Rediscovery of the Elements

Jöns Jacob Berzelius

James L. Marshall, *Beta Eta 1971*, and Virginia R. Marshall, *Beta Eta 2003*, Department of Chemistry, University of North Texas, Denton, TX 76203-5070, *jimm@unt.edu*

Berzelius always seemed at the center of nearly every significant scientific discovery in chemistry.[1]

For several years now, we have been trekking across Europe and North America following the careers of various chemists. During these wanderings, we have often crossed the trail of Jöns Jacob Berzelius (1779–1848): at Riddarhyttan[2] he was a discoverer (with Wilhelm Hisinger) of cerium, and with H. M. T. Esmark of Norway[3] he was discoverer of thorium. Spending most of his professional career in Stockholm, he also discovered selenium, and he was the first to prepare elemental silicon and zirconium. In his laboratories his student, Johan August Arfvedson (1792–1841), discovered lithium and his assistant, Carl Gustaf Mosander (1797–1858), discovered lanthanum, didymium (a mixture of praseodymium and neodymium), erbium, and terbium.[4a]

By the early part of the 18th century Europe was already awake to this remarkable chemist of Sweden. Noting the breadth of Berzelius' knowledge and his extraordinary activity, the contemporary Scottish biographer Thomson[5] remarked, "There is no living chemist to whom analytical chemistry lies under greater obligations than to Berzelius, whether we consider the number or exactness of the analyses which he has made."

At an early age Berzelius had been impressed with the chemistry of Jeremias Benjamin Richter (1762–1807),[6a] who discovered the Law of Neutrality and coined the term stoichiometry, and Joseph Louis Proust (1754–1826),[6b] who discovered the Law of Constant Proportions. These scientists were challenging Claude Louis Berthollet (1748–1822)[7] who believed that compounds did not have constant composition but instead consisted of arbitrary blends of elements. The decision between these two views was not

Figure 1. This statue of Berzelius stands in Berzelii Park in Stockholm, opened in 1853. This park is 200 meters south of the house where he did the famous work in his early years, the German Baker's House.

clear-cut because analyses were not yet sufficiently accurate. Berzelius felt it his mission to prove the correctness of the former view, and he realized to do this he needed to improve chemical analysis to a new level of accuracy. He developed enhanced laboratory techniques and even prepared his own reagents with the required purity (he complained that commercial caustic alkali was fit only as a "laundry agent").[4b] He turned his attention to the analysis of ores, and showed the composition of a given mineral was constant. Being the first to recognize that silicon oxide was an acid, he addressed the composition of stony minerals, which had been previously thought to be haphazard and uninteresting mixtures, and he established the "happy idea . . . that most of the

Figure 2. Swedish cities prominent in Berzelius' life. He was born in Väversunda, received his high school education in Linköping and his M.D. degree in Uppsala, and lived the rest of his life in Stockholm. He discovered selenium in a laboratory in Gripsholm, from an ore taken from the Falun copper mine. Lithium was discovered in his German Baker's House laboratory, from an ore taken from the Utö iron mine. Cerium was discovered in Riddarhyttan, using the facilities of Wilhelm Hisinger in Skinnskatteberg.[2]

stony minerals are definite compounds of silica."[5] His fame spread internationally and aspiring scientists would send samples to him to verify their discoveries. He confirmed Sefstrom's vanadium,[8a] but refuted Osann's discovery of new platinum group elements.[8b] In 1818 he published the accurate atomic weights of 45 of the 49 known elements,[9] and these data were continuously refined and expanded for another decade. By 1826 he had revised his atomic weights on the basis of the isomorphism data of E. Mitscherlich[8c] and the specific heat data of Dulong and Petit[10] by dividing by 2 or 4 some of the atomic weight values. Remarkably, the precision of his values were such that they vary only slightly from modern values. These data were eventually critical for the development of the Periodic Table.[11] (Note 1)

In his laboratories were trained a number of German chemists, including Christian Gottlob Gmelin (1792–1860), who became a professor at Tübingen; Eilhard Mitscherlich (1794–1863), who discovered chemical isomorphism;

Figure 3. This is the home of Berzelius' mother's family (Sjösteens), which is in the village of Väversunda (N 58° 20.81 E 14° 42.67). An adjacent church has existed since 1160; inside its walls are painted with beautiful murals dating from the 1600s. Three generations of the Berzelius family were pastors, who preached in the province of Östergötlands.

Figure 4. Katedralskolan (Cathedral School) in Linköping, which Berzelius attended, and of which his father was principal (Hastskogatan, N 58° 24.65 E 15° 37.10). Katedralskolan was founded in 1627. A bust of Berzelius as a youth, depicting him as he appeared when in attendance at the school, was erected in 2007 in front of the Katedralskolan. Across town is Berzeliusskolan (Berzelius-School), founded in 1953, which is devoted more to technology and less to arts and philosophy.

Heinrich Rose (1795–1864), Gustav Rose (1798–1873), and Gustav Magnus (1802–1870), who became professors in Berlin; and Friedrich Wöhler (1800–1882) who destroyed the concept of vitalism (i.e., organic compounds had a special "vital force" that distinguished them from inorganic compounds), and who eventually became professor at Göttingen.[4c]

Berzelius had an incredible ability to assimilate all the current chemistry and understand the significance of the important current discoveries. With typical energy he launched in 1806 (in partnership with Wilhelm Hisinger, 1766–1852, the codiscoverer of cerium) his own journal *Afhandlingar i Fysik, Kemi och Mineralogi* (Treatises in Physics, Chemistry, and Mineralogy), and in 1821 when elected secretary of the Swedish Academy of Sciences began publishing *Årsberättelser öfvre Vetenskapernas Framsteg* (Annual Surveys of Progress in the Sciences). In these journals he single-handedly reported and evaluated on all of the recent significant discoveries, and advanced his own personal scientific ideas. All of these were translated into German in his *Jahres-Bericht*.[12] It was Wöhler, his lifelong close friend, who faithfully and accurately did most of the translation of Berzelius' Swedish writings into German. Jahres-Bericht was instrumental in Berzelius' growing fame in Great Britain and the Continent: "It is impossible to overestimate the influence by. . . the German students who went to Sweden in the 1820s, worked under Berzelius and learned the Swedish language, enabling them to translate his writings into an international language."[4d]

In *Jahres-Bericht* Berzelius rapidly recognized the importance of Wöhler's isomerism (inorganic ammonium cyanate into organic urea) and extended it to a general concept, including fulminates and cyanates, tartaric acid and racemic acid (optically inactive tartaric acid), etc.[4e,12a] He distinguished between isomerism (same formula) and polymerism (multiple formulas, but same percentage composition).[12b] He perceived the significance of Mitscherlich's isomorphism and proclaimed that it was "the most important since the doctrine of proportions."[12c] (By this doctrine, compounds which had the same crystalline structure showed atoms in the same relative positions, and thus indicated analogous formulas; for example, phosphates and arsenates had the same crystalline structure, hence had similar formulas PO_4^{-3} and AsO_4^{-3}). Recognizing that the phenomenon of "isomerism" could extend to an element (e.g., diamond and graphite), he gave it a name, "allotropy";[12d] he used this concept to suggest that red phosphorus was actually a modification of elemental phosphorus[12e] (a fact born out later by Anton von Schrötter in Vienna).[13] Berzelius conceived the idea of catalyst, proposing the term in a remarkable essay in his *Jahres-Bericht*,[4f,12f] where he grasped the significance of special agents in plants that promoted biochemical reactions, thus anticipating the discovery of enzymes by almost half a century.[8d] If he sensed an inaccuracy in a scientific report, he would check it out in the laboratory before commenting on it. His comments in these journals were carefully studied by others; he was so highly regarded that he could make or break the career of an aspiring scientist with his pen.

He resisted pressures from others to classify minerals in terms of their geological origins and/or external appearance, but instead classified them strictly on the basis of composition. Realizing from Mitscherlich's work that minerals with similar "acid group" elements (e.g., phosphates and arsenates) would have the same geometrical form, he proposed a nomenclature wherein the anion, instead of the metal cation, would determine the mineral category.[4g] This concept is still used today: in mineralogy

Figure 5. The island Riddarholmen: the location of Collegium Medicum, where Berzelius in 1807 was appointed the first professor of chemical medicine and pharmacy. He had his first tiny laboratory in the Royal Bakery by the shore (to minimize the risk of accidental fires in the palace); the building no longer exists. This professorial appointment was providential, because otherwise Berzelius might have continued his career as a routine medical doctor and been lost to chemistry (he had been appointed physician to the indigent in Stockholm). The spire is Riddarholmskyrkan. View is southeast from Stadshuset, the present City Hall, the site of the old Glasbruket (E of Figure 6).

reference books, minerals are not organized according to the "iron" group or the "silver" group (as originally suggested by miners who were only concerned in the smelted metals), but instead they are classified according to sulfides, oxides, carbonates, etc. Adapting Gahn's[14] method of blowpipe analysis, he took his analysis of minerals to a new level so that their classification by chemical content became routine. He carried his blowpipe with him as he traveled about Europe, pulling it out at a moment's notice to demonstrate its ability to settle quickly a question of the identity of a mineral in one's collection.

Understanding the importance of quantitative analysis and stoichiometry, he proposed a system of symbolism that denoted not only the identification of a compound, but also the composition of the compound. It is to Berzelius' system, with some modifications (Note 2) that we owe our modern symbolism for elements and compounds. Thus, instead of Lavoisier's ⊕Δ["nitrate d'argent," silver nitrate] symbolism, we use $AgNO_3$.[4h] Berzelius internationalized the symbols and originated "natrium" for sodium, "kalium" for potassium. Berzelius stressed that this formula represented not only composition and chemistry but also amount—$AgNO_3$ represents one "volume," thus anticipating the concept of the mole by half a century.

Berzelius traveled about Europe often, thereby exemplifying his belief that science was universal, and he admonished others when they ignored the work of other countries or cultures. His work often anticipated others; for example, his M.D. dissertation[15] in 1802 was on the action of the galvanic cells (just invented by Volta in 1800) on the human body, and he continued this work into chemistry to demonstrate that voltaic cells could separate electropositive and electronegative elements. When Sir Humphry Davy received credit for the discovery, Berzelius graciously acceded and in fact continued a vigorous and friendly professional relationship with him. (Note 3)

Berzelius was so instilled with these early electrochemical studies—where he observed

Figure 7. Left: German Baker's House, owned by Wilhelm Hisinger, where he lodged and performed his famous atomic weight research and where his student Johan August Arfvedson (1792–1841) discovered lithium in 1817. His kitchen laboratory was on the second floor of the building to the right. Hisinger, an early friend and benefactor of Berzelius, "was a jovial and original old fellow. . . , an ironmaster on his almost princely estate [Skinnskatteberg], surrounded by magnificent lawns, gardens, and large iron-works."[4a] The building was torn down in 1907. Right: Today Jerns, a fashion shoe store, occupies the site.

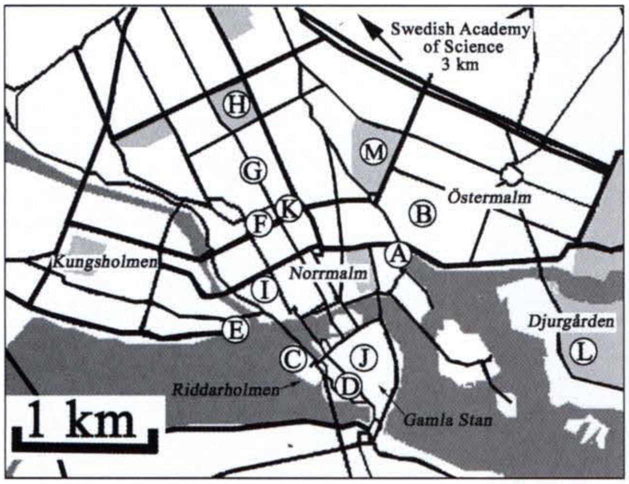

Figure 6. ***Key sites in Stockholm associated with Berzelius.***

A. Berzilii Park, near Nybroplan (N 59° 19.96 E 18° 04.50).

B. German Baker's House, corner of 9 Nybrogatan and 14 Riddargatan (N 59° 20.06 E 18° 04.62).

C. Riddarholmen, site of Collegium Medicum (N 59° 19.51 E 18° 03.73), where Berzelius had his first professorship, five years after receiving his M.D. Berzelius had a small laboratory in the Old Court-Bakery (Gamla Slottsbageriet).

D. First Swedish Academy, 1779-1828, Stora Nygatan 30 (N 59° 19.44 E 18° 04.17).

E. Glasbruket, where the new Karolinka Institutet moved in 1816, and where Berzelius was given new quarters with a laboratory. Glasbruket was removed in 1865. The site is beside the Stadshuset (City Hall) on Kungsholmen (N 59° 19.66 E 18° 03.28).

F. Klara Norra Kyrkogatan 22–24 (N 59° 20.02 E 18° 03.52). This is where Berzelius generally took his meals 1806–1809.

G. Second Swedish Academy, 1829-1915 Wallingatan 2 (N 59° 20.26 E 18° 03.52).

H. Observatory Museum (Observatorie Museet), Dottninggatan 120 (N 59° 20.50 E 18° 03.30), the future site of the Berzelius Museum.

Other landmarks in Stockholm:

I. Stockholm C (Central railroad station) on Vasagatan. Every Berzelius site is within walking distance of the railway station.

J. Stortorget, where Scheele had his apothecary[20] (N 59° 19.51 E 18° 04.23).

K. Konserthuset (Concert House), Hötorget 8 (N 59° 20.09 E 18° 03.82), where the Nobel Prize is awarded every December 10.

L. Djurgården (Zoo Garden), the site of the zoo and the historic village including the Scheele pharmacy.[20]

M. Humlegården, the location of the Scheele (N 59° 20.41 E 18° 04.51) and Lineaus (N 59° 20.34 E 18° 04.37) statues.

Figure 8. This is the laboratory at Gripsholm (N 59° 15.40 E 17° 12.75) where Berzelius in 1817 discovered selenium in a sludge from a sulfuric acid plant in which he had joint ownership. The selenium was from metal selenides, a contaminant in the pyrites (iron sulfides) used as a raw material in the manufacturing process. Berzelius analyzed the slude because of the "odor of radishes" emanating from the selenium compounds (when he was working on selenium, friends reportedly avoided him). The pyrites were mined from the Falun Mine.[14]

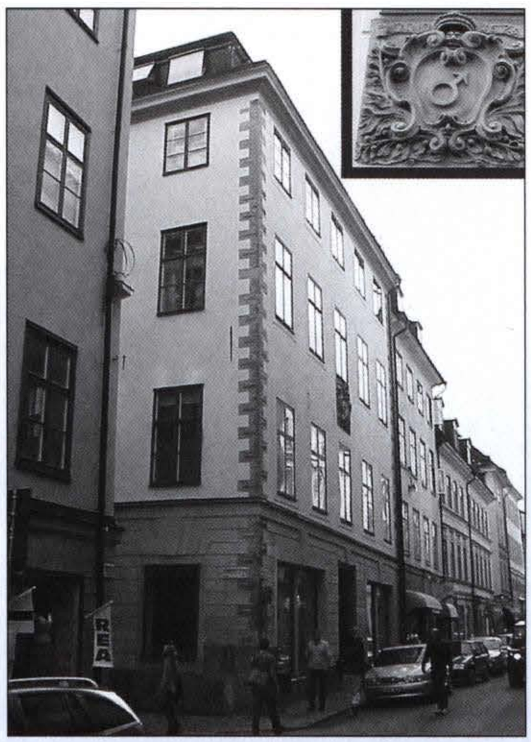

Figure 9. First site of Swedish Royal Academy (Stora Nygatan 30), where Berzelius moved in 1819 (white building on corner). Here metallic silicon and metallic zirconium were prepared in1824 and thorium[3] was discovered in 1828. This is where Wöhler worked (1823–1824) and actually performed preliminary ammonium cyanate to urea isomerism experiments, thus disproving the principle of "vitalism." Wöhler later published this work when he returned to Berlin.[14] Insert: the plaque which can be seen between the first and second level of windows. The symbol is for iron (a strong Swedish commodity), and the construction date 1675 is given.

the separations of "acids" and "bases" as they drifted toward their respective electrode—that he stubbornly embraced throughout his lifetime his dualistic idea that all chemical bonding was electrostatic in nature. This was probably the only weakness in his chemical wisdom: he could not understand how electronegative chlorine could substitute for electropositive hydrogen in organic compounds, as Dumas was demonstrating;[7] he rationalized Dumas' report by doubting a correct analysis. He could not conceive of such a thing as covalent bonding, and a chemical bond between two similar atoms (such as in diatomic elements) was beyond his imagination. (Note 4)

Berzelius declined the chair at the University of Berlin vacated by Klaproth when the old German died in 1817, and he kept his home in Sweden his entire life. Overall he wrote 200 papers in addition to his *Jahres-Bericht*, plus several editions of his Lärbok (chemistry textbook). He married late in life (1835), but remained childless. He earned 12 royal orders and was a member of 94 learned societies. He earned so many decorations that he felt he "had more of these things than can be hung around the neck and pinned to the coat of a scientist even on great occasions without making him ridiculous."[41]

Rediscovering Berzelius. (Figure 2) Jöns Jacob Berzelius was born during a family vacation in the home of his mother's family at Väversunda, Östergötlands, a tiny village 200 km southwest of Stockholm (Figure 3). His father was a principal at the Katedralskolan

Figure 10. Second site of the Swedish Royal Academy (Wallingatan 2), where Berzelius moved in 1829. Here his assistant C. G. Mosander discovered lanthanum in 1839, didymium (a mixture of praseodymium and neodymium), erbium, and terbium in 1842. Top: modern view. Bottom: Drawing from about 1840. The church in the background is the Adolf Fredriks Kyrka (church), inauguruated in 1774, still existent.

(cathedral school) in Linköping, which Berzelius attended 1793–1796 (Figure 4). His father died when he was four, and his mother when he was nine, and he was moved about frequently among the homes of various relatives. After receiving his M.D. in 1802 at Uppsala, by writing a dissertation on the effect of the galvanic cell on ailments such as paralysis, varicose ulcers, and the Saint Vitus' dance,[15] he joined the Collegium Medicum, presently on Riddarholmen in Stockholm (Figure 5), and he remained in Stockholm the rest of his life (Figure 6).

His famous first work, concentrating on determining the atomic weights of the elements, was performed in a kitchen-laboratory of his lodging at the German Baker's House (Figure 7), which was rented to him by the owner Wilhelm Hisinger, with whom he discovered cerium.[2] At Gripsholm where he had an investment in a sulfuric acid factory, he discovered selenium in 1817 (Figure 8). In 1819 he moved to the first site of the Swedish Royal Academy of Science in the Gamla Stan (Old City) (Figure 9) and in 1829 moved to the second site of the Swedish Royal Academy (Figure 10).

Berzelius suffered from migraine headaches when young, gout when old. As his health failed, to his devoted friend Wöhler he wrote, "Dear Wöhler, please work hard as long as you have the strength. You cannot imagine what a creature man becomes when he begins to get old." His memory failed; he could not remember the chemicals in some of his bottles, leading him sadly to destroy the contents. He died August 7, 1848.

Figure 11. The present Swedish Royal Academy of Sciences since 1915 (Lilla Frescativägen 4A), where the voting for the Nobel Prize is carried out. Directly across the courtyard from the old location of the Berzelius Museum, the new museum will be at the Observatory (Observatorie Museet).

Berzelius' legacy lies with us in the Berzelius Museum, which was directly across from the modern Swedish Royal Academy of Science (Figure 11). This museum comprises many rooms, and holds many citations, paintings, books, furniture, and other personal memorabilia (Figures 12–16) of Berzelius, along with equipment and apparatus, chemical samples, and models from his laboratory. The museum is now being moved, and soon will be at the Observatory Museum (Observatorie Museet), constructed on a hill in north Stockholm in 1753. ○

Acknowledgments.

The authors are indebted to Karl Grandin, acting director, Center for the History of Science at the Swedish Royal Academy of Science (Kungl. Vetenskapsakademien) for furnishing much material in the preparation of this article, including a tour of the Berzelius Museum and detailed biographical data about J. J. Berzelius.

Notes.

Note 1. As discussed in an earlier "Rediscovery" article,[7] a completely correct table of elements was possible only after the distribution of Cannizarro's paper at the Karlsruhe

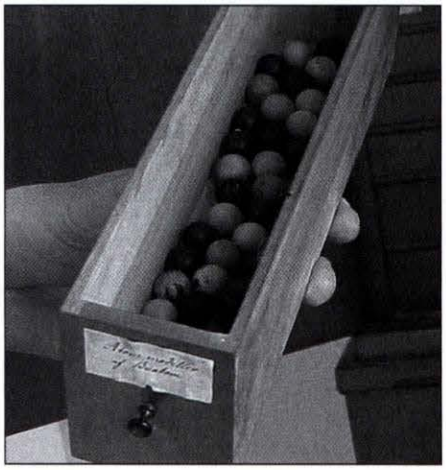

Figure 13. Models of atoms carved from boxwood by Berzelius. Berzelius in his earlier years did not accept Dalton's atomism, but later was convinced of its validity and performed his atomic weight determinations to confirm it. He later considered the isomorphism work of Mitscherlich and the specific heat research of Dulong and Petit as the most important corroboration of the atomic hypothesis.

Conference of 1860. The values of Berzelius that were not corrected until that time were the alkali metals, silver, boron, silicon, and some rare earth elements. Berzelius' errors were due to his incorrect assumptions of oxide formulas, e.g., AgO and NaO, not Ag_2O and Na_2O.

Note 2. Berzelius stressed that the symbolic representation of a compound should define its composition and chemistry; example, the formula of copper sulfate would be $CuO + SO^3$ [superscript intended]. Eventually he simplified by denoting oxygen atoms by dots and representing two elements of an atom by a bar through the symbol. For example, water was $\bar{H}$ with a dot over it. The response of some, particularly the British, was vehement; Dalton, who preferred to denote water as O⊙, called the symbols "horrifying," "like Hebrew letters."[8e] Typesetting difficulties were an additional burden for transcribing the special symbols, and finally Liebig and Poggendorff (in *Liebig's Annalen der Pharmacie*) declared that they were no longer willing to use special type and would subscript numbers; henceforth copper sulfate would be $CuSO_4$, and butylene would be C_4H_8 (not $C^2 H^4$ with horizontal bars through the letters).[4h]

Figure 15. Berzelius learned glassblowing at an early age and used this skill to prepare his own glassware. Note this was before the use of fritted connectors and corks.

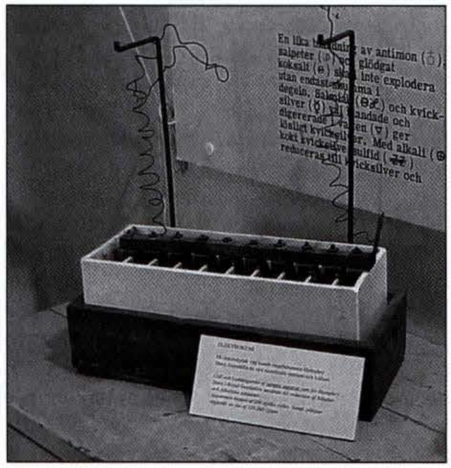

Figure 14. The galvanic apparatus that Berzelius used to demonstrate the differential migration of ionic species. This work was actually done before Davy's famous preparation of metallic potassium and sodium, and Berzelius made to Davy to help the latter in his preparation of the alkaline earth metals. The ability of a battery to separate compounds into positive and negative species so impressed Berzelius that to his dying day he embraced the "principle of dualism" whereby he thought all compound bonding was electrostatic in nature (i.e., present day concept of ionic bonding).

Note 3. Berzelius studied the migration of electropositive and electronegative species promptly after the invention of the voltaic cell; some believe his early work on the voltaic action on aqueous solutions is not as fully credited as it should be. In 1802–1803 he and Hisinger wrote on the action of an electrical current on salts.[16] Davy duplicated this work and in 1807 prepared metallic potassium and sodium.[17] The preparation of the alkaline earths was not as easy, and Berzelius gave Davy important suggestions on how to proceed by suggesting the use of a mercury amalgam.[18] Vauquelin, president of French Academy of Sciences, told Berzelius in 1819, "We consider it our duty to inform you that we would have divided the first prize awarded by us to Humphry Davy between him and both of you, had we learned earlier about your and Mr. Hisinger's work on chemical reactions of the voltaic pile."[19]

Note 4. Berzelius' view that all acids contain oxygen kept him from accepting Davy's classification of chlorine as an element. After the discovery of iodine in 1811, and the evidence obtained by Davy that iodine truly was an element, Berzelius graciously acceded—in 1823 he instructed his cook to no longer call bleach "oxymuriatic acid" but instead "chlorine."[8f]

Figure 16. Berzelius' wheelchair, in the Berzelius Museum.

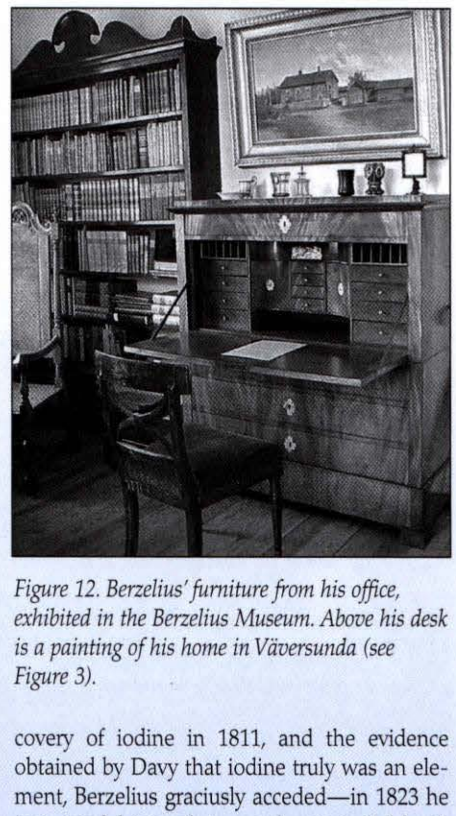

Figure 12. Berzelius' furniture from his office, exhibited in the Berzelius Museum. Above his desk is a painting of his home in Väversunda (see Figure 3).

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