. This elusive element, appearing in nature perhaps in utterly undetectable amounts, was eventually found in uranium fission products in 1947 and named promethium, after the mythic Prometheus who brought fire from the gods to humans.[40,41] The reason why Auer and so many others kept looking for additional elements was the lack of theory governing the then-known periodic table. Dmitri Mendeleev's idea of ordering the known elements according to their atomic weights, superseded by Antonius van den Broek's (1870–1926) and H.G. J. Moseley's (1887–1915) atomic number, was insufficient for explaining the occurrence of the many strange daughter products of radioactivity and the weird similarities of the rare earths. Frederick Soddy (1877–1956) solved the former

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[37] Fontani et al. [26].

[38] Auer von Welsbach [27].

[39] Element 61 took on many names, among them florentium, illinium, and cyclonium

[40] Marinsky et al. [28].

[41] Marinsky [29].

problem with his isotope hypothesis, but it would take major developments in atomic theory before the number of rare earths possible could be determined and how they could properly be placed in the periodic table.

Auer was not the only one searching the rare earth horizon. His old rival, Georges Urbain continued his research program, perfecting his spectroscopic techniques and developing a new one: measurement of magnetic susceptibilities. It had been known for quite some time that the rare earths had, for the most part, magnetic properties and that their magnetic susceptibilities could be an index for positive identification. In 1911, having fractionated lutetium "to the limit," he finally obtained a mother liquor that would not crystallize; further, the substance's spectral and magnetic properties seemed to be those of a new element. So in 1911, Urbain announced the discovery of *celtium* (symbol Ct), a name chosen to honor early inhabitants of France.[42] Thinking that this new element was the last of the rare earths, with an atomic number of 72, he journeyed to Oxford in June, 1914 to have his rare earth fractions examined by Moseley, who failed to confirm the presence of element 72.

Work on *celtium* ceased abruptly. In August 1914, World War I broke out. Moseley immediately enlisted and died the following year at the campaign at Gallipoli. Urbain enlisted in the service of national defense and worked full time in that capacity until 1919.

After the war, Urbain began a collaboration with a young X-ray spectroscopist, Alexandre Dauvillier (1882–1979), who found some weak lines identified as *celtium* in a mixture of lutetium and ytterbium oxides. Certain that these results confirmed *celtium*'s existence, Urbain proclaimed its place in the periodic table as element 72.[43] The conclusion was widely accepted at first, but *celtium*'s credibility began to fray as a result of some theoretical developments in Copenhagen.

4.4.3 Niels Bohr's Theory and Hafnium's Discovery

Niels Bohr, working in Copenhagen, applied the fledgling quantum theory to electron shell structure theory in the atom. He hypothesized that the property of periodicity observed by Mendeleev was due to the filling up of a new electron shell and that a new period would begin once a shell was completed. This idea would explain the periodicity of chemical properties which depended above all on the actual external electron shell. The rare earths presented a problem for Bohr but he suggested that after lanthanum, the filling of the external shell stops and continues in a shell closer to the interior by two—thus explaining the great similarity in chemical properties of the rare earth elements: the external electron shells of these elements were identical. According to Bohr's idea, lutetium, element 71, marked

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[42] Urbain [30].

[43] Urbain [31].

the end of filling one of these shells, so element 72 would not be a rare earth at all but a higher homolog of the group 4 elements, titanium and zirconium.[44]

Propelled by these ideas, two postdoctoral researchers in Bohr's institute, George de Hevesy (1885–1966) and Dirk Coster (1889–1950), began to search for element 72 in zirconium earths—a search that paid off almost immediately on 2 January 1923[45] with the announcement of the discovery of hafnium.

4.4.4 The Dénouement

Georges Urbain immediately cried foul. Perhaps he could foresee the downfall of his *celtium* already, but little did he know that it foreshadowed his priority for the discovery of lutetium as well. A veritable battle in the literature ensued, shedding not very much light on the heated discussion. Scientists took sides for reasons that did not have much to do with science, but more with personal grudges and national pride. For example, Bohuslav Brauner lined up with Urbain because, among other reasons, the latter recognized him as wronged in the case of the splitting of didymium, as this excerpt attests[46]:

> There is no doubt that the blue bands [observed by Brauner] belonged to praseodymium and the yellow bands to neodymium. Thus von Welsbach, to whom the discovery is generally attributed, was only further along than you in the separation of your two elements. ….I am not surprised that the honor of discovery has been attributed to him; in such a matter, the learned world is indifferent, and is willingly deceived by appearances. It is notorious that lutetium has nearly repeated the history of praseodymium, and you tremble more than me for the fate of *celtium*. I hope that this argument will shift the balance in your favor in the future, and that justice will at last be universally restored to your credit.

In this phrase, Urbain recognized that he and Brauner were bedfellows with respect to being on the wrong side of a priority dispute. As we recognized earlier, Brauner worked on the splitting of didymium simultaneously with Per-Teodor Cleve and in effect seemed to have stepped aside to leave a clear field to Cleve—but not really. Brauner had always thought of himself as the true discoverer of praseodymium and neodymium and even almost brought the matter to court in 1908. Brauner finally acknowledged Auer's priority, though it is not clear why.[47] He always felt that Auer von Welsbach had "plagiarized" him.[48,49] Not so oddly,

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[44] Szabadvary F. Discovery and separation of the rare earths. In Gschneider and Eyring [32].

[45] Coster and Hevesy [33].

[46] Urbain [34], written when Brauner retired from an active scientific life.

[47] Štrbáňová [35]. The author comments: "Priority disputes represent in history of science an intriguing phenomenon. If at all, only primary sources can give us relevant answers about the individual cases, but their interpretation deserves deeper historical analysis."

[48] Kragh [36].

[49] Even though Brauner and Auer worked in Robert Bunsen's laboratory they probably had never met since their terms there did not oveerlap. In 1883, while Auer was still working with Bunsen,

Urbain used the same loaded word to claim that he had been wronged by the discoverers of hafnium—that he was the true discoverer of element 72. The irony of the situation was not lost on either Brauner or Urbain.

However, here is the great tragedy for Urbain. Once hafnium was recognized as the "true" element 72, and that it belonged in the zirconium group, what then was Urbain's *celtium*? Further assiduous work on the part of impartial researchers soon made it clear that Urbain's *celtium* was nothing more than his lutetium in pure form! In other words, Urbain did not even recognize his own child. And why not? Because it was so impure—that the sample he held up to the world as lutetium contained very little of that element, so little in fact, that he could hardly be called the discoverer. Auer von Welsbach's comment on the extraneous lines noted in Table 4.1 came home to roost.

So as *celtium* crumbled, so lutetium disintegrated as well. And as lutetium's star declined, *cassiopeium's* was raised up. At least among the German-speaking countries, rehabilitation of Auer's claim proceeded apace. The *Deutsche Atomgewichtskommission*[50] in recognizing hafnium in 1923, also gave priority to Auer's *cassiopeium*, which entered the periodic table as element 71. In deference to Marignac, element 70 remained ytterbium[51]:

> In view of the situation described [the damning experimental evidence against Urbain is first cited], it is regrettable that the two outstanding investigators to whom the chemistry of the rare earths owes so great and valuable results, did not reach an amicable agreement on the naming of the elements which they had discovered at the same time. If, on the other hand, the decision is to be made by a third party, we cannot agree with the decision of the former International Atomic Weights Commission in assessing the question and the knowledge obtained in the last year. Auer von Welsbach must also take priority for the splitting of Marignac's ytterbium. Since his extensive publications on the lack of homogeneity of ytterbium confirm his assertion from 1905 and 1906, and because at the time of Urbain's first publication he clearly had succeeded in the purification of the two ytterbium components, the Commission therefore selects for element 71 the name Cassiopeium proposed by Auer with the symbol Cp. But retains for element 70 the name ytterbium, which Marignac gave the elemental mixture he discovered.

Cassiopeium survived in Germany, Austria and the Scandinavian countries for several decades, being abandoned in favor of lutetium in the 1950 s. However, even though neither of Auer von Welsbach's "starry" names survived, he is generally recognized as a co-discoverer of lutetium along with Georges Urbain, and in some remote parts of Austria, he is given priority for ytterbium (under the name of *aldebaranium*) as well.

A blow-by-blow description, including copies of original correspondence between the interested parties on both sides of the Urbain-von Welsbach and the

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Brauner came for a visit, but claimed that while he was there, Auer did not "present himself." (Letter from B. Brauner to M. Speter, 18 May 1933). Reproduced from [37].

[50] This was the German equivalent of the International Committee on Chemical Elements set up independently after World War I because of the Allies' policy that excluded any nation from the former central powers, from sitting on the International Commission.

[51] Deutsche Atomgewichts-Kommission [38].

Urbain-Hafnium disputes is given by W. Gerhard Pohl in "Carl Auer von Welsbach als Konkurrent von George [sic] Urbain".[52]

Postscript: Both Auer and Urbain were nominated multiple times for the Nobel Prize, all unsuccessfully. It has been hypothesized that both scientists were immersed in international contentiousness which prompted their supporters to take sides and the unresolved impasse reflected negatively on the Nobel deliberations.

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Chapter 5
Plus Lucis

Passing by Währingerstraße in Vienna, one encounters a gray, roughly triangular building block, the chemical, mathematical and physical institutes (in alphabetical order) of the University of Vienna. There is a simple monument in front of the entrance to Währingerstraße 38—a square with a stylized male figure and the words "Plus Lucis"—"more light."

The monument to which we refer was dedicated, on the 7th of November, 1935 in the presence of his extended family, to the great scholar, Carl Auer von Welsbach, the most outstanding chemist in Austria. For Auer, there was no separation, no difference between basic curiosity-driven and applied, commercially exploitable research. He not only did great things in both of these fields, but he also reaped the fruits of his research activity as a successful entrepreneur. For him, "Plus Lucis," his life's motto that appears on his coat-of-arms, is not only symbolic, but also has a very practical significance, because he has given us all, through his inventions, "more light."[1] E. Baumgartner remarks in this respect[2]:

> In order to understand why the matter of light was so important to him, one must remember how desperate the search for cheap, long lasting sources of light was in Auer's days. The industrial revolution was at full blast, and the problem of illumination – before Auer's invention only by the means of candles and paraffin lamps – was urgent, especially in winter.

This chapter documents Auer's great success in this endeavor, beginning with a brief history leading up to his discoveries.

5.1 Gaslight

Over the course of human history, lighting has been an important need, and ancient humans quickly learned how to overcome the lack of daylight, both indoors and out, by using the light emitted from combustible objects, such as plant materials and animal fats and oils. By the eighteenth century, and thus fairly recently on the scale

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[1] Komorek [1].

[2] Baumgartner [2].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_5

of civilization, a major development was a new light source derived from the combustion of marsh gas (largely methane, later called natural gas) and coal gas (largely hydrogen, methane, and carbon monoxide).

Although England is considered the classic land of gaslight technology,[3] occasionally and elsewhere observations and experiments with combustible coal gas, a byproduct of the destructive distillation of coal, were made. For example, the professor of natural philosophy at Leuven (Louvain), Jan Pieter Minckelers (1748–1824) had already set up a small gas installation in 1783 which he used two years later to illuminate his lecture hall. His interest in gases arose from his membership on a committee that was studying the best gases to fill aerial balloons. In 1794 he was appointed professor of physics and chemistry in his home city of Maastricht where, to this day, one may see his statue equipped with an eternal flame.[4]

James Murdoch (1754–1839), for years in the employ of James Watt (1736–1819), is generally credited with inventing a way of replacing oil-based lighting with gas. Sometime between 1792 and 1794, he succeeded in demonstrating how one could produce and contain coal gas for lighting purposes. By the early 1800s, Murdoch was able to light up key industrial buildings in Birmingham and Manchester, and within a few decades, most towns and cities in Britain were lit by gas provided by their own gas works.[5] Wilhelm August Lampadius (1772–1842) provided the city of Freiberg with gas lighting as early as 1811, and by 1816 he had established the first gasworks installation on the European continent.[6] In close competition with Lampadius, Johann Joseph von Prechtl (1778–1854), the founder and first director of the Vienna Polytechnic Institute, introduced a coal gas generating plant there in 1816, and within two years had constructed 25 gas lamps in the city.[7]

Gas lamps were only as good as the gases that they were fed. Specially synthesized illuminating gas from the distillation of soft coal or peat was found to produce flames of much greater brightness than natural gas. It was later found that the brightness was due to incandescence arising from a greater proportion of hydrocarbons in the coal gas.

5.2 Incandescence

The original definition of incandescent light was a luminous gas flame in which carbon atoms, produced by incomplete combustion of the fuel, are rendered incandescent by the flame's heat. The reason that incandescence occurs is because

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[3] Both England and Scotland boasted of a long tradition in pneumatic chemistry through the work of renowned early researchers such as Joseph Black (1728–99), Robert Boyle (1627–91), Joseph Priestley (1733–1804), Henry Cavendish (1731–1810), and Stephen Hales (1677–1761).

[4] https://en.wikipedia.org/wiki/Jean-Pierre_Minckelers (last accessed 15 January 2018).

[5] Thomson [3].

[6] https://www.deutsche-biographie.de/ppn118726145.html#ndbcontent (last accessed 15 January 2018).

[7] http://www.cesa-project.eu/en/lexicon/authors/johann-joseph-von-prechtl (last accessed 15 January 2018).

the heat of the flame creates atoms with very high thermal kinetic energies. Some of this energy is transferred to cause electronic excited states within the solid, which then relax by emission of photons. We say that an object incandesces when sufficient radiation is emitted so that it can be seen by its own visible light. Solids must be present for incandescence to occur because only in solids is there a near-continuum of electronic energy levels, thus yielding a continuous non-discrete spectrum. The most familiar incandescent body for inhabitants of Earth is the sun that, with an average temperature of 6600 K, defines the color mixture we call “white light.” Since there is no solid substance on Earth that can be heated to this temperature without melting, it is impossible to exactly match sunlight’s color mix.[8]

The light gases, such as hydrogen, methane, and carbon monoxide, burn with a nonluminous flame; therefore, they are not acceptable for lighting purposes. What makes a gas luminescent when it burns is the presence of particulates, such as soot, that, when heated to a white heat (above 850 K), glow. Thus, the gases produced by coal, oil, or hydrocarbons like ethylene and acetylene, can exhibit highly luminous flames only because of the presence of incandescent bodies produced by incomplete combustion. Improvements in luminosity came about by (1) changing the shape of the flame by the proper construction of the burners, (2) providing a supplemental supply of air to more intensely heat the particulates, thus causing them to glow more brightly, and (3) changing the chemical composition of the fuel to burn compounds more likely to produce more particulates. It was Michael Faraday who used this third principle, called carbonization, by mixing such fuels as naphthalene and benzene, to produce the soot necessary for a highly luminous flame during combustion. The two most important systems of the newer lighting technology, use of incandescent solid bodies as light sources, and the electric light bulb, are based on this principle as well. The only difference between the two is the method of applying the heat to the glowing body.[9]

Over time, the term “incandescent” took on a broader meaning. The incandescent body no longer had to be derived from the gas supply itself. The source of light and the source of heat could be separated from one another such that the luminous body could be any solid substance brought into contact with a luminous or non-luminous flame. It is appropriate at this point to review the development of incandescent systems that preceded Auer von Welsbach’s invention.

5.2.1 The Incandescence Principle

David Brewster (1781–1868) seems to have been the first inventor to whom the essence of the incandescence principle became fairly clear. He came to this realization by a series of experiments which he made around 1820. He dipped wooden sticks into solutions of lime and magnesium salts, incinerated the sticks, and

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[8] MacIsaac et al. [4].

[9] Sedlacek [5].

observed the ash in the outer surface of a candle flame. A strikingly strong, white light was emitted "without noticeable reduction by more than two hours." He also observed that the brightness was inversely proportional to the particle size of his samples, and directly proportional to the temperature of the applied heat. He guessed at once that this phenomenon could have some practical use, but little did he realize that the impregnation and burning of the wood to obtain an ash skeleton serving as a luminous body was a direct forerunner of Carl Auer von Welsbach's incandescent mantle.[10]

An important development in terms of increasing the amount of solid capable of incandescing came about in the 1820s with Goldsworthy Gurney's (1793–1875) discovery that a block calcium oxide (lime) emitted a brilliant white light when heated with a fuel source of his own invention, the so-called "oxy-hydrogen blowpipe." This phenomenon was quickly exploited to construct optical systems, using focusing lenses, for use in lighthouses and in the theatre as spotlights. It was popularized by a Scottish engineer, Thomas Drummond (1797–1840), in 1826, and his working version of the light came to be called the "Drummond Light."[11] This invention, having entered our vocabulary as "limelight," was the first practical incandescent system, although it required constant supervision and by its very nature was extremely hazardous. The fact that the system was widely used in theatre spotlights gave rise to the metaphorical use of its name to mean public attention or fame.

The constant search for better luminescent sources was stimulated by the realization that reliance on carbon-based particulates in a gas flame was extremely inefficient and a tremendous waste of energy. Inspired by Sir Humphry Davy's (1778–1829) miners' safety lamp investigations, Alexander Cruickshank proposed heating quartz and platinum wire networks or balls with non-luminous gases. He also tried coating platinum wires with alkaline earth oxides, but with little success.[12]

Other inventors began to turn to such substances as the oxides of the other alkaline earths, in addition to calcium in the form of lime, to aluminum, zirconium, and the noble metals of the platinum and gold families, as well as the heavy metals, and virtually all other metals in the d-block of the periodic table. Many of these substances proved to be unsuitable as luminous bodies because they were not fireproof, they were volatile, brittle, and became distorted by a powerful flame. A further requirement was that the body had to have a great capacity for the emission of light, and this varied from substance to substance.

5.2.2 Theoretical Basis of Incandescence

Early chemical literature distinguishes between the phenomena of incandescence and luminescence. The latter is the emission of nonequilibrium or nonthermal

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[10] Brewster [6].

[11] https://en.wikipedia.org/wiki/Limelight (last accessed 15 January 2018).

[12] Cruickshank [7].

radiation due to the discharge of stored energy as a function of increased temperature,[13] whereas incandescence pertains to emission of radiation from a body at thermal equilibrium. When a solid material luminesces when placed in a flame, the phenomenon is called candoluminescence, as opposed to thermoluminescence in which the body is excited by radioactivity or other means of excitation, but luminesces only when the temperature is raised.[14]

Simply speaking, incandescence is a form of light emission from solid bodies heated in flames, such as blackbody radiation, and other types of emission processes such as selective thermal radiation and candoluminescence are now included in this category. Blackbody radiation, the most famous of these phenomena, occurs when a crystal lattice vibrates upon application of heat, causing electron scattering, which in turn causes transient oscillating dipoles. The oscillating dipoles emit electromagnetic radiation, the intensity of which is proportional to the body's temperature. Blackbody radiation corresponds to the upper limit of the amount of radiation that a substance at thermal equilibrium emits at a given temperature.

Selective thermal radiation, on the other hand, is a relatively rare phenomenon exhibited naturally by some materials[15] and induced in others.[16] Selective thermal radiation emitters and absorbers are able to engage in radiative heat transfer that exceeds blackbody predictions, possibly due to tunneling of evanescent waves, but in any event, to the displacement, with increasing temperature, of the ultraviolet absorption band toward the visible. It is presently the subject of intense research because its study may result in an improvement in energy utilization efficiency, which is required in a broad range of fields, including lighting, energy harvesting, and sensing.[17]

Though, in the past, the very existence of candoluminescence, defined as non-equilibrium radiation at elevated temperatures, was called into question due to ignorance of its mechanism, it is generally now recognized that it arises when high energy species in flames, often free radicals, recombine with intense emission of radiation in the visible region.[18] Some authoritative researchers in this area thought at first that the phenomenon was merely an example of selective thermal emission, exhibiting very high emissivity in the visible and weak emissivity in the ultraviolet, where maximum blackbody radiation is likely to be observed. Recent consensus admits to an overlap between candoluminescence and selective thermal radiation, depending very much on the nature of the materials involved, the heating method, the type of flame, and the actual position of the solid relative to the flame. High performing radiators such as some rare earth elements and thorium can have their visible emissivity increased many-fold by the addition of small amounts of

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[13] Harvey [8].

[14] Mason [9].

[15] Wood [10].

[16] Asano et al. [11].

[17] Greffet et al. [12].

[18] White [13].

impurities, like cerium oxide. Several reasons for this behavior have been advanced: (a) that the mixture represents a chemical compound or stable solution that has its own individual radiation characteristics; (b) that the cerium oxide catalyzes the oxidation, thus increasing luminescence, (c) that cerium oxide is a good selective radiator that, when mixed with the poor radiator, thorium oxide, can reach a very high temperature.[19] However, it is more than likely that the impurities, like cerium oxide, act as dopants to form energy states within the bandgap of the bulk material, resulting in allowed transitions across the energy bandgap.[20]

5.3 Breakthrough: Invention of the Welsbach Mantle

By 1885, it had become abundantly clear to would-be inventors of the period, who had been trying their hand at solving the lighting problem over the past 60 years, that two components were necessary to develop a large-scale illumination system: an intense nonluminous source of heat and a durable solid capable of brilliant radiation of light upon heating. The need for the first component gave rise to the development of numerous types of burners that kept the patent offices busy over a period of years. Essentially, they were all modeled on Robert Bunsen's original burner (with which Carl Auer von Welsbach was intimately familiar due to his extended time working with Bunsen at Heidelberg) that provided a cleanly burning, quiet, nonluminous flame when adjusted to the correct mix of air and fuel. However, to achieve extremely high temperatures, the oxy-hydrogen flame was often utilized, which meant that burners had to have the capability of safely mixing the two gases prior to combustion. An example of such a burner is that of Wolters and Roslin,[21] shown in Fig. 5.1.

Other burners could have additional features that became more and more complicated. Many inconveniences accompany raising the temperature of the natural coal gas flame, forcing inventors to use special fuels not universally applicable and somewhat expensive. Some necessary refinements included interposing non-conductive materials to prevent heat transfer from the incandescent material to the gas entry tubes, or a protective sieve to prevent strike back of the flame.[22] However, the simplicity of the original Bunsen burner was ideal for commercial development; it would be similarly ideal to find an incandescent material that provided the desired luminosity in such a flame without the necessity of elaborate devices designed to increase the flame's temperature.

One particular type of burner, however, that came on the scene around 1905, was a very important development. Called the "Invertbrenner" or inverted burner, it actually burned upsidedown, thus eliminating the shadow cast by the incandescent material.

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[19] Phillips [14].

[20] Ivey [15].

[21] Wolters and Roslin [16].

[22] Gentsch [17].

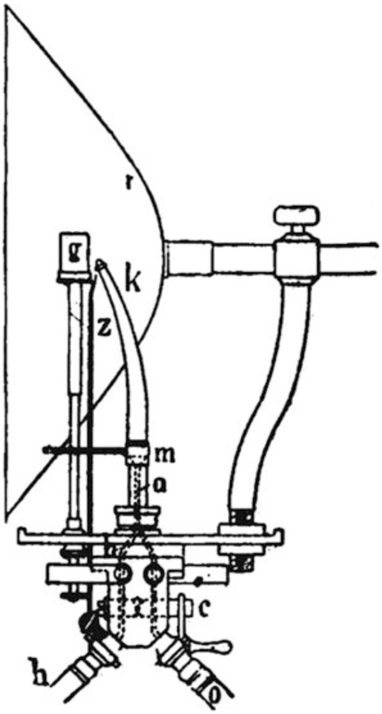

Fig. 5.1 Burner of Wolters and Roslin. The two gases enter the burner through h and o, are mixed at m, and are ignited at k in close proximity to the incandescent material, g. It can be used with or without a reflector, r

Turning our attention to the incandescent material itself, virtually every element in the periodic table was tried, and in fact, found wanting. Here again Auer von Welsbach had another great advantage: he was intimately familiar with a whole class of elements, the rare earths, that were not household words to the majority of scientists. Not only that, as a result of his two-year project to separate the rare earth elements in didymium, he had on hand in his laboratory large quantities of highly-purified lanthanum and other rare earth elements. Again from his work with Bunsen, he realized that they possessed incandescent properties, a fact not lost on many others. The problem was how to construct a system that could utilize this property easily, safely, and cheaply over the long term and with the right mix of elements.

All of the inventions up to this point seemed to be "tinkering" with small improvements that did not get to the root of the problem. They seemed to be just an accumulation of engineering designs with little by way of actual development. None of them resulted in active manufacturing establishments; they were short-lived, only of local importance, or for special purposes. None of them were maintained, appreciably improved, further developed, or marketed. They disappeared as they had come, and some became better known only when they were "exhumed" and compared with Auer's invention.

Auer was a very practical scientist. He read little, and published less. His great joy was to spend hours, thousands of them, working in the laboratory. He developed a storehouse of empirical knowledge, particularly about the properties of the rare earth elements, from the two years he had recently spent separating them one from the other, in the process discovering new ones. It was now time to use this information to find the right incandescent material.

5.3.1 The Lanthanum-Zirconium Incandescent Lamp

Carl Auer von Welsbach managed to completely solve the problem of incandescent lighting and thus created a revolution in gas-lighting technology around the world. But his solution, like all great inventions, was not the result of a brilliant idea, but of consistent and persevering labor. His solution came in two stages. The first, the lanthanum-zirconium incandescent lamp, was only partially successful.

Auer knew that although the rare earths were luminous when heated, they actually radiated very little light. He also knew that they were not very durable. However, his genius lay in the idea that if he found the right mixture of rare earths, and if he found a way to alter their properties by some kind of treatment, that he could possibly develop a material with properties quite different from those of the individual components. Furthermore, he was quite familiar with the spectral properties of these elements, giving him a certain control over the color of the radiation by doping the mix with the desired color emitter.

After a great deal of trial and error, Auer came up with some mixtures that he felt would work, as shown in Table 5.1. All of these mixtures, when heated very strongly, are transformed into a new material with properties quite different from the individual components. All the annealed substances radiate a dazzling white light, but they can be modified in several ways. Increasing the proportion of yttrium oxide shifts the color to a light yellowish white. Addition of neodymium-zirconium oxide, which luminesces orange-yellow, can shift the tone to yellow. Addition of erbium-zirconium oxide shifts the radiation maximum toward the green. It should be noted that mixing magnesium oxide and zirconium oxide, since they are both basic, diminishes the good qualities noted otherwise.[23]

But we are still a long way from the structure that marks Auer's breakthrough. We have the luminous substance; how can it be made into a practical lamp? What form should this solid roasted material take in order to be set on a lampstand? It was obvious that the solid itself needed to have its surface area greatly increased in order to provide the needed luminosity, but grinding the material into a powder was not the answer: a structure was needed for the flame to play on.

After much more experimentation, Auer found that these mixtures could be pulverized and made soluble as nitrates, sulfates, acetates, bromides, or iodides. Once the proper proportion of components was rendered soluble, the creative imagination and tenacious adherence to a self-imposed goal that he had inherited from his father came to the fore. He never documented how he hit upon the following idea: he dipped a light network of cotton batiste into the salt solution

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[23] Gentsch [18].

Table 5.1 Composition of mixtures of potentially luminous materials

Component	Mix 1	Mix 2	Mix 3
Magnesium oxide	60%		
Lanthanum oxide	20%	30%	50%
Yttrium oxide	20%	10%	
Zirconium oxide		60%	50%

(usually nitrates at concentrations of 1–2 M), thus saturating it.[24] Upon drying, the cotton network could be incinerated, leaving behind the salts, reconverted into their oxides, as an ash skeleton, with more or less moderate structural stability, in the form of the original cotton network, or what has been termed "a coherent 'inorganic textile' of the corresponding oxide."[25] This skeleton would incandesce brightly when a flame was applied to it. And thus the incandescent mantle, original and absolutely unique, was born.

In the original German, the cotton network was referred to as a "*Strumpf*," i.e., literally a stocking, for that was its shape. Our English word, mantle, for the same object comes from the German word "Mantel" which, among other things, means "overcoat" or, in the technical sense, the "envelope" or "boundary surface" of a flame where complete combustion takes place. The structure is also sometimes called a "cap" or a "hood," particularly in England. Figure 5.2 shows drawings of the mantle's structure and operation.

But we are getting ahead of ourselves. Let us go back to the laboratory and accompany Auer on his quest.

By his own testimony, as he was examining the rare earth elements, he tried to find a way to make their emission spectra as bright as possible. He felt that the easiest way to accomplish this was to take a small amount of the earth, form it into a bead, melt it onto a platinum wire, heat it to a white heat, and then to view it through a spectroscope. But he found that the resulting spectrum was quite feeble. "So, I asked myself the question," he reported later in a lecture[26, 27]: "How can I place the earth more appropriately in the flame to make the light effect more intense? Then I thought, quite by chance, 'I could absorb (and concentrate) the salts of these substances on cotton fabric and then burn the fabric away. It was highly unlikely that this experiment would succeed because the flame would destroy the fabric and the resulting ash would have no consistency. But, on the contrary, the experiment did succeed." The earth as an oxide ash remained in the original form of the fabric, conserving the structure of the weaving. "When I went back to visit Robert Bunsen, my former mentor in Heidelberg and told him what I had done, he shook his head and said that it seemed highly unlikely that the oxides would retain a

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[24] Other inventors had tried applying slurries of salts to fabric, but these networks were unsuccessful because of uneven distribution of the incandescent material and and the fragility of their bonds to one another.

[25] Jørgensen et al. [19].

[26] Auer von Welsbach [20].

[27] Auer von Welsbach [21].

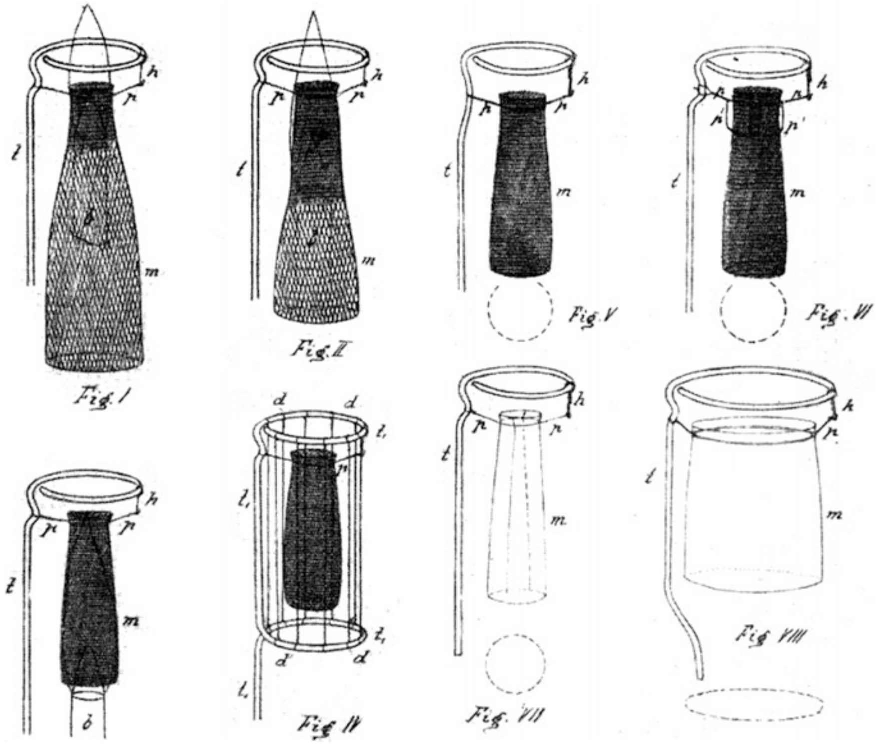

Fig. 5.2 Incandescent light mantle (Strumpf), showing the mounting structure and the burning off of the fibers. Welsbach [22]

consistent form. I recall with pleasure the astonishment on his face when I reached into my bag and produced just such a perfectly formed *Strumpf*.'"

Auer goes on to say that after a variety of trial-and-error experiments, he came across a substance, the rare earth compound, lanthanum oxide, that gave an extremely large light output on heating. He made a perfectly formed *Strumpf*, or mantle, impregnated with the earth and incinerated it. Then came his first disappointment: he returned to the laboratory after a few days and found his faultless mantle had disintegrated into a fine dust. Then he thought that lanthanum oxide, whose light-emitting properties had already been ascertained, could be made more durable by intimately mixing it with a substance that did not as easily absorb water vapor and carbon dioxide from the air. The first of these substances that he experimented with was magnesium oxide, recognizing the great importance of finely grinding the solids together. When incinerated, he got from the two white compounds an incandescent material with a dark brown color with totally different properties from the original mixture. It gave a beautiful light when subjected to a strong flame but, unfortunately, after about 70 or 80 h of flame exposure, the fine porous structure sintered and gave way to the formation of a glassy substance. Another failed experiment!

And so it went, until he finally hit upon a mixture that worked, shown in Table 5.1 as Mix 1. In his patent application, he emphasizes that this incandescent mixture, when heated by a Bunsen burner, yields an intense, almost white glow that does not decrease over time, is not volatile, and remains unchanged in the presence of air. He indicated that other compositions of earths (Mix 2 and Mix 3 in Table 5.1) exhibit similar properties. He continued to emphasize again and again that the constituents of the incandescent bodies had to be in a state of molecular mixtures and that this was the core of his invention. Also, the ash skeleton, by virtue of the very fine distribution of luminous material, fulfilled one of the theoretical requirements for high light-emission capacity. (The emission spectrum produced is independent of the nature of the solid, but the degree of emissivity is highly contingent on the nature of the mix.) One might even venture to say that with this invention, solid state chemistry was born.[28] Further details in the patent specify how the mantle was constructed. The cotton cloth was purified by treatment with a dilute solution of HCl, impregnated with a 10% solution of the nitrates and acetates of the appropriate cations, immersed in gaseous ammonia, and dried. A rectangular piece of the fabric is formed into a cylinder, sewn at the seam, suspended as shown in Fig. 5.2, and incinerated. The light intensity was estimated at about 15–20 Hefnerkerzen.[29]

With the impatience and optimism of the inventor, trusting his star, he made his invention, perhaps somewhat prematurely, known to the public, and yet it was a good thing to do so. There was great interest in any new development in the field of lighting technology. Public lighting had been in use for about a century but was still highly unsatisfactory. The brightest lamps were feeble and gave off large amounts of heat, a particularly unwelcome quality during the summer months. They were inefficient, consumed a great deal of gas, and were uneconomical. All the many efforts and proposals to improve gas lighting had failed miserably. The luminosity still depended solely on the quality of the gas, which was becoming increasingly scarce and rising in price. It was time for a change.

And so, the independent researcher supported by his mother's modest means, made his début in the business world. The heads of all the Viennese Newspapers received courteous, lithographed invitations at the beginning of 1886: Dr. Carl Auer von Welsbach would be available every evening from 6 to 9 PM at the Chemistry Institute to demonstrate and explain his invention of a new incandescent light source, which he christened “Actinophor” and later, “Auerlicht.”

As soon as the word got out, Auer was besieged by professionals from all over the world who flocked to the Chemical Institute in Währingerstraße, where his laboratory, still in the borrowed space of Professor Lieben, was situated. In the days that followed, supportive and encouraging reviews appeared in the newspapers, and the new discovery became well-known. While Auer experienced an enthusiastic

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[28] D'Ans [23].

[29] One Hefnerkerze has a light output of 0.920 cd. The unit is based on the Hefner lamp, the luminosity standard in the late 19th and early 20th centuries in Scandinavia and the German-speaking countries. Palaz [24].

reception, there was also a great deal of skepticism expressed. One business magnate, when asked if he wanted to get involved with the new discovery, declared that his company only dealt with serious matters.

In those days, a former colleague of Auer's, Hans Heger, arrived at the laboratory for a demonstration. He could not quite believe that an ash skeleton was sufficiently robust for any practical purpose. His second objection was that the future of lighting lay in the use of electricity. Auer could only reply with a smile that he had already sold a million gulden[30] worth of his discovery to the industrial giant, Lindheim. This inspired Heger to print an article on the discovery in his technical journal, the *Pharmazeutischen Post*, although it was skeptically evaluated. In it he remarked that since the incandescent substance in the lamp was presumably made up of rare earth compounds, their very cost would make any widespread use of this invention impracticable. However, he also admitted that there was a complete revolution going on in the field of the gas industry. In the same issue, there was a report from the 26th Annual Meeting of the German Association of Gas and Water Specialists at Eisenach. There was great interest in Auer's invention expressed at the meeting, with the hope that there would be further development and that the obvious difficulties could be overcome.

On the 9th of April, 1886, Auer gave an experimental lecture to a business association in Lower Austria to acquaint the members with his invention. He shared with them some performance data on the new incandescent system: an ordinary gas streetlight, consuming hourly 142 L of gas, had a light output of about 12 candlepower, whereas his light, with an hourly gas consumption of 65 L, had a light output of between 17 and 25 candlepower, a saving of 60–70%.[31]

Following this initial success, things began to move very quickly. The industrial proprietary rights for Austria had been acquired for 20,000 gulden. The firm of R. Pintsch bought the rights for Germany. Frederick Williams, from England, had visited Auer and literally hand-carried one of the fragile incandescent bodies to London where he raised so much interest that he could send a specialist from a capitalist association to Vienna to get a better look. This was too much at once for Auer (see Fig. 5.3), and since he was very deficient in English, he entrusted his invention to the long-time laboratory assistant, Ludwig Haitinger (1860–1945), and asked him to negotiate with the Englishman. So the business magnate from England, who received a higher daily wage than the university assistant's monthly salary, had to spend a few days with Haitinger, until Auer decided to appear. They struck an agreement with the English syndicate. Auer received a lump-sum payment and a share in an English company to be founded, which took over the production and distribution of the incandescent mantles. The production of the impregnation liquid was, with the exception of the United States, the province of a special company, Welsbach and Williams.

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[30] The gulden was the unit of currency in the Austro-Hungarian Empire until 1892; 1,000,000 gulden had an 1890-dollar value of about $414,000.

[31] Sedlacek [25].

Auer and Haitinger worked with cerite ores and zirconium ores, sometimes in platinum crucibles, and dealt with industrial quantities of pure lanthanum and zirconium nitrate. Constrained for space, in the summer of 1887, Auer bought the bankrupt chemical and pharmaceutical plant, Würth & Co., located in Atzgersdorf, a suburb of Vienna. Haitinger took over the management of the factory where the manufacture of the salts of rare earths and their solutions proceeded on a greatly enlarged scale. The mantles for Austria-Hungary were manufactured and distributed by Lindheim & Co. in Vienna. R. Pintsch introduced them into Germany. To Pintsch the introduction of knitted stockings is due, as well as the improvement of the burners, which he and Viennese lamp manufacturers produced. The glass cylinders for the chimneys[32] were supplied by a Bohemian glass works.

The promising beginning did not last long: the public gradually rejected the greenish light. In addition, the mantles were very sensitive and the enveloping glass cylinders jumped around too much. In addition, the luminosity of the mantle decreased noticeably over the course of its service life. In the United States, Auer's first incandescent light was received better, especially where natural gas or gas-rich luminescent gas was used since its utilization for lighting purposes was only possible by means of this invention, and the higher combustion temperature also gave a somewhat more appealing color to the light. But the initial euphoria and the promising production was over. In 1899, the plant at Atzgersdorf had to be closed and capable employees had to be let go.

Auer, who was by now the only chemist, continued to improve his incandescent light, partly in his laboratory, which he had set up again in his house after the cessation of work at the factory. His long-term secretary, Felix Kuschenitz (1868–1936), who also assisted Auer in the laboratory and in the area of measurements, continued to conduct whatever business there was.

This was now a time of decompression after a huge workload. But in it, the seeds of new fruitful work were being sown. On the one hand, Auer was concerned with the technical problems of illumination in order to explain the enigmatic strong light emission of his luminous fluid of the thorium oxide with which he had repeatedly worked; on the other, he worried about the inexplicable, but downright annoying fluctuations in the brightness that Haitinger had managed to reduce by adding cerium. One must not forget that physics at that time knew almost nothing at all about the radiation laws, and that, for example, the luminosity of the gases under the influence of high-voltage electrical current in Geissler tubes approached the ideal of cold light, a phenomenon that was very little explored. It can be compared with the light of fireflies, which glow without heat production. Auer must have pondered cold light, for he collected fireflies and examined their light in his spectroscope. He soon abandoned these studies and let the rest of the fireflies go. But he continued to think about these considerations of light-development temperature, the amount of heat employed, which were so very different according to

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[32] Chimneys were used to enclose the mantle and allow the gas flame to impinge upon it in a controlled space.

Fig. 5.3 Portrait of Dr. Carl Auer von Welsbach, age 26, from the title page of the "Illustriertes Österreichisches Journal," 20 February 1886

the oxides or mixtures of oxides used, and they took him in a definite direction, as we shall see later.

To add to Auer's woes, his invention was the subject of a string of patent infringements, particularly in Germany and in England. He found himself on the defensive and, in some instances, the loser in a patent suit because the patent examiner did not understand the uniqueness of his invention. One such well-documented patent infringement suit in England sought to overturn the uniqueness of his claim. The case is cited as an entire chapter in W. Gentsch's historic book on the incandescent gas light.[33] Reading the remarks of the honorable justice, besides being a source of entertainment due to his wry humor, makes one realize how thoroughly he studied the principles of chemistry in order to come to his decision. He also comes across as a stand-in for the public relations agent that Auer did not possess. A few excerpts from the judgment will give the reader a taste of the tone of the judgment:

> There appears to me…to be no ground whatever for the attack upon the patent on the score of want of novelty. The field upon which Welsbach entered was untrodden, and marked only by the absolute failure of every attempt to penetrate it.
> In 1885…neither the salts of zirconium nor those of any of the rare metals in question were in any true sense commercial articles…There was, in fact, at that time no commercial use for them at all…except for laboratory experiments, and I think it clear that under these circumstances the patentee is not hurt by the fact that, now that, in consequence of his invention, a large industry in these things has sprung up…
>
> Welsbach certainly discovered, for the first time, a method by which a skeleton, frail but durable, of the resistant earthy oxides mentioned by him could be obtained which would give practically a means of obtaining light by incandescence, which would surpass the economy of the best modes known of getting illumination from gas.
>
> [Welsbach] molded his illuminants into shape by a chemical process of reduction from salts, and not by coating; it was absolutely necessary that he should select his substances from those which he had ascertained would give suitable illumination in the end; and the use of the rare earths is beyond all doubt, for this reason, of the essence of his invention.

Needless to say, the decision went against the defendants.

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[33] The Decision of Justice Wills in the English Welsbach Suit. In Gentsch [26].

5.3.2 The Thorium-Cerium Incandescent Lamp

These years of the "interregnum" must have been very difficult for this success-driven man, not knowing when better times would come. In spite of his serious failures and the financial fiasco that followed, many of his business friends remained loyal and had confidence in him. The necessary stimulus for fresh new, successful work was maintained by Haitinger, but the question remained unresolved: whether small impurities impair the brightness, or whether they may be of decisive importance for the radiation intensity of the oxides. Haitinger had already tried many times to settle this question. After the closure of Atzgersdorf, he returned to Lieben's laboratory where, almost immediately, a new opportunity arose. He received a request to write a chapter on the rare earths and the metals chromium, molybdenum, and tungsten for Dammers' *Manual of Inorganic Chemistry*. In the course his literature search, Haitinger came across works by Crookes and Lecoq de Boisbaudran. These two investigators had already noticed the brighter illumination of oxides due to minor impurities in the Bunsen burner flame. The problem of the mantles immediately came to mind and he wondered whether there were any similarities. He did experiments with alumina-chromium oxide mixtures, and found that with a small quantity of chromium oxide, he could achieve optimum brightness of the mantle: up to 60 candles, almost three times that of the best lanthanum-zirconium light. However, the patent taken out by Haitinger was never of practical importance since the mantle had a lifetime of barely 200 h because of the volatility of the two oxides in the Bunsen burner.

On New Year's Eve in 1890, Haitinger reported his observations and gave Auer some of his impregnation liquid. The mantles produced were photographed a few days later in the laboratory. Haitinger's important findings had fallen on fertile ground: in working up one ton of monazite sand for lanthanum, Haitinger had carefully extracted about 50 kg of thorium as raw thorium oxalate, and set it aside. This precious material, the quantity of which was probably much greater than the rest of the entire world's stock of thorium salts, was fortunately on hand for his experiments. Auer had already worked with thorium oxide in Bunsen's, as well as in Lieben's laboratory, and from his own experiments had known the superior fire resistance of this oxide, which by far exceeded that of lanthanum and zirconium oxide, and he also knew that it had good, but variable, light-emission capacity, greatly diminishing after 60–70 h of operation. Auer took a part of this thorium supply and initiated fractional crystallizations of the thorium, since he doubted its purity. As a criterion for the success of separation, he used the light emission capability of the oxide this time, and on the one hand came to fractions that barely shone, while others showed an excellent brightness, so he was almost certain that the thorium was a mixture of two elements, one of which was luminous, but the other not. That Haitinger's information could set the direction to these experiments, that led eventually to the new Auer light, is due to the chance of the random supply of 50 kg of thorium oxide and the still luckier choice of thorium's purification method.

Auer fractionally crystallized the thorium as a thorium-ammonium nitrate, a method that was very familiar to him from his work of separating praseodymium and neodymium. This method is the most effective one, not only because it separates thorium from the other rare earths, in particular cerium, but it also separates it from all other impurities such as iron, aluminum, calcium, magnesium, etc., which accumulate together in the final mother liquors. Auer had probably accumulated cerium in these mother liquors, but he could not prove by this separation method that cerium oxide is the substance that causes the bright illumination of individual thorium nitrate fractions. Only by means of controlled experiments, by the addition of precisely measured quantities of cerium to the non-luminous fractions, did he ascertain clearly the conditions which led to the invention of the thorium-cerium incandescent light. At the same time, however, an extraordinarily important fact had emerged from these experiments, namely, that the other impurities, which were much neglected, had a considerable influence not only on the luminous power but also on the lifetime of the incandescent mantles. Ignorance of these facts at first created the greatest difficulties for many thorium manufacturers in Germany. The new mantles, which had an optimum brightness of 60–70 candles with a gas consumption of about 120 L, contained 1% cerium oxide in the purest thorium oxide, yielding a mixed oxide of $Th_{0.99}Ce_{0.01}O_2$. Theoretical work on the reason for the necessity of cerium places the origin of the absorption of the mantle either from a M.O. consisting mainly of a linear combination of oxygen 2p orbitals to the empty 4f shell localized mainly on the cerium atom[34] or it is active chemo-luminescence due to the possibility of Ce containing one 4f electron as Ce (III) or no 4f electron as Ce(IV).[35] The new mantles were also far superior in their strength to the old lanthanum-zirconium mantles. Continuous burning in the strongest gas flames caused hardly any sintering or decrease in their brightness.

In August 1891, Auer registered the patents for the new lights, and then he embarked with great energy, driven by his perennial optimism, on their manufacture. Williams and the English Society generously gave him a good start by ordering a delivery of a year's supply of thorium solution. As early as November 4, 1891, the café at the Vienna Opera was burning the first new incandescent lights. The new light's appearance was so pleasing that the demand became persistent, but the requisite thorium production did not follow. The commercial directors of Auer's Viennese company had to telegraph him daily at Atzgersdorf to order new solution, and even sent out messengers, so that the manufacture of the incandescent lights in Vienna would not be interrupted. The supplies, however, flowed very sparingly. Auer was not born to be the director of a factory.

In the spring of 1892, Ludwig Haitinger decided to give up his scientific activity at the university and to take over the management of Atzgersdorf again, realizing the exigency of obtaining a substantial and steady supply of the rare earth source material.

At first, Auer went to the original source in Sweden, Ytterby, where he procured eight tons of cerite, but he soon recognized the need for a greater supply of rare earth minerals. He sent Haitinger to the United States to procure a ton of North Carolina sand left over from placer gold activity. Then through the agency of the

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[34] Jørgensen [27].

[35] Jørgensen [28].

mineral trader who sold him the North Carolina consignment, he was able to contract for an additional quantity of about two tons of Brazilian coastal monazite sand, sufficient for the first production.[36]

Additional shipments from newly discovered monazite deposits in Travancore, India supplemented the growing need for this raw material. To keep shipping costs down, on-the-spot separation facilities were set up near the source supplies to separate the denser monazite from quartz and other mineral impurities prior to shipping. At that time merchandise transport was still carried out almost exclusively with sailing ships, which usually returned to Europe without freight and therefore tended to heel. The stabilization of the ships could be improved with sand as ballast. So, Auer persuaded some shipping companies to load monazite sand as a ballast, resulting in further savings. It was the cheapness of this raw material that enabled the fledgling enterprise to compete with the electric lamp.[37]

Auer has described and worked out the processing of the monazite sands for thorium; it is one of his most important basic principles. His method of solving the digestion problem, with sulfuric acid, has remained the best of the methods found to this day. The enrichment of the thorium, which originally took place as the oxalate, was with sodium carbonate or ammonium carbonate. The purification in Atzgersdorf was always carried out by fractional crystallization of the ammonium double nitrate.

Over the course of the next five years, Auer constantly worked to improve the performance of his mantles, especially for strengthening them. He found that the weight and area of the oxide ash as well as the kind of weave, usually a type of chain-stitch, were factors that influenced the light emission of the mantle.[38] He even invented a scheme for regenerating the mantles, that is, recoating them with a new oxide solution after the candlepower of the mantle had become diminished—by brushing, spraying, or dripping the solution, or by capillary action, to cover the whole structure. In order to strengthen mantles for transportation, he coated a finished mantle with rare earth salts which were then exposed to ammonia vapor in order to avoid emission of NO_2 upon pyrolysis, but to form mixed hydroxides and NH_4NO_3 in the pores of the mantle. This turned into a gummy, elastic mass which, on incineration, was converted to the oxide and did not interfere with the light-emission properties of the mantle.[39] Another inventive way to transport the mantles safely was to pack them in collodion which, when pyrolyzed at their destination, would burn off. He succeeded in perfecting many details to make his lamp more practical although all of his work was empirical: he was breaking new ground in a field that still awaited the aid of a theoretical basis.

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[36] Commercially viable deposits can only be found along the seashores in countries that escaped the erosion due to prehistoric glaciers, namely the Brazilian coast and the coastlines of North and South Carolina. Furthermore, beaches are constantly subjected to the vagaries of weather and tide, so the localities of the deposits are considerably unstable, even from day to day. Nitze [29]. In Gentsch [30].

[37] Habashi [31].

[38] Ives et al. [32].

[39] Barrows [33].

Other countries, principally Germany, England, and the United States, began to produce mantles on the assembly line. Starting with hand-operated machines to knit lengths of the stocking-like tubing made of various types of fibers like cotton or ramie, they were soon replaced with automatic multi-spindle systems that could produce 50,000 mantles a day. Mantle processing was very painstaking, demanding thorough washing to eliminate any impurities that might affect the ultimate brightness of the device. Mantles had to be cut from the parent material, sewn, reinforced, and impregnated with the incandescence-producing fluid, and pressed with a pre-set pressure that assured the correct amount of fluid remained on the fibers. The mantles were then dried on molds subjected to hot air, then incinerated.[40]

While Auer himself was involved in technical improvements for the Auerlicht, it was Ludwig Haitinger who worked out the large-scale production problems in Atzgersdorf, which Auer always gratefully acknowledged. In lecture after lecture, especially to specialists in gas lighting, he said that one cannot mention "gas mantle" without commemorating Haitinger.[41]

5.4 Lighting up the World

The new, improved light mantle came at the right moment. The advent of electricity as an energy source for lighting was yet in its infancy and very unsatisfactory. The Auerlicht was a fitting challenge to the (unpatented) carbon filament lamp invented by the German-American Heinrich Göbel (1818–93) in 1879 and its subsequent industrial exploitation by Thomas Alva Edison (1847–1931) in 1893. However, for the time being, the much more economical and significantly lighter luminous gas lamplight prevailed. The new Auerlicht, too, was the first energy-saving lamp to provide four times as much light at half the gas consumption.

The technical significance of Auer's invention was quite obvious. However, it also had an impact the gas industry and therefore on the entire technology. It actually saved the gas industry in a period when it was only slightly compromised by the threat of electric lighting. Despite some gloomy predictions in 1893, by 1899, 90% of all gas burners in Germany were equipped with incandescent Auer

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[40] Stock [34].

[41] Ludwig Camillo Haitinger was the precocious scion of an old Viennese family. He published his first paper at the age of 17, a treatise on the direct nitration of aliphatic compounds. In 1879 he completed his "Matura" examination and from 1880 on he worked as Adolph Lieben's private assistant. He and Lieben jointly determined the exact structure of chelidonic acid. He also discovered a number of cases of observed tautomerism. With the advent of the Welsbach mantle, he entered wholeheartedly into the venture and took over the management of the company named "Welsbach-Williams Ltd." in Vienna-Atzgersdorf. In 1893, when the gas mantles were already being used on a large scale, he became Director of Gasglühlicht AG. Vienna. Haitinger's main contribution to the science of the mantles was chiefly in the recognition of the importance of adding small amounts of certain annealing oxides to enhance the luminosity of the lamps. He remained Carl Auer von Welsbach's trusted assistant throughout the rest of his career.

mantles. In the years before 1914, the world production of incandescent mantles amounted to about 300,000,000 per year. 300,000 kg of thorium nitrate from around 3000 tons of monazite sand were required. Never before had any other invention spread so rapidly around the world.

After the widespread adoption of the gas incandescent mantle, the gas industry was able to virtually eliminate the use of soot-forming and harmful light-emitting gas additives, such as benzene, ethylene and naphthalene, because the Auerlicht was due only to the complete combustion of natural gas in the Bunsen burner flame and required no other additives. In addition, the gas, now purified, could also be used for cooking and heating. Previously unwanted admixtures of gaseous sulfur compounds, which formed sulfur dioxide during combustion, could also be eliminated, obviating its concomitant health hazards. The gas industry had once again found a secure foundation for its development through Auer's invention, and with enthusiasm, progressed with the improvement of its technical facilities and the expansion of its works. The enormous increase in gas consumption thus triggered the establishment of correspondingly large gasometer systems.[42] The construction of the gasometer in Vienna-Simmering was the largest building site in Europe in 1898.

The initial problems with the lamp cylinders produced by the Bohemian glassworks, which could not withstand the heat radiation from the Auer incandescent mantles, had given rise to complaints. This problem stimulated innovations in other scientific fields. For example, the Schott & Genossen firm (founded in 1884 by Otto Schott, Ernst Abbe and Carol Zeiss) in Jena succeeded in finding a satisfactory solution through the development of "Jenaer-Glas," a heat-resistant borosilicate glass with a low heat expansion coefficient. It was used for the first time as the Auerlicht lamp cylinder. Since then, this glass has become an integral part of many technical applications in laboratories and as glass cookware; it is still manufactured by the Schott Co., now known as Schott AG.[43]

By this time, Carl Auer von Welsbach had become a celebrated and wealthy lighting technician. In 1892 alone, 90,000 Auer gas incandescent lamps were sold in Vienna and Budapest and by 1913 the annual production was increased to 300 million items. By 1929, over five billion Auer mantles had been produced worldwide. If one were to place each one at a distance of 40 m, they would be able to illuminate the entire surface of Europe. For lighting purposes, up to 1935, 300 billion cubic meters of combustible gases had already been used to light the incandescent mantles. Due to their much higher luminosity compared to mantles used previously, gas consumption was greatly reduced.[44]

The Auerlicht (see Fig. 5.4) crossed the ocean in the form of the Welsbach light, and thousands of them were used to light the streets of major cities like New York

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[42] Gasometers were gas storage containers at atmospheric pressure and ambient temperature.

[43] Adunka [35].

[44] Estimated candlepower for the Welsbach lights, depending on their form, was between 75 and 100 candlepower, with an estimated lifetime of not less than 1000 h.

and Philadelphia in subsequent years.[45] The Franklin Institute of Philadelphia reported on its experience of the Welsbach light in *Science*[46] as part of the literature surrounding its award of the Elliott Cresson Medal to Auer "for his discoveries regarding the metallic oxides which may become incandescent when heated, and for the invention of a mantle by the use of which these metallic oxides are commercially available as sources of artificial light." The report continues: "Also, in view of the many details wrought out by the Welsbach Light Company, of Gloucester, N.J., in putting a thoroughly practical mantle on the market, the Franklin Institute awards to them, the said company, in addition, the Edward Longstreth Medal of Merit." These awards were among the first of many others to follow.

Carl Auer von Welsbach certainly lived up to his motto of "Plus lucis" (see Fig. 5.5) to the highest degree. His contribution to lighting technology in the latter years of the 19th century and the early decades of the 20th attest to that.

Auer's incandescent mantle literally shifted night into day. In hospitals, emergency surgery could be performed even at night with bright, safe, reliable lighting. In shop windows, the Auerlicht shone brightly onto the sidewalk, where passers-by could walk safely and securely. After eons of daily activities being curtailed by nightfall, it was finally possible to extend the length of the day by artificial light. Thus, social life took on a completely new dimensionality. Rarely has there been such a tremendous upheaval in human society brought about by an invention. All previous revolutionary inventions, such as the steam engine, automatic looms, the railroad, etc., were initially regarded with suspicion by the general public. There had even been violent acts like the Luddite revolution in Great Britain, because these inventions had led to streamlining and, consequently, to the loss of jobs. In times without social security, this brought terrible and degrading poverty to many members of the working class.

On the contrary, the Auerlicht had the opposite effect. It became possible to create evening and night shifts in factories, thus increasing production. Given the bright and continuous light, it was possible to open night schools and extend library hours to further the education of the working class. Furthermore, the light emitted by the mantles had spectral properties that were very desirable for printeries, textile factories, and paint workshops—a bright, even illumination that approached that of sunlight. No other artificial light had ever approximated this property.

It was actually recognition of its continuous, even spectral distribution over the wavelength ranges of the visible region[47] that prompted the physicist, Heinrich Rubens (1865–1922), to use a Welsbach mantle for his determination of the energy-temperature relationship of radiating blackbodies in September,

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[45] The [New York] City Record (1906) 34, Part 2:1441.

[46] Report of the Franklin Institute [36]. This report was quite thorough in that it gave a brief history of the development of incandescent gas lighting, including the work of two Americans, W. M. Jackson in 1881 and Charles M. Lungren in 1881, with additional patents as late as 1887. In its description of Auer's contributions, they make special note of the great attention to detail he gave in his lamp development to make its use practical. It also gives the numbers and dates of Auer's most important U.S. patents.

[47] Jørgensen [37].

Fig. 5.4 Commercial example of a Welsbach light for sale in the USA

1899.[48,49] Rubens noticed that there was something peculiar about his results: the residual rays from the Auer burner after being multiply reflected from fluorite at 24 and 32 μ were extraordinarily more “energy-rich” than Wien’s Law would predict for a blackbody at the same temperature. Unwilling to put this effect down to a failure of Wien’s Law, Rubens attributed his observation to the peculiarity of the Auer burner at longer wavelengths. In October of 1900, he informally reported his results to Max Planck (1858–1947) who immediately derived a formula based on quantization of energy that was consistent with Rubens’s results—and quantum physics was born[50]! Thus, the Welsbach mantle facilitated the development of one of the most important theoretical scientific advances in history.

There were other practical advantages to the Welsbach mantle. It burned longer and brighter than any of its distant competitors. And the early electric lamps, which many thought would supplant gas lighting in the future, were very expensive, four to six times as much in the year 1892.[51] In fact, many businesses that had converted over to electric lighting changed their minds and reverted to using Auer’s incandescent mantles once again.

This almost incredible scale-up in use was accompanied by equally unprecedented financial success. The Austrian Gasglühlicht-Aktien-Gesellschaft took over the Viennese production as well as Auer’s patents and contracts with foreign companies. The impregnating liquid, the production of which remained an industrial secret, was supplied at a contractually fixed price. The greatest success was achieved by the German Society in Berlin, despite the sharp competition in Germany which

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[48] Rubens [38].

[49] Rubens and Aschkinass [39].

[50] Kangro [40].

[51] Lecture given at the 32nd annual gathering of the Deutschen Vereins von Gas- und Wasserfachmännern in Kiel on 28 June, 1892 (as cited in Hartwig G (1894) Das Gasglühlicht. Hellmuth Henkler’s Verlag, Dresden, p. 49).

Fig. 5.5 Auer von Welsbach Coat-of-Arms. In the center of the shield is a torch; the upper right quarter of the shield depicts the gothic archway entrance to the city of Wels

came about from an unfavorable outcome of patent proceedings. Let it suffice to say that the company paid a dividend of 130%, according to the annual accounts of 1893/94. Also, the foreign companies, the English, French, Belgian and Dutch, as well as the Irish and Swiss Gasglühlicht-Gesellschaft made huge profits.

During the 40-year period of the Welsbach mantle's existence, the Austrian and German Auer-Gesellschaft taken together produced about 1500 tons of thorium nitrate, which corresponded to at least 1500 million incandescent lamps. The production of the American Auer Society and of the many foreign factories, which together produced more than double that number, brings the world consumption to an estimated 5 billion incandescent mantles. Based on these reports, it is not surprising that Auer von Welsbach became a very wealthy man in a relatively short period of time despite so many unfavorably-judged patent litigations.

Given all these positive effects, it is almost not worth mentioning that there were some glitches. Besides the fragility of the mantles themselves, and their sporadic failures, there were some problems of a local nature like insects clogging the holes of the burners and lizards destroying the mantle's ash skeleton. One might simply count these difficulties as the price to pay for moving out into environments not ever dreamed of by Europeans.

It is no wonder, then, that in the city of Vienna alone the number of Auer burners increased from 1240 in April, 1893 to over 42,290 by November of that year. In Germany, in the 15 months between September, 1892, and the end of 1893, a half-million Auer burners came into use, 100,000 in Berlin alone. And at the beginning of 1894, there were at least 150,000 in private use in Paris.[52]

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[52] Sedlacek [41].

When, in 1901, Kaiser Franz Josef elevated Auer to the hereditary nobility, conferring on him the title of “Freiherr,”[53] he is said to have remarked: “You have had, so I hear, considerable success with your discoveries,” to which the newly created Freiherr von Welsbach quickly replied, “Yes, Your Majesty, up to the present more than 40,000 people throughout the entire world have found employment through my discoveries.” This reply left Franz Josef speechless.[54]

And Auer’s later contributions, as we shall see, were to have even more far-reaching effects that continue to affect the lives and livelihoods of thousands of people even today.

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[54] Feldhaus [42].

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Chapter 6
New Perspectives

6.1 A New Location

Through his tireless, purpose-driven efforts and his mother's unremitting confidence, Auer's period of difficulties and failure was blessedly short. What followed, however, were two years of uninterrupted, feverish research to improve the incandescent mantle. This effort required that he invest all his time and energy into not only the research, but into all the other duties that were consequent upon success: patent applications, organization and reorganization of factories, recruitment of employees and executives, procurement of raw materials and supplies, and the thousand other responsibilities that required truly titanic endeavors. This feverish activity could not help but have its effects on Auer, now thirty-two years of age and beginning to feel it. And as his successes continued to pile up, so too did the accompanying emotional and psychological distress due to patent litigation, slanderous press reports, and verbal attacks from competitors.

Just when Auer was beginning to feel overloaded with work and stress, he received a kind invitation from a physician friend to take a summer holiday with him in Austria's southernmost province, Carinthia, a vacation mecca for many Viennese. This was a chance for him to relax, recharge his batteries, and allow himself a few days away from the desk and the lab.

However, this turned out to be one of the happiest times in Auer's life. He felt relaxed and rested in a way that made him, now a wealthy businessman, look around the area with a different perspective. He began to entertain the idea of relocating and settling in Carinthia. His great opportunity arose in 1893 when the famous actress and singer, Marie Geistinger, offered her beautifully appointed villa, "Marienhof," for sale at an attractive price. It is said that when he first met the actress, the magnolia tree in front of the house was in full bloom and so enchanted Auer that he decided to buy it on the spot. Situated near the village of Meiselding, with the Karawanks range to the south near present-day Slovenia, and the High Tauerns to the north, that blocked out the cold north winds, the place seemed to have an ideally balanced

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_6

Fig. 6.1 “Schloss Welsbach” today

climate. For 100,000 gulden, Auer was able to purchase both the villa and the adjoining Rastenfeld estate, which included the largest cattle stable in Carinthia.

Carl Auer von Welsbach temporarily moved from Vienna to his newly acquired home in order to find some necessary recreation. But something was missing—a laboratory. Around 1895, he commissioned an architect with the construction of a laboratory near the villa. But even as the building work progressed, Auer decided to expand the building on the left and on the right by adding side wings and towers. The construction of what was to become “Schloss Welsbach” (see Fig. 6.1) on the hill became more and more expensive. Over 100,000 horse-drawn carts were needed to bring up the building material. Auer paid the drivers well—one crown per load—so there were no delays. In 1899, the castle was ready for occupancy.

6.2 A New Status: Marriage and Family

Auer von Welsbach designed and constructed a beautiful and expansive park, with a large pond and a swimming pool. Since it was situated at an altitude of 800 m, it was only with great effort and many attempts that he achieved success with some of the more delicate plants. The Lebanon cedars concerned him most of all, but he treated them so patiently that eventually they flourished. He was so involved with his garden and orchards that he took on certain tasks, such as the viniculture and rose pruning, himself, demoting his gardeners to mere observers. His peach trees and grapevines were also very special. He looked after them all by himself and cut them with his own hands.[1] Something was lacking to this tranquil domesticity, a fact that Auer realized better than anyone else. So, on New Year’s Eve of 1898,

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[1] Auer-Welsbach [1].

accompanied by only two servants and two of Auer's close associates, Felix Kuschenitz and Adolf Gallia (1852–1925), Auer and his bride, Marie Anna Nimpfer (1869–1950), traveled to Helgoland. Marie, a native of Vienna,[2] had been a close and helpful confidante of Auer's for years and had supported him in a number of difficulties, especially those involving litigation disputes. At that time, Helgoland, a North Sea archipelago and favorite spa of the European upper classes, was a popular venue for exclusive weddings.

Auer was smart enough to appreciate Marie's independent nature, and she was wise enough to play a role that did not contradict a woman's image at the time. She was to have a great influence on her husband's future choices. Private happiness, in any case, gave him additional confidence in the tasks ahead.[3] And within a few short years, there were four new additions to the family: Carl Maria Johann (b. 1900), twins Herbert Karl Maria and Hermann Karl Maria (b. 1902), and Hildegarde Marie Karola (b. 1903).[4] In this regard, Carl mirrored the life choice of his own father,[5] who postponed marriage until he was at the height of his career, and very soon afterwards had sired four children.

6.3 A New Venture: From Blast Furnaces to High Technology

In Carinthia, the blast furnace industry, which was more than two thousand years old, was at an end. The charcoal required for the smelting of any iron ore still available could no longer be obtained from the immediate area. The surrounding forests, exploited for centuries, had no more wood for charcoal. Charcoal had to be supplied by faraway producers from Hungary and Slovenia. In addition, the Bessemer Converter and the Thomas Converter made steelmaking possible using molten pig iron. As a result, other industrialized countries were able to use poorer ore and also coke derived from low-sulfur bituminous coal in the iron smelting process. Since these converters could oxidize the impurities in the ore with pressurized oxygen, they needed neither phosphorus- nor sulfur-free ore, nor expensive charcoal, for iron production.

As a result of the depletion of raw material and the introduction of a new technology, an industry based on the use of charcoal declined dramatically in Carinthia within just a few years at the end of the nineteenth century. Of the many thousands of employees, hardly anyone thought at the time that such a long-established industry could ever be destroyed. With the blowing down of the last blast furnaces, a time of misery began which developed into a general emergency without a glimmer of hope. At that time, there was hardly any public funding for the many hopelessly unemployed workers in the iron industry: miners, foresters,

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[2] Daughter of Alois Nimpfer and Marie (née Broβmann) Nimpfer.

[3] Dahlmann [2].

[4] Genealogisches Taschenbuch der adeligen Häuser Österreichs [3].

[5] Alois Auer von Welsbach was 36 at the time of his marriage; Carl was 40.

charcoal burners, forwarders, blacksmiths, ironmongers, and more, who were now all in dire straits. Thousands of job-seekers roamed around, hoping to at least find some work as day-laborers, in order to feed themselves and their families. No one could count on a steady income in these times.

In its extreme distress, the Carinthian provincial government approached Auer von Welsbach with a petition to invent something to improve the hopeless economic situation of his adopted region, which had previously been dominated by the iron industry. As a response, in 1897/98, he bought the ironworks in Treibach, which had been shut down and disassembled, about 5 miles from his home, for 607,400 gulden. On this expansive site he began, in 1898, to establish the largest chemical-metallurgical research and experimental enterprise in the Austrian Empire.

Realizing the need for a sufficient supply of electricity in Carinthia, he harnessed the water power of the local Gurk River to supply the energy for a new power plant. He named this research enterprise "Dr. C. Auer von Welsbach-Werk Treibach." Here, in his now principal place of work, he continued his experimental activities. He had actually created a private technology park.[6]

6.4 Meliorem Lucem

Despite his enormous success in the field of gas incandescent lighting, Auer, as an inventor, knew that he could not stand still nor even continue to improve an old idea. He realized that, given the right conditions, electricity would replace gas as a source of energy. More than fifty years before he was born, inventive geniuses like Louis Jacques Thénard (1777–1857) and Humphry Davy were tinkering with heating metal wires with electric current until they glowed. Many would-be inventors, American, English, Russian, Belgian, German, and French followed, right up until the end of the century. The luminous bodies of choice were either platinum or carbon filament, and in two cases, a platinum-iridium alloy. The ignition atmospheres were vacuum or air, but in some cases, nitrogen was used.[7] Although these efforts failed for one reason or other, many of them served to pave the way to what eventually came to be our modern and better system of lighting. Auer moved away from "plus lucis" to "meliorem lucis" (better light).

6.4.1 Early Attempts

In 1838, a Belgian inventor and lithographer, Marcellin Jobard (1792–1861), proposed that an electrified thin carbon rod in a vacuum or rarefied air could glow with a durable, intense light.[8]

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[6] Adunka [4].

[7] Shavinina [5].

[8] Benjamin [6].

Two years later, William Robert Grove (1811–96) built what might be considered the first precursor of the metal filament lamp. He attached a coil of platinum wire, the intended luminous body, to two conducting copper wires well-insulated with varnish and the assembly was made to stand upright in a glass of water with a smaller diameter empty tumbler inverted over the whole. Attaching the projecting ends of the copper wires to a voltaic battery, the ignited wire gave a steady light that continued as long as the battery lasted.[9] In 1841, Frederick de Moleyns was the first person to patent a platinum filament lamp that incorporated powdered charcoal that trickled over a glowing wire spiral in order to increase the luminosity *in vacuo*. Three shortcomings made the lamp unsuccessful: the charcoal blackened the inside of the glass bulb, platinum must be heated to near its melting point before it glows, and thus it disintegrates rapidly, and lastly, vacuum technology of the time was inadequate to prevent filament oxidation.

Other inventors who entered the lists were John Wellington Starr (1822–46), Edward Agustin King (d. 1863), Charles de Changy (b. 1817), and William Edwards Staite (1809–54). In 1848, Staite hit upon the idea of using iridium as a lamp filament because of its higher melting point, 2450 °C. He also succeeded in making it sufficiently ductile for mechanical shaping by continuous rolling and hammering in white heat. This resulted in a useful metal filament lamp, but production was obviously limited because of the exotic metal and the efforts to “tame” it. De Changy, ten years later, observed that platinum threads could be rendered more resistant to extreme heat if they were heated slowly during evacuation of the bulb, freeing them from adsorbed gases. None of these attempts were very cost-effective.

In 1850, Joseph Swan (1828–1914) solved the disadvantage of cost by using carbonized paper filaments in place of ones made of platinum. The bulbs, as usual, had to be evacuated to extend their lifetime, but the construction of a complete and enduring vacuum still eluded technology.[10]

Eventually, Thomas Alva Edison (1847–1931) came on the scene. Already a successful inventor, Edison took up the problem of the electric light bulb by building on the experience of his predecessors and trying to improve upon them. Realizing that platinum threads melted too easily, he tried to circumvent the necessity of extreme heat by winding platinum wire around metal oxides known to incandesce when heated, hoping to set up a resonance between the two filament materials so that they would glow at a lower temperature. He tried other combinations, coating platinum wires with fire-resistant oxides like lime, magnesia, zirconium oxide, cerium oxide, and even coal. He even tried to form incandescent materials from finely divided platinum with zirconium and with iridium, but none of these trials was satisfactory.

Finally, in 1878, he abandoned his work on metal filament lamps and found a usable alternative in a special type of carbon filament: charred bamboo fiber. This was the basis for the first successful incandescent lamp powered by electricity and

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[9] Grove [7].

[10] See https://en.wikipedia.org/wiki/Incandescent_light_bulb (last accessed 15 January 2018) for an account of the evolution of the incandescent light bulb.

the launching of an equally successful business that promoted this invention worldwide. Edison's competitors immediately dropped their attempts at finding a successful metal filament and concentrated their attention on finding organic materials which, when carbonized, could give a better filament than Edison's bamboo fibers (which, of course, by this time, were patented). Edison's success with the carbon filament lamp was due to carbon fibers that had long service life (600–1200 h), state-of-the-art vacuum pumps, and a carbon disk variable resistor that prevented overheating and extended the lifetime of the bulb.[11]

An interesting patent dispute arose at the time that Edison's bamboo fiber lamps were in their heyday. A naturalized German-American named Heinrich Göbel, anglicized to Henry Goebel, claimed to have invented just such a lamp in the 1850s but never sought a patent. This anticipatory claim, if true, would void Edison's patent and allow anyone to exploit his idea. Consequently, disallowing Goebel's claim, Edison's firm had to file patent infringement suits in a number of instances, but the litigation dragged on beyond the point of the expiration date of Edison's patent. There was enough evidence to indicate that Goebel's assertions were fraudulent, but there were also credible witnesses who attested to having seen Goebel's lamps long before Edison's appeared. A book that appeared in 2007 states definitively that there was no merit to Goebel's claims, but Wikipedia also states[12]:

> So-called *Goebel Original Lamps* are in the archives of the Henry Ford Museum, Dearborn. A technical examination with today's methods of science to establish, if possible, a final truth on the production year of the lamps and to clear up technical points of dispute in the litigations did not take place yet.

So seemingly things remain unresolved to this day.

A variety of methods were employed over time to try to improve the light output of the carbon filaments including making pastes of carbon black or graphite with suitable binders, or making viscous solutions of cellulose or nitrocellulose, and forming filaments by extrusion through a spinneret plate. These attempts improved the product somewhat, but the light output, mechanical strength, and durability problems remained. At this point in time, these lamps required an energy output twice that of the Auer incandescent mantle because carbon's resistance, as opposed to metallic behavior, is inversely proportional to the temperature, leading to increased current consumption with increased temperature—the carbon filament only emitted more heat instead of emitting more light. This made the mantle the leader in the field, but as Auer himself knew, not for long. The time had come to do something about it.

6.4.2 The Osmium Lamp

Undoubtedly, one of the most impressive features of our portrait of Carl Auer von Welsbach as a scientist, technical specialist, and industrialist, is expressed by the

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[11] Sedlacek [8].

[12] https://en.wikipedia.org/wiki/Heinrich_G%C3%B6bel (last accessed 15 January 2018).

fact that, after the unprecedented success of his gas incandescent lamp, giving the world truly modern gas illumination, he turned to the natural competitor of this type of lighting, the electric light. It was evident, by examining the publications of the time that gas specialists and electrical engineers did not talk to one another. Each touted the virtues of one's own technology from behind barriers built out of prejudice, fear, and professional pride. Auer crossed, or even tunnelled through, the barrier with his attitude. Ever since he was very young, he applauded the attempts to create electric light. He loved this field, and decided to see if he could help it along. In his new research park in Treibach, he had the space, the help he needed, and above all, a reliable and abundant source of electricity.

Auer arrived at the invention of the osmium lamp by a very circuitous route, which involved his lifelong interest in the rare earths[13]:

> In many of my experiments dealing with how luminous bodies differ in their ability to radiate light, I have often had the opportunity to see how extraordinarily different the bodies behave in this respect. On the one hand, a body heated under certain conditions readily emitted white light, but these observations were chiefly related to the use of prodigious amounts of thermal energy, and were thus not directly related to the processes induced by electric current. On the other hand, bodies heated up by electric current might have considerable differences in their luminous and radiative characteristics, and the colors of their lights might be different. My focus, in particular, is on the fusible metals which I assume might be quite different in a[n electric] lamp. Information of whether they would behave better than carbon in this regard, as far as I know, does not exist.
>
> My aim, then, was to find a metal which, in the form of a thin, elastic thread or wire, was able to withstand heating to white heat without change in shape. Platinum, with its relatively low melting point, is beyond consideration. The other metals, however, which are very difficult to melt, could not be obtained as thin filaments or wires. Then I had a somewhat peculiar idea. I had once seen that a very fine aluminum wire, which could be gradually heated by a[n electric] current, could be heated to a bright, white heat without melting. This was a surprise considering the relatively low melting point [660 °C] of aluminum. I repeated the experiment and succeeded, and finding the explanation was not difficult. The aluminum wire, which gradually comes to red heat, is covered with a gradually melting aluminum oxide layer, by which the molten metal, held as almost in a "tube," can be brought close to the boiling point without the half-molten "tube" bursting.

This approach is characteristic of Auer's method. He did not try to remain current with the technical literature and more than likely did not know of earlier experiments with metals such as iridium, which were much more difficult to melt. His first idea came from recalling his experimentation with aluminum.

He goes on to say that he planned to repeat the experiment with what he called "more promising modifications": substitution of platinum for aluminum, and an enamel-like coating made from almost infusible thorium oxide. To do this, he drew a thin platinum wire through his fingertips that were moistened with a dilute solution of thorium nitrate, annealed the wire in a flame, and repeated this procedure until the wire was visibly coated with a layer of thorium oxide. When bent in the form of a bow and connected to the two poles of a source of electricity, the wire sputtered and

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[13] Auer von Welsbach [9].

glowed, and by gradually raising the current, he could make the entire wire glow with a white heat. However, in the process the platinum had melted inside its shell and when the wire was moved or the current was turned off, and then reapplied, nothing happened. The conduction through the platinum had been interrupted.

Realizing that these oxide rods were a dead end, practically speaking, he began to examine the other refractory platinum metals until he came to high-melting osmium. He described osmium as a brittle body that was impossible to draw out into elastic threads under any circumstances, and that it also gave dangerous and toxic combustion products.[14] Falling back on his old method of impregnating cotton fibers with soluble salt solutions, then annealing them, and then covering the threads with finely pulverized metal, he was again disappointed. However, he says:

> But one of these experiments showed me very clearly that osmium was far superior to the other platinum metals, and that I could hope to find in it the suitable metal for the new lamp.

Trying another procedure, this time he stretched metal wires [he does not say of which metal these wires were made] in a wide tube and then filled the tube with reducing gases containing highly toxic osmium tetroxide (OsO_4). On heating the metal filaments using an electric source, osmium began to deposit on them, and this process was continued until the filaments "had assumed the desired strength." He says that this method was still not technically advantageous, partly because it was difficult to remove the filament core, and partly because the filaments were not sufficiently uniform and elastic.

Auer quickly hit upon a method that worked very well. He was able to manufacture amorphous osmium by gently annealing osmylditetramine chloride [$OsO_2(NH_3{\cdot}NH_3{\cdot}Cl)_2$], which he pulverized with sugar to make a very fine powder. This was then mixed with a viscous solution of collodion or caramelized sugar and kneaded into a paste. The paste was placed in a container fitted with a very fine nozzle and passed through the nozzle under high pressure to make threads which were collected on a movable base, cut into suitably sized pieces, formed, and then brought to red heat in a furnace to remove the carbon. The final product was an osmium filament that could be placed in a light bulb. This "paste process" was described in detail in his patent application of 19 January 1898.[15]

Auer's 1893 foundation of the Österreichische Gasglühlicht- und Elektricitäts Gesellschaft and his patent of 1898[16] marked the birth of the metal filament lamp industry.[17,18] These lamps were a commercial and economic success, requiring only 1.5 W per candle power as opposed to 3.5 W for the carbon filament lamp. Its

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[14] Auer consistently invested his entire body in the chemical enterprise regardless of health consequences. Fully aware of the dangers of working with highly toxic osmium, which is why no one had considered a technical use for this element at the time, he did not shrink from exposing himself to physical harm in order to gain new knowledge.

[15] Auer von Welsbach [10].

[16] U.S. Patent, Welsbach Light Company, 27 July 1898.

[17] Baumgartner [11].

[18] Auer von Welsbach [12].

serviceable lifetime was a whopping 5000–6000 h. Manufactured at the old plant in Atzgersdorf, their chief market was in Germany and Austria. However, they could not be shipped large distances because the filaments were very fragile, and osmium metal was so expensive that the manufacturers wanted to recycle the lamps after they burned out. Hence the lamps were not sold outright, but only rented to their users so that the osmium they contained could be readily recovered.

Auer personally took up the manufacture of the glass light bulbs to the astonishment of his senior assistant, Felix Kuschenitz, who knew nothing about his boss's glassblowing apprenticeship in Heidelberg. He also set up an osmium plant in Treibach under the supervision of Anton Lederer (1870–1932) where the production of osmium filaments and other research projects were carried out.[19]

The Auer-Oslampe made its début at the Paris World Exposition in 1900. The public places and exposition halls were flooded with both the new metal filament lamp and thousands of Welsbach gas mantles as well. The view from the top of the Eiffel Tower astounded the Parisian public. Even the Emperor Franz Josef, keenly interested in the Auer-Oslampe, had them installed in the royal residence, the Schönbrunn. He sent a letter to Auer expressing his appreciation for this "ingenious invention…a very valuable achievement in the field of electrical lighting."[20]

Auer bought all the osmium he could, but the element was in short supply, which certainly limited the popularity of the lamp. It would soon be superseded by the tungsten filament lamp, a metal with a higher melting point, and one that Auer had overlooked. By 1905, the Atzgersdorf plant had ceased their manufacture.

It was only in 1906 that the Atzgersdorf plant managers recognized tungsten as the metal with the highest melting point and began to gradually replace the scarce and expensive osmium. The brand name, OSRAM[21] derives from the combination of the two metals, which Auer entered into the trademark register for incandescent lamps and arc lamps at the Imperial Patent Office in Berlin under WZ.86.924, creating the basis for a worldwide company (See Fig. 6.2). In that same year, Felix Kuschenitz took over the company in Atzgersdorf in partnership with Westinghouse; it was a relationship that was to last for 82 years.

As a result of having chosen osmium for his metal filament invention, and having specified only osmium in his patent application, Auer lost out economically when tungsten entered the scene as the only viable alternative to metal filament technology. Furthermore, its scarcity as the least abundant stable element in the earth's crust[22] consequently makes it one of the most expensive elements as well at today's price of $13,000 per kg (tungsten costs about $110 per kg). So, the osmium filament became obsolete very quickly; the OSRAM filament lasted, by contrast, for the entire 20th century.

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[19] Howell [13].

[20] Letter of 28 September 1900.

[21] The name was coined by an Auer co-worker, Fritz Blau (1865–1929).

[22] 1.8E-7%; tungsten is a thousand times more abundant.

Fig. 6.2 Right: OSRAM logo; Left: Ad for the Osram-Light, cheaper than gas

Three factors in the area of science and technology, however, made Auer's invention invaluable. First, other inventors used his ideas to advance lighting technology; secondly, he moved light bulb technology out of the organic realm into the inorganic; and thirdly, he pioneered the field of powder metallurgy by creating the first powder-metallurgically shaped body with a very high melting point. His procedure for shaping hard and brittle materials was a breakthrough toward more use for these exotic materials.

More than a scientist and inventor, Auer was a person who sought to improve overall living conditions. This was the driving force in all that he did.

6.5 Sparks Spark a New Invention

For the millennia prior to the advent of electric lighting, fire was the only artificial energy source capable of lighting up the night. From the bonfires of Stone Age humans to the incandescent mantles devised by Auer von Welsbach to expand normal daylight hours, the only available means was the use of combustible materials. But achieving combustion itself was a major problem, solved in clever ways in the course of time.

6.5.1 Early Fire-Producing Methods

The archaeological record is clear that one of the most important economic endeavors of the Paleolithic and Neolithic eras was flint mining. A microcrystalline form of quartz (SiO_2) sometimes called chert, it has been a valued raw material for toolmaking for over two million years. When properly struck and shaped (the art is called "flintknapping"), flint can form sharp and durable tools, a need that gave rise to widespread flint mining with the rise of agriculture.[23] It also has another very

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[23] Lambert [14].

useful property: when two pieces of flint are struck together sharply, sparks fly. So, with a great deal of skill, flint can be used as a fire starter. This method found its way into the literature by way of Virgil's *Aeneid*[24] and *Georgics*,[25] described as producing "the spark hidden in the veins of flint."

It was soon found that a little less skill was required if flint were struck against another mineral, pyrite (FeS_2). This combination produced a greater quantity of more enduring sparks that could be directed to fall on an easily combustible material. For example, the 5000-year old Iceman found frozen in a glacier in the Tyrolean Alps in 1991 had a toolkit that contained flint, pyrite, and a type of fungus (called tinder fungus), a state-of-the-art means of starting a fire in his day.

Iron ore smelting ushered in the Iron Age, and with it came carbon steel, more than likely produced at charcoal hearths. Hardened steel gave better sparking when struck against flint and thus became the state-of-the-art method for millennia, concretized in the standard tinder box. Flintlock firearms and the so-called "tinder pistol" were later developments.

6.5.2 The Invention of Matches

A breakthrough that made fire production easy and portable was the invention of friction matches, sometimes called "lucifers," in 1826. John Walker (1781–1859), a chemist and druggist active at Stockton-on-Tees, found that a paste made of antimony sulfide, potassium chlorate, gum, and starch could ignite when scratched on a rough surface. Placing a glob of this paste on cardboard strips, and later on wooden sticks, he began to sell them in his pharmacy, but never fully commercialized or patented the product. He was only given credit for his discovery after his death.

Phosphorus eventually became the substance of choice to manufacture matches, leading to exploitative practices that became the hallmark of the Industrial Revolution. The safety match then became the most popular means of creating a fire quickly, easily, and on the spot. It is no surprise that tobacco use rose proportionately with their availability.[26]

6.6 Auer's Solution to a Two-Fold Problem

Auer's invention of the thorium incandescent lamp had an unwanted by-product that took up a great deal of space at the Atzgersdorf and Treibach plants: tons of rare earth residues with seemingly no use. In addition, his most successful

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[24] Book 1, line 174; Book 6, line 1.

[25] Book 1, line 135.

[26] http://museumofeverydaylife.org/exhibitions-collections/current-exhibitions/history-of-the-match (last accessed 15 January 2018).

invention, the incandescent mantle, required a cheap and easy method to ignite it using an automatic ignition device to make it more competitive with electric lighting. His fertile, imaginative brain found a way to solve both of these problems in literally one stroke.

He had earlier tried to use these rare earth waste materials by adding them to arc lamps for movie projectors, but with only modest success. Looking for further applications, he thought to produce the rare earth metals themselves by electrolytic reduction of their chlorides, which melted at around 800 °C. As a result, Auer was able to obtain cerium, and other rare earth metals, and their alloys, in small amounts—thanks to the direct current from the power plant he had built on the Gurk River in Treibach in 1898.

6.6.1 A Special Alloy

Metallic cerium, though not pure, was first prepared by Carl Gustaf Mosander in 1826 by the decomposition of the chloride with potassium vapor to yield the elemental form for the first time. Mosander found it to be a very active metal.[27] A. Beringer, in 1842, came closest to producing the pure metal.[28] Others, like the prominent chemist Friedrich Wöhler, tried chemical-metallurgical means to reduce cerium such as heating the oxide with sodium, calcium, and magnesium. It was Robert Bunsen who, along with his students William Hillebrand (1853–1975) and Thomas Norton (1851–1941) in 1875, who succeeded in producing small quantities of cerium by electrolysis, using a fine iron wire as the cathode. In 1888, W. Borchers used an iron crucible which doubled as the cathode, and found that the cathode current density was less important for the deposition of the compact metal than intense heating of the molten bath. In 1901, his student, L. Stockem, succeeded in improving the furnace in such a way that it was not heated externally but with the electrolysis current itself, whereby it was possible to cool the crucible wall and thus prevent the deposited metal from contaminating it.[29] In Munich, F. W. Muthmann and his students built similar furnaces partially heated by the electrolysis current, and partly by alternating current; they succeeded in producing about ¾ kg of cerium metal in 6 h with a current of 120 A, which represents about a 60% yield.[30]

Auer, eschewing the heated crucible method, employed Robert Bunsen's simpler method of cerium electrolysis. He used an iron cathode, but during the process, a small amount of cerium had adhered to the electrode. Being frugal, he tried to file it away before reusing the iron cathode. As he did so, he easily removed most of the soft cerium metal, but when he came up against the iron, his filing action gave rise to

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[27] Tansjö [15].

[28] Ostwald [16].

[29] Sedlacek [17].

[30] Hirsch [18].

strong sparking. Ever attentive to new developments, Auer concluded that cerium forms a brittle alloy when it is melted with iron at temperatures above 1000 °C. This alloy now puts up so much resistance during filing that sparks are created capable of igniting combustible gases and liquids. Auer alloyed many other metals with cerium —magnesium, zinc, copper, nickel, etc.—but no other metal was as suitable as iron. He coined the word "pyrophorism" to describe the spark-formation and in 1903, he patented his "pyrophoric alloys" manufacturing process.[31] In the application, he described the optimum mix of metals as 30% iron, 60% cerium, and 10% other rare earth metals. This mix was later modified to 30% iron and 70% cerium mischmetal.

6.6.2 The Sparking Principle: Pyrophorics

Iron is a good source of sparks because when struck sharply, minute pieces of iron fly off the steel and, exposed to oxygen, autoignite. This phenomenon can only take place when the iron surface is freshly exposed: under ordinary circumstances, iron, like aluminum, is covered with a thin film of iron oxide that prevents it from undergoing further oxidation. Iron belongs to that group of materials known as "pyrophorics," substances that spontaneously ignite below room temperature (about 70 °F, or 20 °C) in the presence of oxygen. Finely divided metals such as iron, aluminum, and magnesium, especially in powder form, are highly pyrophoric.[32]

There are certain metals that are reactive enough that they are pyrophoric in bulk, a phenomenon that Carl Auer von Welsbach noticed during his student days with Robert Bunsen. The rare earth metal, cerium, is one of these. If it is alloyed with iron, it forms the pyrophoric substance called ferrocerium, capable of sending out showers of sparks when struck or filed. Various theories have been proposed to explain the pyrophoric properties of these alloys. Some say it is due to the presence of nitrides in the ferrocerium; others suggest hydrides, and still others suboxides, but no theory has actually been confirmed by experiment.[33]

In fact, cerium is a relatively soft metal that does not produce metallic chips upon filing. However, when cerium is melted together with iron it forms intermetallic compounds ($CeFe_2$, and at higher temperatures, Ce_2Fe_{17}) which cause the alloy to harden. When struck, the harder alloy, exhibiting a higher resistance to chip production, reaches the temperature necessary, about 200 °C, for the generation of sparks by friction.[34]

Auer, many years after his student days, and unconcerned with theory, found a way to utilize the properties of ferrocerium in spectacular ways, thus pioneering the industrial application of the rare earths.

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[31] Auer von Welsbach [19].

[32] Angelo and Subramanian [20].

[33] Ferrocerium and the other pyrophoric alloys [21].

[34] http://www.rccm.co.jp/factsage/gedb/ce-elem/cefe/cefe.html (last accessed 15 January 2018).

6.6.3 Commercialization

What was achieved on a small scale in the laboratory became complicated when it came to mass production. The attendant problems on scaling up led to the formation of the "Treibacher Chemischen Werke GmbH" in Treibach in 1907.

It was much more difficult to find a method for the industrial production of the alloy than the determination of the optimum composition named in the patent. The first samples provided by electrolysis were ineffective; they were very porous, said to resemble "metallic bread." Pieces that were cut out of the compact mass had a very short shelf life, corroding after a short time due to humidity. However, there were also more durable samples found in newer trials, which gave the researchers some hope in spite of the difficulties. In the midst of these problems, Auer made a daring prophecy: once commercialized and available in shops, his "Auermetal" would supersede matches.

In the summer of 1908 it was finally possible to conduct the electrolysis in such a way as to produce a pore-free and corrosion-resistant "cer-mischmetal."[35] The problems in the metal were phosphorus impurities (a natural component of the raw material, monazite sand). From the monazite, the rare earth chlorides were recovered, which had to be completely freed of the water of crystallization, and only then could they be used in the anhydrous state for fused-salt electrolysis. Auer was already convinced that only phosphorus-free ferrocerium had sufficiently good durability. He, therefore, proceeded to use the minerals cerite (oxides of cerium, lanthanum, and didymium) and allanite (cerium, yttrium, and lanthanum silicates) as his raw material. A year later, his very competent assistant, Franz Fattinger (1881–1954) (See Fig. 6.3) succeeded in carrying out the processing of the "mountains" of residual monazite in such a way as to produce phosphorus-free cerite chlorides.[36]

Franz Fattinger, born at Waidhofen an der Ybbs, Austria, studied at the Technical University of Vienna (TU Wien). After two years of working as a chemist at J. Medinger & Söhne in Neufeld an der Leitha, in 1908 he joined the Vienna Patent Office as a preliminary examiner and in that same year took his doctorate at TU Wien. He then went to Treibach to work for Auer von Welsbach. Fattinger was particularly interested in the implementation of the ferrocerium patent process, in which he became deeply involved. As chief executive of the Treibacher Chemischen Werke, he organized the commercial production of rare earth alloys, and later on, the manufacture of ferro-alloys and the utilization of formulations of radium and mesothorium (now recognized as Ra-228). Fattinger's scientific publications treated, for the most part, the mechanism of spark formation of pyrophoric alloys.[37]

Fattinger's work led to the economic exploitation of the monazite residues for ferrocerium production. It was his intention to use ferrocerium for all possible

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[35] A term used for a mixture of rare earth metals.

[36] Gamber [22].

[37] Fattinger [23].

ignition purposes: for lighters and gas fires, as an ignition device for bicycles, automobiles, firearms, signaling devices, and mining apparatus such as safety lamps. These miners' lamps could be ignited without risk even in the event of severe weather. For this purpose, a cerium alloy was specially developed that sparked at temperatures below the ignition limit of the hazardous methane gas commonly generated in mines.

Initially, three brands of pyrophoric alloys were produced. "Cerium" or "Auermetal I" was an alloy of fairly pure cerium and iron for ignition purposes. A mixture of cerium, lanthanum and iron was designated "Lanthanum" or "Auermetal II," a mixture of cerium, lanthanum, and iron, which gave great bright sparks and was to be used for light signals. "Earth metal" or "Auermetal III," was composed of iron and natural cerium mischmetal, used without separating out the accompanying metals such as lanthanum, neodymium and praseodymium. Auermetal I production turned out to be not very cost-effective and Auermetall II performed disappointingly. So, both of these products disappeared and only a single one, "earth metal," consisting of 30% iron and 70% cerium was retained. Renamed Auermetal I, it spread throughout the world.

Although the original ferrocerium patent was contested both in Austria and abroad because of an erroneous interpretation of the application, Franz Fattinger, a patent expert, was able to clarify the issue so that Auer won the priority dispute and his patent remained in full force.

As in the case of his other great inventions, Auer von Welsbach, once the new industry had been created, withdrew from it, in order to free all his powers for his research. And this time, too, he had managed to place his work in the right hands by giving over the leadership of Treibacher Chemical Works to Franz Fattinger.[38]

Ferrocerium, as Auermetal, was originally produced in forms suitable for striker lighters. Today we call them lighter flints. Around 1910, the first friction wheels came on the market, and the model has remained essentially unchanged to this day. To get some idea of how this industry took off, in the year 1949 alone, a million kg of ferrocerium were produced, and this quantity is the current estimated annual worldwide production. This amount of ferrocerium yields 6 billion lighter flints, and these in turn yield six trillion firings, which in turn replace 6 trillion matches, for the production of which two million cubic meters of wood would be consumed. This statistic alone underlines the ecological significance of the invention and illustrates what would have been done to our forests without this invention.

In order to establish the production of lighter flints for the American market, Auer founded the company "Treibacher Chemical Works New York," but due to circumstances beyond his control, it turned out to be something of a failure. Soon after construction, protracted patent litigation began, which he won only after enormous court costs and attorney fees. Following a fire in the factory, additional costs arose: in World War I, all Auer companies and holdings in the United States, Great Britain, and France, including patent and trademark rights, were confiscated

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[38] Sedlacek [24].

Fig. 6.3 Franz Fattinger, First Chief Executive of the Treibacher Chemical Works

Fig. 6.4 Historic trade mark for the Treibach ignition devices

as enemy assets. The company name was then changed to Ronson®, the brand name that Americans are familiar with today.

Notwithstanding these setbacks, ever since 1903, the original "Auermetal"® has been produced by today's "Treibacher Industrie AG," founded by Carl Auer von Welsbach in 1898 (See Fig. 6.4). Since then, it has fulfilled a considerable portion of the world's annual demand for lighter flints from the tiny little town of Althofen-Treibach nestled in the southern Austrian Alps.[39]

And thus, it was that Auer's third great invention, the discovery of the first corrosion-resistant lighter flint, was the most important application of rare earths until the 1930s, and gave the impetus to the rare earth industry as we know it today.[40]

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[39] Adunka [25].

[40] Baumgartner [26].

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Chapter 7
Entrepreneurship, Innovation, Patents and Products

There is no question that Carl Auer von Welsbach was a supreme innovator—his fertile imagination was able to take ordinary observations, made time and again by others, and transform them into useful inventions, as evidenced by the three great examples described in the previous chapters. That his entrepreneurial abilities were called forth by the necessity of promoting his inventions were obvious, but need to be analyzed.

7.1 Entrepreneurship

Entrepreneurship is the powerful engine that has caused the greatest progress in civilization in the economic, social, and cultural spheres. Innovation is its handmaiden, but the two qualities are not necessarily, nor even often, found in the same person. The most influential economic historian of the early 20th century, Joseph A. Schumpeter (1883–1950), was the first person to propose a theory of entrepreneurship in which he laid out the qualities needed to contribute to economic development. In doing so, he realized that "the future was the descendant of the past. He looked backward in order to look forward."[1]

While Schumpeter never gave any examples of the ideal entrepreneur, he asserted that entrepreneurship is really a calling, as opposed to a profession. A true entrepreneur is a person with a vision and a mission who pursues his or her vocation in an ahedonic, or non-selfserving, manner. Such persons let nothing stand in the way of achieving their goals, but they persevere with an almost metaphysical determination.

Some traits that make for successful entrepreneurs in Schumpeter's view are:

Singularity The entrepreneur is a creative outsider who transforms the economy through the process he or she has developed. This is a person who brings about spontaneous, discontinuous, qualitative change.[2]

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[1] Reisman [1].

[2] Metcalfe [2].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_7

Energetic Action Energetic action is the basic principle of economic development.[3] The entrepreneur who exhibits extraordinary energy of action has the ability to overcome the active and passive resistances of other economic subjects. External resistance is more fascinating than frightening. Rejection and counter-defenses are irrelevant to the one who wishes to accomplish something new and extraordinary.[4] This is especially true when there is no money, when there is a tough or slippery market, when certain discoveries do not pan out for a variety of reasons, but if the founder toils on, and figures it out in the end, the enterprise has the greatest chance of success. There are many things that will make the entrepreneur stumble, but none of them spell failure as long as the vision and mission remain intact.[5]

Impulse for Change Entrepreneurs emanate a steady impulse for change—they are, indeed, the bearers of the mechanism of change. They cause development in the sense that they are steady sources of change and they create change in the economy out of the economy itself.[6] This change can take the form of creative construction, a change in the given circumstances that brings about distinctly new phenomena. Creative construction is evolutionary in the sense that it has to take into account existing data, and cannot create anything new in the future than what the present provides the seed for.[7] Furthermore, change can take the form of creative destruction—the breaking down of the old way of doing things to make room for the new. Such destruction fundamentally displaces old equilibria and creates radically new conditions.[8] Put baldly, the process of creative destruction is what capitalism is all about: "it is what capitalism consists in and what every capitalist concern has got to live in."[9]

Many-faceted Technical Expertise The entrepreneur/innovator has to be one's own technician, consultant, machinist, glassblower, apparatus designer, laboratory assistant, experimentalist, patent expert, librarian, marketing manager, public relations officer, and business partner.

Good Judgment The entrepreneur makes the right decision by taking into account an uncountable number of different elements, some of which cannot be precisely assessed at all, and then moves that decision forward.[10]

Cooperation The entrepreneur has need of cooperation from a variety of sources in order to execute planned activities. These consist of goods of all kinds, labor, services, tools and raw materials and proceeding into action depends upon their

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[3] Schumpeter [3].

[4] Dahlmann [4].

[5] Shah [5].

[6] Becker et al. [6].

[7] Becker et al. [7].

[8] Schumpeter [8].

[9] Becker et al. [9].

[10] Becker et al. [10].

availability. However, the far-seeing entrepremeur must take action beforehand to secure these goods.[11]

Responsibility Entrepreneurs have a sense of responsibility for the society they are part of and from which they have garnered many benefits. They may not give back in some of the more obvious ways like public charitable donations, but they give back in many other ways that are beneficial to the society at large.

Other traits, according to Shah[12] are:

Openness This quality correlates to integrity, honesty, and a willingness to see other points of view. Openminded individuals are often able to see the world very clearly for what it is; they have an "intellectual honesty" about the world around them. They can not only see the market with clarity, but also the opportunities and problems that might impinge on their success trajectory inside and outside of their own enterprise.

Fluid Intelligence This quality measures the ability someone has to rapidly learn and apply rule-sets. In other words, it is the ability to think on your feet. The sheer number of opportunities and problems, the constant rollercoaster ride, force entrepreneurs to make important decisions under very constrained periods of time.

Resilience This quality is important to entrepreneurs, for whom many days can be a street fight—and one for which they are often ill-equipped. To come out on top after being beaten up pretty badly is hard to do, and having that steadfast resilience is important.

7.2 Invention and Innovation

Schumpeter distinguishes entrepreneurship, i.e., economic leadership, from invention, observing that inventions are economically irrelevant if they are not carried into practice. And carrying any improvement into effect is quite different from inventing it. So although entrepreneurs may be inventors, this is not something that is necessary to their function, but only by coincidence.[13] Indeed, Schumpeter makes clear that an entrepreneur is not an inventor in principle: where one happens to be an inventor, it is because of a random pairing of different functions. Inventions play merely a secondary role to entrepreneurship: they only increase the number of possibilities, which is already infinite.[14]

Schumpeter's definition of innovation is simply the setting up of a new production function, covering the case of a new commodity, as well as new forms of organization, or the opening up of new markets. He also assumes that innovation is always associated with a rise to leadership of new individuals. The entrepreneur

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[11] Becker et al. [11].

[12] Shah [5].

[13] Schumpeter [12].

[14] Becker et al. [13].

may, or may not be, the inventor of the good or process introduced,[15] but if so, the holding of a patent confers a monopoly on the good or process, rendering that resource inaccessible to others.

In summary, then, the economic development promoted by the entrepreneur/inventor can be broken down into five cases: (1) the introduction of a new good or a new quality of good; (2) the introduction of a new method of production which may or may not be the result of a new scientific discovery; (3) the opening up of a new market that did not previously exist or had never been entered before; (4) the acquisition of a new source of supply of raw materials, pre-existing or newly created; (5) the realization of the new organization of an industry, for example, like the creation of a monopoly position.[16] In the next section, we shall see how each one of the criteria named above is exemplified in the life and work of Carl Auer von Welsbach.

7.3 Carl Auer Von Welsbach as a Model of Schumpeterian Entrepreneurship and Innovation

A 2017 Ph.D. dissertation by the economist, Jesko Dahlmann[17] analyzes nine innovative entrepreneurs from the German-speaking nexus of Switzerland, Austria-Hungary, and Germany according to Joseph Schumpeter's Theory of Economic Development. In the previous two chapters, Auer von Welsbach's (Fig. 7.1) activity in this area was described in some detail. The rest of this chapter section will connect his activities with the Schumpeterian criteria (Reference to Dahlmann's work will be given by page numbers only in this section).

Auer was a creative outsider who transformed the economy through the innovative processes he developed. Auer was never part of the business and industrial establishment, nor was he a member of the professorial rank he was an unemployed independent researcher working in borrowed space (p. 45).

The failure of his first business attempt, the production of the thorium-zirconium lamp, was a bitter pill for Auer. He had to close his first manufacturing site, let his employees go, and hold out empty hands to his creditors. Nevertheless, he went immediately back to the laboratory and labored unceasingly for the next two years, ever believing in eventual success (p. 326).

At the beginning of the 1930s, more than 50% of dwellings and 70% of streets and squares were illuminated with the "Auerlicht" in the thriving metropolis of Berlin. His invention had five billion sales worldwide and was a competitive mass product for over 40 years. But he never sat back on his laurels: his work between research and enterprise was always his passion and vocation, and occasionally pure pleasure (when there were no patent disputes). The adjective "visionary" was linked to his name early on (p. 335).

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[15] Becker et al. [14].

[16] Schumpeter [15].

[17] Dahlmann [16].

Fig. 7.1 Carl Auer von Welsbach in 1911 (aged 52)

Despite the success of his gas incandescent mantle, Auer did not throw all of his effort into perpetuating this method of lighting. He realized that the future would lie in electricity and early on he began to “creatively destroy” his gaslight empire by inventing ways in which to form and utilize high quality filaments of osmium and tungsten (p. 335, 376).

Auer was aware of the economic potential of his osmium lamp, and in order to secure a supply of raw materials, mainly osmium-bearing minerals, he contracted to establish a worldwide monopoly on their production and importation. He also took legal steps to protect the manufacturing process of the osmium filaments used (p. 339).

Three of Auer’s entrepreneurial activities, in particular, highlight his skills in research, marketing, and innovative thinking:

- His research on production of osmium filaments led to the breakthrough, after many unsuccessful attempts, in producing thin and pure tungsten filaments (p. 344).
- His clever marketing strategy in 1906 gave rise to the catchy brand name suggested by his co-worker Fritz Blau, OSRAM, for the light bulbs containing filaments made of osmium and tungsten (wolfram) (p. 345).
- In the context of his pyrophoric–ignition-alloy, which is the chemical-technical basis for lighters used to this day, he acted as a powerful, energetic entrepreneur, looking for a way to utilize the waste products from the processing of tons of monazite sand (p. 373).

Auer, as inventor, became an entrepreneur when he founded the Treibacher Chemische Werke GmbH (Fig. 7.2) in 1907 in order to be able to produce and market his now patented industrial-scale invention. In this case, the idea, research, invention, development, marketing, and implementation of the innovation were almost exclusively made possible by Auer’s talent and hard work (p. 373).

Auer’s determination and strength of character in the implementation of his innovations, most evident in the case of his gas incandescence mantle, was tried to the limit: he had no business partners, no financial backing, no connections. Only his technical expertise, his passion, tenacity, and untiring energy eventually opened the doors for him to acquire creditors (p. 374).

Fig. 7.2 The Treibacher Chemische Werke GmbH, 1923

The acquisition of the factory in Atzgersdorf was a difficult and important step requiring vision and courage. Auer possessed these and other characteristics which can be subsumed under Schumpeter's concept of "force of action." Even decades after his first breakthrough, he impressively demonstrated that both energy and know-how were ever present. His successful innovations could not have been developed or sold on the market without Auer's determination and creative powers (p. 375).

Auer, as a passionate researcher and scientist, never lost his almost child-like fascination for chemistry, physics, and technology. His driving motivation was to tease out of Nature her last secrets. He was also pleased to be able to improve people's lives through his chemical and technological innovations, which was the ethical standard of his lifes work (p. 376).

The Schumpeter innovative entrepreneur is distinguished by a visionary far-sighted view of future developments and promising innovations. Auer was such a visionary who recognized intuitively promising opportunities before the competition (p. 380).

Auer's entrepreneurial success was rewarded by many honors, not the least of which was elevation to the hereditary peerage by Emperor Franz Joseph in 1901. A greater honor could scarcely be imagined by a subject of the Habsburg monarchy. He also received five honorary degrees, was awarded the prestigious Werner von Siemens Ring, and was nominated multiple times for the Nobel Prize in Physics (p. 382).

Auer was a successful entrepreneur who gave back to society. He was an example to his fellow human beings not only for his diligence, tenacity, and honesty. His friends and acquaintances have lauded him as a person with a pronounced social conscience. Auer made repeated substantial donations to charity, especially to help students and children, because he believed in giving something back to a society that did so much for him.[18] More detail of Auer's philanthropic activity can be found in Chap. 8, Sect. 3.

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[18] Bonyhady [17].

Ingrid Groβ summarized his entrepreneurial career in a single cogent statement: "With his predisposition to encounter obstacles, resistance, and doubts, he corresponded to the Schumpeterian ideal of the 'true innovator'…Innovation and not mere 'imitation' was the principle of his action."[19]

7.4 Patents

Carl Auer von Welsbach spent most of his life experimenting in his laboratory. He spent little time publishing, and even less in theorizing—his was a practical, empirical, experimental approach to science. However, the list of his patents far exceeds the number of his publications and one might even venture to say that his patent applications, written with meticulous attention to detail, and nonpareils with respect to practicality, were his true publications.

In 1884, at the age of 25, Auer patented his first invention. He soon recognized that it was not technically viable and abandoned its production. A year later, he received his first Austrian "privilege" (a forerunner of patents), and thus began a practice that continued over the course of his long life.

7.4.1 Patents and the Law

The legal bases for Auer's inventions were the Austrian *Privilegesgesetz* (Law of Privileges) in force from 1852 and the patent law that superseded it in 1897. However, the term "privileges" was retained for inventions. An invention was defined as a new discovery, invention or improvement. The formal requirements consisted of the obligation to provide a detailed description of the invention and to pay the registration fee, and subsequent annual fees. The legal effectiveness of each "privilege" granted was for a maximum of 15 years, covered the entire territory of Austria, and was transferable in whole or in part.

The first International Patent Congress was held on the occasion of the World Exposition in Vienna in 1873. The resolutions of this congress laid down the basis for the Paris Convention of 20 March 1883, and the principles of modern patent law, introduced by this Convention, regulate the mutual recognition of industrial property rights. Practically all industrialized countries have acceded to this Convention, and in response, on 1 June 1897, the first Austrian patent law was passed. Thus, for the first time a legal claim of the originator of an invention on patent distribution was recognized. The Austrian Patent Office was established as the central patents division authority and the patent court was established as an instance of appeal. From 1899 on, incoming patent applications have been tested for novelty, inventiveness and technical progress.

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[19] Groß [18].

Many companies, including Auer's, grew substantially under patent protection, and this safeguard for their products enabled them to develop and maintain their individual character. The effect that patents have had on the development of technology and have continued to exercise on industry, is not due to a simple formula, nor has it had a uniform effect. It is a complex process with a series of effects and interactions. The patent holder alone has the right to manufacture and distribute the subject matter of the patent for a certain period of time, thus excluding competition. In order that this right may acquire technical and economic importance, namely a temporary corner on the market, the "object" of the patent must also be marketable. The fact that a patent blocks a certain route for other companies obliges them to seek progress by other means, and this forces them to devise new inventions.

7.4.2 Auer Von Welsbach as Patentholder

The first two great inventions of Auer's, "Illuminants for incandescent gas burners, called actinophore," and the "Gasglühlicht," were given in accordance with the Privilegesgesetz (Imperial Patent of 15 August 1852), where the first beginnings of the later modern patent legislation were already discernible. The illuminants were made by soaking fabrics with soluble salt solutions of the rare earths followed by incineration of the textile material, which left the oxide ash skeleton behind. By varying mixtures of the oxides of zirconium, magnesium, lanthanum, yttrium, neodymium, cerium, and thorium, he was able to achieve various nuances of white light from yellowish to greenish. A series of improvements resulted in a number of "privileges" in Austria and patents in the German Reich, but it was a long way from the success of the incandescent gas mantle patented in 1891 and described in Chap. 5.

Despite the great financial success of his inventions, Auer never stopped searching for better technical solutions. One of his guiding principles was "the better is the enemy of good." For example, in the search for an electric lamp filament to replace Thomas Edison's clumsy and expensive carbon filament, he developed the colloidal paste process for osmium that enabled him to make very thin wires from this very brittle metal. His 1898 patent in this regard ushered in the era of the metal filament which prevails to this day. His patents on "innovations in the production of osmium lamps" and "electric lamp and a process for its production" come from this period, although by limiting his patent to one substance, osmium, he missed the boat, so to speak, when tungsten became the metal of choice.

With his last great technical invention, he found that cerium alloyed with iron differed substantially from either pure metal in terms of both its strength and its resistance to oxidation. However, the property that rendered it economically advantageous and patentable was its pyrophoric capacity: when struck by a hard object, it emitted sparks so intense that they could ignite flammable material such as a wick or tinder. His German patent (DE 154807) of 1903 described and protected the invention of what he called "Auer Metall." A string of patents followed one right after the other: "excitation liquid for electrical collectors," "pyrophoric metal alloys," "lighting device," "a gas-burner light-burner with incandescent carrier," and a "chain glider."

Auer held patents in many countries both in his own name, and in conjunction with companies that he owned (see Table 7.1). However, both the application process and the litigation that followed from patent infringement presented ongoing problems for him and his partners. In some instances, the patent office rejected his applications because they did not understand the description of the chemical substance involved. For example, in his application to the Imperial Patent Office dated 12 August 1891, he described the action of thorium oxide with other oxides in a molecular mixture that he called a *Gebrauchsmustergesetz*. The office complained that he was trying to patent a new chemical compound, but all he was trying to do was explain that this mixture had certain properties that the individual substances that made it up did not possess. In another instance, in Germany, after 6 years of litigation, the Chamber of Judges decided that his thorium–cerium incandescent bodies did not enjoy patent protection and that competitors were not guilty of patent infringement.[20]

One of his great success stories was the patenting and trademarking of OSRAM, a word made up of OS(mium) and wolf(RAM), to indicate the content of the metal filament alloy of osmium and tungsten. It was registered in the Imperial Patent Office in Berlin on 17 April 1906. The logo (see Fig. 6.5) was created in 1919 and the oval plus the three colors of orange, white, and blue were protected by 8 German patents.[21]

7.5 Products and Production: The Founding of Industrial Firms

Auer von Welsbach was a personality who succeeded in transforming his technical achievements into the basis for the foundations of his many companies. Such firms, important players in the world market, are the vehicles with which the lifecycle of products can be extended beyond a single human lifetime.

7.5.1 Founding of Auergesellschaft and OSRAM

It all began, as we have learned, in 1885 with the invention of the incandescent mantle. After an initial successful, but short-lived, launch in 1887 that lasted only two years, the new "Auerlicht" stepped out in triumph in 1891 with the foundation of the Österreichische Gasglühlicht Aktiengesellschaft which he presided over as president and which also took over the Viennese factories in 1893. This company was also the mother of the subsidiaries, which are now established world-wide. In

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[20] Weidinger [19].

[21] OSRAM [20].

Table 7.1 Some of Auer von Welsbach's major patents

Patent No.	Date	Content	Applicant
39,162	Sep. 1885	Leuchtkörper für Incandescenzbrenner	Auer von Welsbach
138,135	Jan. 1898	Aus Osmium bestehende Fäden für elektrische Glühlampen und Verfahren zu ihrer Herstellung	Auer von Welsbach
154,807	Jul. 1903	Pyrophore Metall-Legierungen für Zünd- und Leuchtzwecke	Auer von Welsbach
42,296	Jan. 1910	Pyrophore Masse	Treibacher Chemische Werke

1892 the Deutsche Gasglühlichtgesellschaft, DEGEA, later called Auergesellschaft, was founded in Berlin.

The latter had the obligation to purchase the impregnation material, whose composition was a proprietary secret of the Österreichische Gasglühlichtgesellschaft, distributed at a contractually fixed price. In its first year, the company was already in the black with a net income of 3 million marks (equivalent to 710,000 USD). From 1901 on, further foundations followed in England, France, Belgium, Holland and the USA. The Auer company is still very successful today, achieving an excellent reputation after 1920 as a manufacturer of respiratory protection equipment for industry, mining and fire brigades. It belongs to MSA Auer GmbH.[22] The traditional incandescence mantles were made at the Berlin plant until 2007, when operations were transferred to Mumbai, India.

In 1898 Carl Auer von Welsbach took out a patent on the metal filament lamp, and in 1902, the first osmium lamps, which were industrially produced according to the paste process, were marketed under the name "Auer-Oslicht." By buying up all the available supplies of osmium, Auer committed his only strategic and entrepreneurial lapsus because, in the meantime, tungsten was found to have a significantly higher melting point at 3400 °C, which is why this metal came to be used as the metal of choice for filaments in the long term. On the other hand, he took account of this development by creating the trademark "OSRAM," thus laying the foundation for more than 100 years of industrial history.

In 1906, Auer and Leo Koppel (1844–1933), the majority owner, formed the OSRAM company in Berlin and built an incandescent lamp factory there which, in 1912, became Berlin's first high-rise, an 11-storey building. In 1919, OSRAM Werke GmbH KG was founded., which added Siemens and Halske and *Allgemeine Elektricitäts-Gesellschaft* AG (*AEG*) as partners in 1920. Today, OSRAM is one of the three leading manufacturers of illuminants worldwide. In 2006/07, the company generated sales of 4.7 billion euros (6.4 billion USD) with 38,000 employees in 49 plants.

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[22] MSA is the U.S.-based Mine Safety Appliances group.

Initially, the Koppel family bank was the major stockholder in the Auergesellschaft and OSRAM companies. Leo Koppel established the Koppel-Stiftung (Koppel Foundation) in 1905 as a major philanthropic organization supporting German research and development. He died just as the Nazis were coming to power, but his children were forced to emigrate because of their Jewish background.[23]

7.5.2 The Treibacher Chemical Works

When Auer von Welsbach acquired his Carinthian property in Treibach and, in 1898, founded his firm that he called Dr. Carl Auer von Welsbach'sches Werk Treibach, he initially had planned to continue his scientific work on a much larger scale, devoting himself to inventions, to work with the rare earth elements, and to the production of osmium annealing threads to supply his incandescent lamp factories. However, the vision of building a large incandescent lamp industry vanished with the acquisition of the osmium lamp proprietary rights by Deutsche Gasglühlicht, so Auer turned his attention to other tasks. Large quantities of rare earth sulfates, consisting in large part of cerium (50%), lanthanum (25–30%), neodymium (12–20%) and some praseodymium, remained deposited in landfills following thorium extraction from monazite sand at Atzgersdorf. Auer developed a process for obtaining cerium chloride, which he then electrochemically processed to cerium metal by means of melt flow electrolysis. When the cerium was alloyed with iron, a pyrophoric alloy was produced, the so-called "Auermetall," patented in 1903. In 1907, Auer converted his Treibach plant to Treibacher Chemische Werke GmbH. Over the last 120 years, many products have come out of Treibach, but some of them have been discontinued. The production of tungsten metal powder and of special carbides and nitrides of tungsten and other refractory metals is now one of the company's core competencies.

The chemistry of the rare earths continues to play a major role in the company's repertoire. When it was no longer cost-effective to electrolyze pure cerium, the firm began to market the rare earth mixture naturally present in monazite, generally known by the term *mischmetal*. Up until 1990, Treibacher Chemische Werke AG was the world's largest producer of *mischmetal*, with an output of as much as 600 tons annually, until Chinese competition forced a shutdown of this enterprise. However, today, the firm is the world's largest distributor of *mischmetal*, particularly for the steel and foundry industries.

In 1903, when he alloyed *mischmetal* with iron, Auer obtained a pyrophoric alloy, which he called Auermetal (see Chap. 6, Sect. 6.6), with a composition that nearly remains unchanged to this day. The company Treibacher Chemische Werke AG" became the center of the resulting lighter "flints" (in German, Zündstein) developed from this alloy, which enjoyed worldwide distribution by 1908. Initially,

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[23] Robison [21].

the flints were cut out of blocks, but today, production by extrusion is much more cost-effective. In 1908, 800 kg of these flints were sold at astronomical prices; in 1991, sales peaked to several hundred tons. Today, despite Chinese dominance in the field, Treibacher Industrie AG, as the company is called today, is the only remaining Western producer, turning out about one billion flints annually. Each of these flints must be checked for correct length and diameter to fit into a lighter. Previously, this control was carried out manually by approximately 400 employees; today it is done with automated sorting machines.

The source of all this activity was, and remains, Auer von Welsbach's expertise in separating the rare earth elements, giving rise to two new fields: rare earth chemistry and rare earth metallurgy. Today, China dominates with respect to the separation operations, but Treibacher Industrie AG concentrates on the further processing of pure rare earth compounds into special precursors for the catalyst, glass, and pharmaceutical industries, and for high-performance ceramics.

Another area with its origin in Auer von Welsbach's innovations is the production of ferroalloys. Prior to World War I, Treibacher Industrie AG had already worked out the process of producing ferromolybdenum. After that war, the firm gradually added ferrowolfram (ferrotungsten), ferrochromium, and ferrovanadium to its list of ferroalloys. Today, they continue to be the mainstay of the company's sales and earnings, producing several thousand tons per year.

At the time of this writing, the company generates an annual turnover of about 450 million euros (ca. 560 million USD), employs 720 people and indirectly supports roughly the same number of jobs in local ancillary activities. Just as Auer financed schools and supported children and the needy, so too, is Treibacher Industrie AG committed to social issues, and the education of young people is a priority. On the one hand, the firm trains apprentices; on the other, it tries to awaken interest in chemistry and technology among local students by initiating and supporting various educational activities.

Another, and perhaps the most important company concern, is research and development. Carl Auer von Welsbach was a researcher all of his life and had the inner conviction that research is the basis for the successful future of a company. His team consisted only of himself and a co-worker, but today, 70 of the firm's employees work in R&D, with an annual investment of several million euros.[24] See Table 7.2 for a list of Auer von Welsbach's major company foundations.[25]

7.5.3 Sequel: The Fate of Auergesellschaft

When the Third Reich came to power in the early 1930s, it was intent on erasing Jewish presence in every walk of life in Germany. As a result, in 1934, it forced Leo

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[24] Bouvier [22].

[25] https://www.treibacher.com/en (last accessed 15 January 2018).

Table 7.2 Major foundations in the Auer von Welsbach Industrial Empire

Founding date	Name of firm
1882	Welsbach and Williams Limited
1890	Welsbach Light Co., Ltd.
1892	Deutsche Gasglühlicht Aktiengesellschaft
1893	Österreichische Gasglühlichtgesellschaft
1898	Dr. Carl Auer von Welsbach'sches Werk Treibach
1898	Österreichische Gasglühlicht-und-Elektrizitätsgesellschaft
1906	Westinghouse-Metallfaden-Glühlampenfabrik GmbH
1905	Österreichische Gasglühlicht AG
1905	Auerlicht GmbH KG
1907	Treibacher Chemische Werke AG
1919	Osram-Werke GmbH KG
1921	Vertex Elektrowerk GmbH
1923	Auer-Stotz Beleuchtungskörper GmbH
1923	Radium-Licht GmbH
1924	Vereinigte Radiumwerke
1931	Osram Österreichische Glühlampenfabrik GmbH

Abbreviations in Table 7.2. *AG* Aktiengesellschaft (a corporation limited by share ownership); *GmbH* Gesellschaft mit beschränkter Haftung (a company with limited liability, incorporated, and a legal entity unto itself); *KG* Kommanditgesellschaft (a limited liability company with, typically, the sole general partner being a limited liability company)

Koppel to sell Auergesellschaft to Degussa, a German company with vast experience in metal production.[26]

Auergesellschaft's activities in separating radium from pitchblende (see Chap. 8, Sect. 8.1.1) left a great deal of uranium-bearing waste material, which the company was holding in storage. This supply came to the attention of the then-scientific director of the firm, Nikolaus Riehl (1901–90), who decided to exploit its potential. By 1945, he had succeeded in recovering about 100 tons of fairly pure uranium oxide from the waste ore. At the end of World War II, when the Russian army overcame Germany, Riehl, and the entire mass of uranium, were forcibly exported to the Soviet Union to support the latter's nuclear energy ambitions. It is estimated that this supply plus Riehl's expertise, saved the Soviets about a year in their development of the atomic bomb.[27] It is ironic that material originally used to help people in their illness was eventually put to destructive use, an eventuality that Auer could never have foreseen. In 1958, the main branch of Auergesellschaft merged with the multinational Mine Safety Appliances Group.

While Auer's flagship company in Treibach remains a mainstay of the local community and continues to have an impact worldwide, many of his other ventures

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[26] Riehl and Seitz [23].

[27] Oleynikov [24].

eventually merged or were subsumed into other entities over the decades. In addition, some of Auer's inventions, such as the osmium filament lamp, became obsolete, whereas others are alive and well. The present Indo Auerlicht Manufacturing Company based in Mumbai, India,[28] with subsidiaries around the world, continues to manufacture the traditional gas incandescent mantle which finds many uses today not only in street lighting, but in camping equipment and railway and navigational signal lighting. The Welsbach Electric Corporation, a standalone entity since 1877, is now located in Queens, New York. It originally manufactured Auer's incandescent gas mantles; in 1995, it was reorganized as part of the EMCOR Group and delivers quality electrical services. TCW Wien, another firm founded by Auer von Welsbach in 1910, sold the cigarette lighters of various manufacturers under its own brand name in the 1920s and 1930s. These items are now vintage collectible lighters prized throughout the world.[29]

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[28] http://www.auerlicht.com/history/history.htm (last accessed 15 January 2018).

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Chapter 8
A Life for Research, Family, and Community

8.1 Research Interests

Carl Auer von Welsbach made his great discoveries and important inventions in only the space of the twenty years after he completed his studies with Robert Bunsen. In that amount of time, he accomplished far more than most scientists achieve in an entire lifetime of research. As this intense research period began to wind down, he was able to turn his mind to other things—some of a more personal and recreational nature, some with an outward thrust to the scientific world in general, and some to the care and nurturing of his fellow human beings. In all of these new undertakings, the skills he had gained previously were put to work in new contexts.

8.1.1 Research Chemicals for the World

As we have seen in previous chapters, Auer von Welsbach developed his rare earth separation skills to a point that they were unmatched by other scientists of his time. Through his expertise, he was able to provide the purest samples of these elements possible at the time. Thus, it was natural that when the Austrian Imperial Academy of Sciences saw the need to begin a large-scale, industrial radium production project to supply the radioactivity community with large, research-grade amounts of this precious commodity, they turned to him for guidance and factory space. The well-known geologist Eduard Suess (1831–1914), who was then President of the Academy, commissioned the work, a significant move for the development of nuclear physics for the next 30 years.[1]

Because he and his co-workers at his factory in Atzgersdorf (Fig. 8.1) had years of experience in extracting thorium and cerium from the minerals in which they were contained, Auer was conveniently placed to provide the necessary infrastructure and

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[1] Kutschera [1].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_8

experience to extract radium from the pitchblende residues from the Joachimsthal mine, located at that time within the borders of the Austro-Hungarian Empire.

So, in March of 1904, he gladly placed his Atzgersdorf factory at the disposal of the Academy, thus setting up the mechanism for the first industrial production of radium compounds in the world. This catapulted Austria into a position equal to France as a center of radium standards and a calibration center for radium preparations for numerous governmental, scientific, and health-related entities.[2] Auer financially supported much of this enormous endeavor out of his own resources. He delegated his long-time assistants, Ludwig Haitinger, Karl Peters, and physicist Carl Ulrich, to devise the extraction process. Bohemian pitchblende from the Joachimsthal mine (the original source of the raw materials used by Marie (1867–1934) and Pierre Curie (1859–1906)), with an average uranium content of 53.4%, was treated with sodium sulfate to produce sodium uranate, which was subsequently dissolved in dilute sulfuric acid. The radium remained in the residue. Haitinger, Peters, and Ulrich were able to extract 3.0 g of radium chloride and 0.236 g of radium bromide from 10,000 kg of pitchblende (about 11 US tons).[3]

At that time, the following quantities of raw materials were required to produce a gram of radium: ten tons of ore, three tons of hydrochloric acid, one ton of sulfuric acid, five tons of soda, and ten tons of coal. In addition, it took two months of work in the laboratory to purify the radium. In 1911 the chemist Otto Hönigschmid (1878–1945) (Fig. 8.2), a world-famous atomic weight specialist,[4] was able to determine its exact atomic weight by means of the high-purity Atzgersdorf radium.

Radium was at that time a very precious element since it was indispensable for the initial radiotherapy for cancer control, thus rendering a gram of radium worth more than the price of 260 kg of gold in 1914. This spurred searches for more efficient separation methods. Since a ton of uranium ore contained only 0.1 g of pure radium on average, it was like looking for the proverbial needle in the haystack.

Between 1907 and 1909, thanks to Auer's expertise and generosity, the Vienna Academy was able to furnish radium to learned societies and institutes in Britain and the continent at a nominal cost. The Academy, in addition to aiding the Curies, provided samples on loan to Ernest Rutherford (1871–1937) and William Ramsay (1852–1916), among others. Impressed by these accomplishments, the lawyer-industrialist Dr. Karl Kupelwieser (1841–1925) endowed the Academy with 500,000 crowns

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[2] Löffler [2]. The figure on the page cited, p. 53, shows clearly, through the certifying signatures of Stefan Meyer, Marie Curie, and Ernest Rutherford that radioactivity research in Austria was on equal footing with that of Paris.

[3] Robison [3].

[4] Otto Hönigschmid studied chemistry at the University of Prague from 1897 to 1904 and received his doctorate under Guido Goldschmidt (1850–1915). After postdoctoral studies with Henri Moissan in Paris from 1904 to 1906, he eventually taught at the German Technical University in Prague in 1911 and at the University of Munich in 1918. His specialty was the development of precise determination methods of atomic weights, carried out on 47 elements; he also contributed to isotope research. His most brilliant achievement was the redefinition of the atomic weight of radium in 1911, which he repeated in 1933, when further precision and accuracy was required.

Fig. 8.1 The Atzgersdorf factory (about 1900)

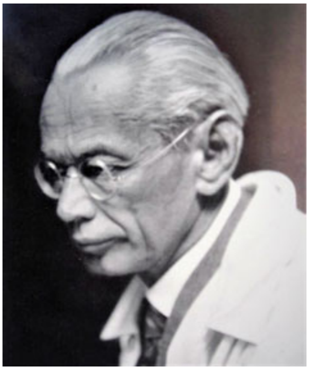

Fig. 8.2 Otto Hönigschmid

(equivalent to five million euros) to build an institute for radium research. The institute was opened in 1910 by Stefan Meyer (1872–1949) and was active until 1938. Auer von Welsbach's radium was the institute's most important research material.

The residues from radium production were also subjected to analysis for other elements and compounds of interest, among which were thorium and actinium. Thorium was of particular interest because it was believed to contain two elements, thorium and ionium; the latter was suspected of being the mother substance of radium. Auer von Welsbach failed to separate ionium from thorium, which is not surprising given that ionium, unbeknownst to Auer at the time, is an isotope of thorium, ^{230}Th. This was clarified only after the concept of isotopes was proposed by Frederick Soddy in 1913. It was also found that the percentage of ionium in mineral sources varied with location. Otto Hönigschmid determined that the ionium content in the Auer von Welsbach preparations was 30%.

Because of their ultrahigh purity, it was Auer's rare earth preparations that enabled physicists like Niels Bohr in Copenhagen, Ernest Rutherford in Cambridge, and Stefan Meyer in Vienna to determine the inner-electron shell structure of the entire series of rare earths from lanthanum to lutetium. These measurements showed that lutetium exhibited a closed-shell, a fact that Bohr capitalized on by theorizing that the next element beyond lutetium should be the higher homolog of zirconium, thus paving the way for its discovery, named hafnium, by George de Hevesy and Dirk Coster in 1923, as described previously in Chap. 4. In addition, two years later, Friedrich Hund (1896–1997), in Göttingen, formulated the rules for the spin coupling of multi-electron systems (Hund's Rules) and from them was able to deduce the magnetic properties of the rare earth elements. He was able to verify this theoretical work, a major step in the advancement of quantum theory, by comparing it with Stefan Meyer's experimental work based on samples provided to him by Carl Auer von Welsbach.[5]

Anyone who applied to Carl Auer von Welsbach with a request for lanthanide or actinide compounds came into possession of priceless ultrapure chemicals not available anywhere else in the world. As a rule, Auer listed when, where, and to whom he supplied the deliveries of more than 500 specimens, and so distinguished names were found among his hitherto unknown grateful customers, such as Niels Bohr, Dirk Coster, Francis Aston (1877–1945), George de Hevesy, Otto Hönigschmid, Manne Siegbahn (1886–1978), Ernest Rutherford, and Friedrich Wöhler.[6] Figure 8.3 is a graphical representation of his "distribution list."[7]

8.1.2 Radium Today

Radium was the most important material for research in nuclear physics in the early years of the 20th century. It was only when the first particle accelerators were developed in the 1930s that its significance began to decline. At the Institute of Radium Research, however, the radium was conserved, despite this diminishing importance, without any real use for it. However, in the year 2000, this radium was put to an unexpected use. At the Technical University of Munich, a group of nuclear physicists, radiochemists and nuclear physicians, with the support of the US company Actinium Pharmaceuticals, had turned to the production of the radioisotope actinium-225 (^{225}Ac) for alpha-immuno-cancer therapy. The basic idea is to attach the relatively short-lived radioisotope, Bismuth-213 (^{213}Bi, $t_{1/2} = 45.6$ m), to an antibody molecule that has a specific affinity for cancer cells. When the antibody molecule has docked at the cancer cell, beta decay of the ^{213}Bi to the extremely short-lived ^{213}Po ($t_{1/2} = 4$ ps) produces the immediate emission of alpha particles with an energy of 8.4 meV which can now destroy the cancer cell at close range. In order to have the ^{213}Bi available in a clinical application, you need a slightly more long-lasting mother substance (a "radioactive cow") from which you can "milk" the ^{213}Bi as required. The above-mentioned ^{225}Ac ($t_{1/2} = 10$d) is a favorable starting material. This is where the ^{226}Ra comes into play: ^{225}Ac can best be generated by the nuclear reaction $^{226}\mathrm{Ra} + \mathrm{p} = {}^{225}\mathrm{Ac} + 2\mathrm{n}$. For this purpose, a ^{226}Ra target is needed, a most suitable use for the remaining radium at the Radium Institute, viz. 2.1 g. A fitting end to the feverish production efforts of earlier times.[8]

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[5] Hund [4]; Table 1, p. 857.

[6] Adunka [5].

[7] Löffler [2], p. 125.

[8] Kutschera [1].

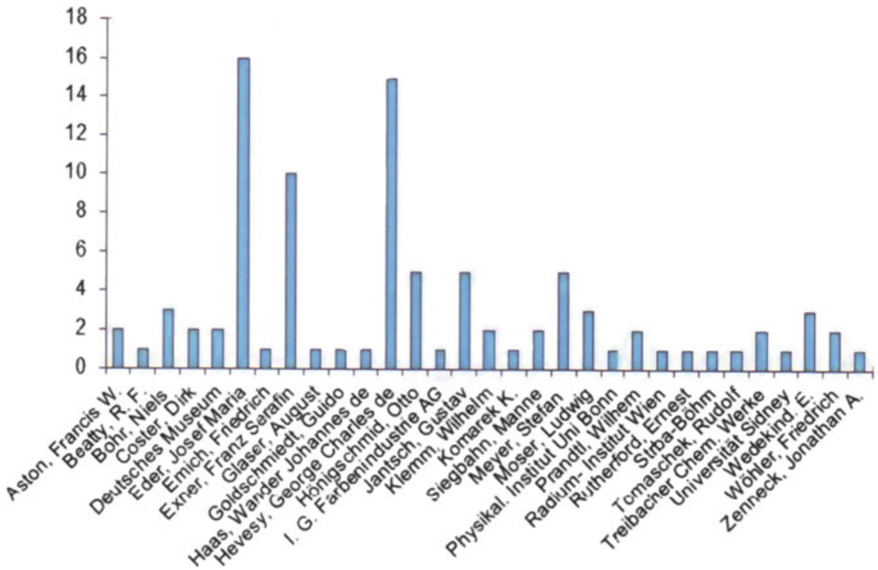

Fig. 8.3 Number of Contacts through Distribution of Auer's Rare Earth and Radiochemical Preparations

8.1.3 A Word of Caution

The damaging effects of radium were underestimated even by scientists. Soon after its discovery, it was thought to be the long-awaited and hitherto undiscovered elixir of life. Since low-dose irradiation led to noticeable healing, it was concluded that higher doses would lead to better results. As a result, radioactive-doped wipes and toothpastes, as well as apparatus for inhaling radioactive gas (radon), flooded the market unchecked and therapeutic radium baths were offered all over the world. Prescribed dosages were often exceeded at the request of preoccupied patients because they assumed that more was better. The harmful effects of radiation only became apparent after long use, so it took quite some time to establish safe exposure guidelines. The voice of Paracelsus (1493–1541) could be heard once again after four hundred years, "All things are poison and nothing is without poison; only the dose makes a thing not a poison."[9]

8.1.4 A Mysterious Observation

Even after Auer gradually became aware of the deleterious effects of his actinide and thorium preparations, he did not abandon his research, continuing to work

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[9] Paracelsus [6], 508–513.

heroically and perseveringly in the service of science to gain new insights. He contributed a detailed note, labeled Part I in the conference reports of the Academy of Sciences in Vienna on this work, carried out before 1910, in which he isolated a substance he called ionium from thorium oxide.[10] Part II was never published.

In a newly-discovered 1910 manuscript in preparation, which now seems to be the missing Part II, Carl Auer von Welsbach reported a "mysterious observation",[11] namely, seemingly induced radioactivity in a platinum crucible placed in "long-lasting contact" with a sample of ionium.[12] After unsuccessfully trying to remove suspected superficial contamination, Auer predicted that this observation could possibly be important for subsequent research: the prevailing theory, of which Auer was well aware, was that a radioactive substance could not activate an inactive material. Modern speculation posits. neutron activation as the cause of the effect[13] The possible neutron source was hypothesized as arising from alpha-particle reaction with beryllium, a common substance in the residues that Auer was working with, to yield a neutron and ^{12}C according to the reaction $^{9}Be(\alpha, n)^{12}C$. The hypothetical activation product was ^{194}Ir. Two problems with this idea is that the neutrons produced are not thermal, yet no possible moderator could be suggested, and that there was no iridium present in the crucibles examined, especially the one that was suspected to have been the subject of Auer's observation. The authors admitted that more historical forensic work had to be done in order to carry this idea forward. They are especially on the lookout for possible candidates for Auer's original crucible.[14]

It should be mentioned that although Auer published little in his long experimental lifetime, he never left off chemical research despite the numerous hobbies that he took up in his later years. Hence, it is exceptional that after a lengthy hiatus, at the age of 63, he wrote and published a long treatise on spectroscopic methodology in analytical chemistry.[15] In this paper, he describes his state-of-the-art dual-purpose spark gap apparatus (for both visual observation of spectra and for photographing them) with four images of the apparatus and a sample set of the spectra obtained. At the end of the paper, he promises a sequel publication, and then a collection of the entire treatise with additional illustrations in book form, a promise that was never fulfilled. This was to be his final scientific publication with the exception of his 1926 paper describing his futile hunt for element 61 (See Chap. 4, Sect. 4.4.2.)

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[10] Auer von Welsbach [7].

[11] This is the first indication at which he hinted at the very beginning of Part I, in Ref. 10.

[12] Now known as ^{230}Th subsequent to Frederick Soddy's proposal of isotopes by in 1913.

[13] Steinhauser et al. [8].

[14] Steinhauser et al. [9].

[15] Auer von Welsbach [10].

8.2 Domestic and Recreational Interests

Despite his many business connections and interests, and despite the fact that he had a working laboratory on the ground floor of his castle that he frequented every day, mostly at night when everyone else was sleeping, Auer developed an intense interest in so many areas that one might say that he “invented” the career of full-time hobbyist.

It may have been difficult for Maria Auer von Welsbach to function as the wife of this famous man, given the fact that she had originally been hired for office work and research. But her love, youth, and joy of life triumphed. With great respect, empathy, and clever planning, she managed to shield her husband from the numerous trivialities that would interrupt him, allowing him all the time he needed for his scientific and entrepreneurial activities. However, he also spent a great deal of time with his children, teaching them the mechanical skills they would need as they matured and sought out their own vocations as adults (Fig. 8.4). As his children grew older, he drew them into his confidence and came to depend more and more upon his sons, especially as his deafness increased.

His work schedule was rather unusual, but the family was habituated to it. After breakfast around 10 AM he worked until lunch at 2 PM. Afterwards, he worked until he took a break at 9 PM, when he had dinner in the family circle. His peculiar habit from his student days of working far after midnight he maintained until the end of his life.

His mother, Therese Auer von Welsbach, frequently traveled from Vienna to visit her youngest son and his family at Welsbach Castle. During her stays, Auer and his wife always took the best possible care of her. She became the source of family history for her grandchildren and, of course, regaled them with stories of the exciting events in the capital.

8.2.1 A Variety of Hobbies

Auer’s many interests included hunting and fishing, which he enjoyed very much. His large estate gave him ample opportunity to sally forth with gun or rod and reel in hand. He also employed a butterfly net, and built an extensive collection of the indigenous butterflies and moths of the Carinthian region which can now be found in the Natural History Museum in Vienna. His other collecting specialty was minerals, consisting primarily of rare earth and thorium minerals. And, of course, the thorium mineral Auerlite,[16] which was named in his honor, gave rise to correspondence from all over the world. This fact led to a bit of stamp-collecting as well since he arranged the various stamps he received in an orderly fashion.

He was already an enthusiastic car owner by 1902. At the time, a chauffeur-mechanic was provided by the manufacturer when the car was purchased. This was the person who had assembled the car and knew the detailed functions of the engine, and how to do the frequent necessary repairs. For this reason, the

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[16] Hidden and Mackintosh [11].

Fig. 8.4 Carl Auer von Welsbach working in a shop with his sons Carl and Hermann

automobile manufacturer Gottlieb Daimler (1834–1900) predicted shortsightedly: “The global demand for cars will not exceed one million worldwide—if for nothing else due to a lack of chauffeurs.”[17] Besides needing a resident mechanic, early automobile owners also needed a lantern carrier to run ahead of the car after dark because there was no street lighting at all. Auer avoided this legal requirement by equipping his car with his own invention, the metal filament lamp, as early as 1906. In the interests of safety and convenience, Auer also financed the acquisition and installation of international traffic signs for Carinthia.

And his interest in sound recordings resulted in some that can be heard to this day, given the correct equipment! This all began when he met Thomas Edison to compare the latter’s carbon filament lamp with his own metal filament bulb, and discovered that Edison had invented a sound-recording device that he called a “phonograph.” At the end of a sound-directing funnel was a so-called sound box, which had a diaphragm which could be excited by sound waves. In the middle of this membrane, where the vibrations were most pronounced, a pointed needle was attached so that its mobility was not restricted too much. With this device, it was possible to engrave sound signals on a wax cylinder rotating uniformly on a shaft.

In 1900, Auer began to produce sound documents—“home recordings”—using the twenty wax rolls that came with the device. At the beginning of each recording, Auer himself explained which persons could be heard on the roll in question, including not only his mother, who was born in 1831, but his wife, the directors of his companies, the builder of his castle, his forester, etc., and also the staff working in the castle. These original rolls, with an average running time of 3.5 min each, were found nearly 100 years later at his estate. The Austrian Academy of Sciences

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[17] Löhr [12].

Acoustic Research Institute in Vienna was able to digitize them so that the voices could be easily understood. Uncanny voices from the past!

Following in the footsteps of his father Alois, who invented the nature self-printing process (see Chap. 1), Auer was successful not only as an inventor, discoverer and entrepreneur, but also as a talented artist of light. A pioneering photographer who is credited with producing the first color photograph in Austria, he was using the French Autochrome method introduced by the Lumière brothers as early as 1908, just a year after it became commercially available.[18]

Photography, at that time, was a luxury affordable by only the very wealthy since every camera, and its accompanying lenses, had to be individually made to order. Auer had an advantage as both a spectroscopist and a chemist: he had his lenses made specially for him by the Steinheil Company of Munich, provider of his personal spectroscope; his familiarity with chemicals enabled him to set up his own working darkroom to develop his glass photographic plates in a carefully controlled setting. As a result, his archival color photographs come very close to today's standards.

The family photographs, which he took between the years 1900–1920, are unique. Those of his four children in various activities are an impressive record of an upscale lifestyle during the declining years of the Austro-Hungarian monarchy. They also are precious documents at the very beginnings of color photography and stereophotography. In view of the extensive and heavy photographic equipment necessary and the low sensitivity of the photoemulsions, photography at that time was not suitable for anything but still shots within a limited range. Without a tripod, no photo shoot was possible. That is why virtually all of Auer's photographs were taken within a few kilometers of Welsbach Castle. In addition, exposure times of several seconds in full sunshine were required for any kind of good resolution. That is why it is quite surprising how his four children (Fig. 8.5) could stay still at the same time. However, they were not always so good; this is evident by some blurring in a number of the photos, a problem that only appeared after the development of the photoplates.

Auer's various types of photographs range from micro-, macro- and stereophotography in black and white and color. There was no other amateur photographer of the time who dabbled in so many genres of photography with such high-quality results.

8.2.2 Botanical Ambitions

Auer managed his extensive estate personally, sometimes even pruning his own rose bushes and fruit trees by hand. When he cut back the vines in February, the only task that the gardener who accompanied him had was to hand him his tools: like a virtuoso surgeon, he insisted on doing, very meticulously, the actual cutting himself.

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[18] This additive color process was in use until it was superseded by the more efficient, and certainly less clumsy, subtractive color process in the 1930s. https://en.wikipedia.org/wiki/Autochrome_Lumi%C3%A8re (accessed 15 Jan. 2018).

Fig. 8.5 The four Auer children enjoying a dip in a spring. 1908

He took great joy in not only raising flowers, but in developing his own varieties. One of his prize roses had a deep, red-black tone that was very rare at the time. And with endless love and patience he cultivated the laboriously acclimatized Lebanon cedars, chestnut trees, magnolias and the other exotic trees that he had imported into his estate.

In 1897, Auer extended the estate's orchard, planted with many different types of apple trees, to 8 ha; it was later extended to 30 ha. He appreciated the many different apple varieties he had, but remaining unsatisfied, he enthusiastically began cultivating a new variety. The result was a deep red, slightly acidic, highly aromatic apple, which could easily be stored for up to ten months due to its low sugar content. Such a delicious apple with the characteristics described above was previously unknown. In honor of its developer, it became known as the "Auer von Welsbach apple" (*Malus domestica*-Auer von Welsbach), a new variety of the Canadian Reinette, an old French cultivar of domesticated apple which Auer refined to his liking. The neighboring municipality of Althofen liked it too: today this apple tree can be found in the public parks and private gardens around the town.[19]

8.3 A Generous Community Member

Carl Auer von Welsbach not only provided the world with light and fire through his inventions, but he also lightened the burden of many members of his community, both in Carinthia and in Vienna. Mention has already been made of his donation of time, space, and means to the research establishments of Vienna and the rest of Europe (Sect. 8.1). He also gave large amounts of money to needy people, associations, hospitals, relief organizations and, institutions so as to benefit not only the general public, but also individual persons. His generosity extended to his local community in Althofen, Meiselding, and the surrounding towns of Carinthia in a personal and caring manner: when he noticed a need, he hastened to fill it in a particular way. For example, he realized that children living in the area of Sankt Veit an der Glan lacked adequate

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[19] Adunka [13].

clothing during a particularly difficult economic period, and were especially needy during the winter season. So, in 1898, he provided about 3200 children in need of help with winter clothes and shoes. All the tailors and shoemakers in the area had their hands full trying to deal with this huge order by Christmas.

In 1904, the hospital at St. Veit was also a beneficiary of his generosity in the form of an X-ray apparatus that placed it in the forefront of diagnostic treatment in the area. At that time, the hospital did not yet have the necessary electrical system to operate the device. The diesel generator donated by Auer for the hospital's use was put to multi-tasking: when the X-ray machine was not in operation, it was used to drive a circular saw to cut firewood. In place of the hospital's unhygienic wooden beds, Auer provided modern iron beds—he seemed to notice every problem and took immediate measures to correct them.

He used a great deal of his wealth to help his own employees. He constructed housing for his workers and included an ample plot of land with each house for use as a garden and recreational space. For the workers who might need to work overtime, he equipped the factory with modern showers and bathtubs. He also saw to it that his workers all had good working conditions and auxiliary benefits, measures that were unheard of in his day.[20]

His commitment to social justice was not limited to his workers, but extended especially to the next generation. He consistently checked that the children in the Treibach region had shoes and a daily ration of milk. To assure that this occurred during World War I, he even purchased milk cows to provide as much as 1000 L of milk daily to schoolchildren as a rickets-prevention measure; he even commandeered is own car to serve as a delivery van in the absence of any other transport method.

Perhaps his most significant and lasting contribution to the younger generation was the rebuilding of the Volksschule (primary school) in the Mölbling-Meiselding school district. It was completed in 1908 on the occasion of the 60th anniversary of the reign of the Emperor Franz-Joseph, in whose honor it was dedicated as the *Kaiser Franz-Josef Jubiläumsschule*.[21] The new school filled a dire need in the area: the old building not only was too small, but it was so humid, drafty, and insalubrious that it had to be closed periodically because of epidemics of mumps, measles, scarlet fever, and other diseases among the children. The new school building, begun in 1906 and financed entirely out of Auer's resources, was a model educational center with elegant classrooms, a conference room, a gymnasium, a school kitchen, a telephone communications system, and a fully-equipped teacher's living quarters.

Auer's philanthropic activity was vast and sustained. While it may never be known to what extent he deployed his resources in this way, what is known is that his beneficial expenditures between 1896 and 1914 alone amounted to almost twice the purchase price of his villa and castle combined, and in 1919, he donated the entire amount realized in the sale of his Viennese palace to charity.[22] In all of his

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[20] Dahlmann [14].

[21] "Josef" is the German spelling of "Joseph."

[22] Adunka [13].

charitable giving, Auer tried to remain in the background, but often unsuccessfully. When, during World War I, he gave a considerable donation to charity, he was told that an official Act on the subject had to pass through the emperor's cabinet office, so he immediately specified that it be anonymous.[23] However, in recognition of his great generosity, the city of Klagenfurt, capital of Carinthia, made Carl Auer von Welsbach an honorary citizen of the first rank.

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[23] Sedlacek [15].

Chapter 9
Legacy of Carl Auer Von Welsbach

9.1 A 70th Birthday Celebration, and Sequel

On the morning of the first of September, 1928, a distinguished contingent of gentlemen descended on the quiet village of Treibach-Althofen and made their way up to the heights of Welsbach Castle to pay their respects to its proprietor on the occasion of his 70th birthday. Perhaps nothing else could demonstrate the esteem and high regard in which Auer von Welsbach was held than the credentials of this honorable group of well-wishers from every part of the world: official representatives of government, industry, scholarly and scientific societies, universities and polytechnic institutes. They greeted him, to his complete surprise, with documents of congratulations, honorary memberships, and an honorary degree—in total silence—which the recipient's own advanced deafness necessitated (Fig. 9.1).

On that occasion, representatives of the Auer Gasglühlicht Gesellschaft presented him with two large crystal vases that radiated a strange light—one the eerie green of praseodymium and the other the violet hue of neodymium—from the two elements discovered by Auer so many years before. These were the first pieces to be colored by these elements in a glassworks. This presentation[1] was followed by a laudatory speech by members of the German Chemical Society to one of its most esteemed honorary members for his research, discoveries, inventions, and methodologies, not only as

> …the undisputed master in science and technology, but also a man who has actively encouraged the investigations of others and who has always been ready to subsume his own arduous investigations in the general scientific effort—one whose modesty and reserve, manifested throughout his life, distinguishes him as much as does the superiority of his abilities and the brilliance of his own famous works. In this unselfish service to science, no less than in the achievements which have made your name immortal, you are our model and our guide…the pride of…chemical science…

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[1] Dingle and Martin [1].

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8_9

Fig. 9.1 Delegation of well-wishers greeting Auer von Welsbach on the occasion of his 70th birthday, 1 September 1928

Less than a year later, on Friday, August 2, 1929, after a brief automobile excursion, Auer suddenly experienced great pain in the abdominal region. A medical examination on the following day brought to light the severity of his illness. Auer, refusing any further diagnosis or treatment, went home, looked around his garden, closed up his study, and burned some papers. His last stop was his laboratory where he lovingly stroked his spectroscope, covered up his equipment, waved farewell, and went immediately to bed. Twelve hours later in the early morning of Sunday, August 4, he gently slumbered forever.[2]

9.2 Beyond "Plus Lucis"

The whole of Auer von Welsbach's creative work was rooted in what he learned, observed and performed in Robert Bunsen's laboratory in Heidelberg. This volume has described his most important works and methods stemming from his study of the rare earths while Bunsen's student:

- Discovery of rare earth elements
- Unique and effective methods to separate the rare earths
- Use of the rare earths to conceive and invent the gas incandescent mantle
- Construction of metal filaments for electric lighting
- Exploitation of the pyrophoric properties of iron-rare earth metal alloys.

Although some of these inventions are now obsolete or have been superseded by more effective methods, the basic ideas and methods are still very much alive and well. Gas mantles continue to be manufactured for specialty uses[3]; the pyrophoric

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[2] D'Ans [2].

[3] Stock [3].

alloys are still an important industry for lighters, and cover much of the world's demand; metal filament lighting, though slowly being replaced by other forms because of energy and environmental concerns, is still the major source of artificial lighting worldwide. Auer von Welsbach's legacy continues to light up the world. However, if one must judge which of his discoveries or inventions was the most important, we must still say, in general, the rare earths.

Little did Carl Auer von Welsbach realize that his interest in and pragmatic approach to the rare earths would lead to a fevered, worldwide search for them that could spill over into international incidents, at best, and war at worst. Only a little more than a century has passed from when he put the rare earths "to work," and now our modern electronics industry cannot survive without them. Gram amounts of metals, including rare earths, are in every smartphone and cell phone, some with no suitable substitute available among the 65 or so other useable metals in the periodic table. Add to that the fact that every hybrid car on the road needs over 20 lb of lanthanum for its battery alone, and every wind turbine demands as much as 600 kg of rare earth metals. Some rare earths have such unique properties that there is no substitute for them. For example, the astounding vibrant reds in television screens can only come from europium; only cerium can buff smooth the multifunctional glass screen of a smartphone to the molecular level. So, there are five good reasons to give us pause in our headlong development of apparatus that need them:

Though they are not "rare," they are dispersed in various pockets around the world, and in some very hard to reach locations;

They are not found as pure mineral veins, making extraction and processing of them very difficult and costly;

Run-off from the rare earth mines, often strip mines, includes environmental pollutants such as radioactive thorium;

There is only a limited supply and no way of replacing them once terrestrial deposits become exhausted or commercially non-profitable: the Big Bang only produced a finite number of their atoms,

Modern technology's appetite for gobbling up rare earths is growing by more than 5% annually, leading eventually to their commercial demise.[4]

One example of an overused and undersupplied rare earth is one of Auer von Welsbach's own discoveries, neodymium. Its role as an extremely strong permanent magnet makes it virtually indispensable in many high tech electronic gadgets.[5]

A glance at Table 9.1 makes it clear that the presence of the rare earths is ubiquitous in so many aspects of our personal, social, and corporate lives.

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[4] Ritter [4].

[5] Veronese [5].

9.3 A Permanent Educational Site: The Auer Von Welsbach Museum

Located in the historic Old Town of Althofen[6] and within sight of Auer's principal industrial endeavor in Carinthia, the Treibacher Industrie AG,[7] the museum (Fig. 9.2) contains many pieces of Auer's original apparatus, historic inventions, documents and correspondence from famous scientists, as well as memorabilia provided on loan by his descendants for exhibition purposes. The six rooms feature in turn (1) personal and family memorabilia; (2) discovery of the four rare earth elements attributed to him, neodymium, praseodymium, ytterbium, and lutetium; (3) history of illumination technology through the ages, including displays of the earliest gas incandescent mantles and metal filament light bulbs; (4) displays on achieving fire by friction and the manifold forms of lighters used today; (5) a small theatre showing a video about the life and work of Carl Auer von Welsbach; (6) a replication of Auer von Welsbach's basement rented laboratory furnished with the original equipment he used during his 50-year period of research and innovation. Although the captions are in German, there is a lengthy museum guide available in a variety of languages.[8] In addition, when Robert Wilhelm Bunsen died on 16 August 1899 in Heidelberg, he left his nephews an extensive private library of approximately 16,000 printed works. In grateful admiration of his teacher, Auer bought this collection, which is still preserved intact in the Auer von Welsbach Research Institute, adjoining the museum. The bibliography, biographies of the authors, and the history of the library can be accessed on the museum website.[9]

In 1956, Auer was honored on a unit of currency, the 25-schilling note (Fig. 9.3), as well as a 25-schilling silver coin, which were both discontinued when Austria converted to the euro. It seems that this may be the only instance of a chemist being honored in such a manner. Auer has also been honored on several Austrian stamps.

More recently, in 2008 (the 150th anniversary of his birth), Auer von Welsbach was selected as a main motif for a high-value collectors' coin: the Austrian €25 Fascination Light. The reverse has a partial portrait of Auer, and other parts of the coin design highlight some of his inventions and discoveries.

In conclusion, Czech poet, Karel Capek (1890–1938), in his teasingly apt work, *The Gardener's Year*, spoke almost mystically of the future being within us[10]]:

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[6] On the main train line between, railway station Treibach-Althofen, Vienna and Klagenfurt, Carinthia's capital. http://fahrplan.oebb.at/bin/query.exe/en. (last accessed 19 December 2017).

[7] https://www.treibacher.com/en/company/history.html (last accessed 14 November 2017).

[8] Adunka [6].

[9] http://www.auer-von-welsbach-museum.at/de/ (last accessed 14 November 2017).

[10] Capek [7].

Table 9.1 The Lanthanide Rare Earth Elements: Discovery and Applications

Z	Element	Date	Discoverer	Applications
57	Lanthanum (La)	1839	Carl Gustaf Mosander	Hybrid car batteries, steel doping, radiometric dating, hot cathode materials, pyrophoric alloys, specialty glasses, biological tracer
58	Cerium (Ce)	1803	J.J. Berzelius, W. Hisinger, M.H. Klaproth	Gas mantles, component of pyrophoric alloys, pigment (as sulfide), phosphors; polishing compound (as oxide), catalyst
59	Praseodymium (Pr)	1885	Carl Auer von Welsbach	Component of Mischmetal, didymium glass, high power magnets (with Nd)
60	Neodymium (Nd)	1885	Carl Auer von Welsbach	Generators, for wind turbines, high performance lightweight magnets, glass colorant & laser component
61	Promethium (Pm)	1945	J.A. Marinsky, C.D. Coryell, L.E. Glendenin,	Specialized pacemaker batteries; source of X-rays. Most stable isotope = 18 y
62	Samarium (Sm)	1879	P.E. Lecoq de Boisbaudran	Nuclear reactor control rods, Sm-Co magnets
63	Europium (Eu)	1896, 1901	E.-A. Demarçay	Compact fluorescent lighting, phosphor, dopant
64	Gadolinium (Gd)	1880	J. C. Galissard de Marignac	Neutron radiography, nuclear reactor shielding
65	Terbium (Tb)	1842, 1843	Carl Gustaf Mosander	Dopant, alloys
66	Dysprosium (Dy)	1886	P.E. Lecoq de Boisbaudran	Sonar systems applications, metal halide lamps, alloys
67	Holmium (Ho)	1878	P.T. Cleve, J.L. Soret, M.A. Delafontaine	Magnets, solid-state lasers, nuclear reactor control rods
68	Erbium (Er)	1842, 1843	C.G. Mosander	Fiber optics
69	Thulium (Tm)	1879	Per-Teodor Cleve	Lasers; eye surgery, brachytherapy
70	Ytterbium (Yb)	1878 Impure 1905 Pure	J. C. Galissard de Marignac, Carl Auer von Welsbach	Atomic clocks, gamma ray source; dental materials
71	Lutetium (Lu)	1906, 1907	Carl Auer von Welsbach, Charles James, Georges Urbain	Earth's crust dating with Lu isotopes, catalytic cracking, PET detectors

> The future is not in front of us for it is here already…we don't know the future because it is within us…if we could only see that secret swarming of the future within us, we should say that our melancholy and distrust is silly and absurd, and that the best thing of all is to be a living man – that is, a man who grows.

And the person who carries the future within oneself is the one that grows. Auer von Welsbach could see all of his life the secret swarming of the future that he eventually brought into the present—and his spirit continues to do so in the many entities that presently carry on his vision and his work.

Fig. 9.2 Auer von Welsbach Museum, Althofen, Carinthia, Austria

Fig. 9.3 The 20-Schilling note bearing Auer von Welsbach‘s portrait, issued 2 July 1956 by the Austrian National Bank

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Milestones in the Life of Carl Auer von Welsbach

1858	Carl Auer von Welsbach was born in Vienna
1877	School-leaving examination at the Realschule Josefstadt
1878	Commissioned as an army lieutenant
1878	Studies at the Technical University of Vienna
1880	Studies at the University of Heidelberg with Prof. Bunsen
1882	Doctorate “insignis cum laude”
1882	Works as an unpaid assistant with Prof. Lieben in Vienna
1885	Discovers the elements neodymium and praseodymium
1885	Invents the lanthanum oxide gas incandescent light (Auer-Licht)
1887	Acquires a factory in Atzgersdorf to produce light mantles
1890	Develops the metal filament light bulb
1891	Patents a gas mantle made of cerium and thorium oxide
1892	Founds Auergesellschaft Berlin and The Austrian Gaslight-Electricity company (Auergesellschaft Wien)
1898	Patents the light bulb with osmium metal filament and the founds the plant in Treibach; marriage to Marie Nimpfer
1900	Makes his first sound recordings that have been preserved to this day; first child born
1902	Market launch of the metal filament lamp (Auer Os-Licht); twin sons born
1903	Invents the lighter flint for cigarette lighters (Auermetall); daughter born
1905	Separates ytterbium into two elements (designated aldebaranium and cassiopeium)
1906	Founds the firm OSRAM in Berlin registered thetrademark OSRAM for the Auergeschellschaft Berlin
1908	Endows the elementary school in Meiselding
1908	Produces the first color transparency in Austria
1910	Produces the world’s first known color paper photographs
1910 ff.	Separates radioactive elements from uranium ores and is described as a pioneer in nuclear physics with the phenomenon “artificial radioactivity”
1916	Constructs the Förolach power plant
1920	Constructs the Seebach Electrical Metallurgical works
1922	Constructs the Mühldorfer hydroelectric power station AG
1929	Carl Auer von Welsbach dies in the 71st year of his life.

R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8

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Carl Freiherr Auer von Welsbach (1858–1929). Symposium anlässlich des 150. Geburtstages. Wien, 4. Juni 2008 (2011) Österreichischen Akademie der Wissenschaften, Wien, Austria. In German. This symposium, organized on the occasion of Auer's 150th birth anniversary, consists of ten chapters plus a foreword and an introduction. It documents his role as mentor for important scientists, as an entrepreneur who founded many companies, as discoverer of rare earth elements, as the chemist who pioneered modern lighting technology, as a patent holder, as a student of distinguished teachers, and as a researcher and inventor.

Dahlmann J (2017) Das innovative Unternehmertum im Sinne Schumpeters: Theorie und Wirtschaftgeschichte. Metropolis-Verlag, Marburg. In German. This recent Ph.D. dissertation presents a 70-page evaluation of the entrepreneurial talents of Carl Auer von Welsbach according to the criteria originally defined by the great 20th century economic theorist, Joseph Schumpeter.

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R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8

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About the Authors

Roland Adunka was trained as a chemical laboratory technician at the company "Treibacher Chemische Werke" and then was educated at the Hamburger Fernlehrinstitut as chemical technician. He spent his career as a chemical technician and engineer at "Treibacher Chemische Werke" (now "Treibacher Industrie AG"), dealing with the chemistry and metallurgy of the rare earth elements, and was active in analytics, research, and operations management. At the request of the municipal community of Althofen, he started the construction of the "Auer von Welsbach-Museum" in 1996, which he has directed since its opening in 1998. In addition to supervising the Museum, he is also Librarian and General Archivist of the Auer von Welsbach papers in the Museum's collection. He is the author of *Carl Auer von Welsbach: Entdecker, Erfinder, Firmengründer, 2nd Ed.* Verlag des Kärntner Landesarchivs: Klagenfurt am Wörthersee (AT), 2015, and of journal articles on the contributions of Carl Auer von Welsbach to a range of theoretical and practical applications.

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R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8

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R. Adunka and M. V. Orna, *Carl Auer von Welsbach: Chemist, Inventor, Entrepreneur*, SpringerBriefs in History of Chemistry,
https://doi.org/10.1007/978-3-319-77905-8