Jöns Jacob Berzelius A Guide to the Perplexed Chemist

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Abstract: Berzelius was one of the most prominent chemists of the 19th century; his scientific contributions were fundamental to the understanding of chemistry and the setting of standards for experimental work. He taught the chemical profession that chemistry should be conducted on a rigorous stoichiometric foundation. Although many of his ideas were eventually modified or proved wrong, he set the stage for the further development of chemistry. Berzelius discovered the elements cerium, selenium, and thorium, and was the first to isolate silicon, calcium, barium, strontium, tantalum, and zirconium in pure form. He also originated the present-day system of chemical nomenclature by using the initial letters of the Latin names of the elements, and then attached to the letters a numerical superscription showing the numbers of atoms in the compound. His Annual Reviews were known as the most comprehensive report on the progress of chemistry and physics. Other achievements include the accurate determination of the atomic weight of most of the elements known in his time; the discovery of pyruvic acid, sarcolactic acid, aconitic acid; and the introduction of the concepts of catalysis, isomerism, allotropy, and protein.

Life and Career [1–3]

Jöns Jacob Berzelius was born on August 20, 1779, in Väversunda Sörgård, Sweden. His father, Samuel, was a secondary school teacher and died when Jöns Jacob was four years old. His mother, Elizabeth Dorothea, remarried to Anders Ekmarck, pastor in Norrköppin, and died shortly afterward. Thereafter, Jöns Jacob was sent back to Väversunda to live with his maternal uncle, and in 1793, at the age of twelve, he was sent away again, this time to school in Linköping, where he earned his room and board by tutoring private pupils. In the autumn of 1796, after finishing four years of secondary school, he went to Uppsala to begin medical studies. The letter of recommendation that he brought from his secondary school stated that although the young man was naturally gifted, he had bad manners and his application to study was less than satisfactory.

Berzelius chose to study medicine because it was both closely related to the natural sciences and likely to provide an adequate income. In the spring of 1797, he was forced to interrupt his studies for a year to earn a little money as a tutor; however, in 1798 he was awarded a three-year scholarship that permitted him to resume his studies. He began his medical studies at the age of seventeen but was forced to withdraw when his scholarship was withdrawn, not, however, before learning much chemistry from Anders Gustav Ekeberg (1767–1813), the discoverer of tantalum. His uncle found him, first, an apprenticeship to a pharmacist, followed by another to one of the physicians to the poor at the Medevi mineral springs, a spa and health resort. At Medevi he performed countless analyses of the spring water and, thus, became proficient with the quantitative techniques that would be the foundation for his later work. Eventually, his analytical experience and rigid standards led him to say that "beginning chemists should not fail to train themselves in quantitative analysis, for although it is nothing but manual work, one should remember that until one has mastered such work one lacks the skill to perform an accurate experiment of a more advanced sort."

While at Medevi, Berzelius constructed a voltaic pile from 60 zinc plates and 60 copper plates, which he used to analyze the effects of galvanic current on various diseases that afflicted the patients at Medevi, such as paralysis, varicose ulcers, and Saint Vitus' dance. Berzelius's conclusions were that galvanotherapy had no effect on them, except in the case of a man with numb fingers. He described the results in his dissertation *pro gradu medico* (*De Electricitatis Galvanicae Apparatu Cel. Volta Excitae in Corpora Organica Effectu*) presented on May 1, 1802, at Uppsala. After graduation, he became an assistant to the professor of surgery at Stockholm. Although he preferred chemistry to medicine economic reasons forced him to serve as regional physician near Stockholm. Eventually, Wilhelm Hisinger (1766–1852), a wealthy mine owner impressed by his analytical abilities, provided him with laboratory facilities in Stockholm.

In 1807 Berzelius was appointed professor of chemistry at *Karolinska Institutet* (Royal Karolinian Medico-Surgical Institute) where he did much inorganic analysis. He gave up this post after being elected secretary of *Kungliga Svenska Vetenskapsakademien* (Royal Swedish Academy of Sciences).

In 1807 Berzelius and six other physicians founded the Swedish Medical Society, and in 1812 he was appointed permanent secretary of the recently created Academy of Agriculture, a position he retained for the rest of his life.

Some of Berzelius's achievements are the discovery of cerium, selenium, and thorium and isolating calcium, barium, strontium, and zirconium in their pure form. His determination of accurate atomic weights based on thousands of analyses allowed the composition of chemical compounds to be ascertained and corroborated the law of definite proportions. His early experiments with electricity and electrolysis led him to develop the dualistic theory of bonding (described below), which could be successfully applied to inorganic compounds, but not to organic ones. Sometimes called the father of

S1430-4171(00)06430-X, Published on Web 11/14/2000, 10.1007/s00897000430a, 560343jw.pdf

gravimetric analysis, he introduced the use of the water bath, dessicator, wash bottle, filter paper, rubber tubing, and improved the blowpipe technique.

To get relief from economical problems, Berzelius became involved in some get-rich-quick ventures such as a plant to bottle mineral spring water and a vinegar factory. These resulted in complete failures that not only led him to lose his hard-earned savings but also saddled him with a debt that took years to pay.

Misfortune and illness were part of Berzelius's life. A laboratory explosion hospitalized him for months and nearly blinded him. Painful migraine attacks, probably of psychosomatic origin, plagued him so often that he actually believed that they were related to the moon phases.

In 1835, at the age of 56, Berzelius married Elisabeth Poppius, the 24-year-old daughter of a cabinet minister. They were childless.

Berzelius died on August 7, 1848, and he is buried in the Solna cemetery, Stockholm.

Honors

Berzelius had twelve royal orders and was a member of 94 academies and scientific societies in many different countries. At the time of the coronation of King Karl XVI Johan in 1818, the new king elevated him to the nobility, and in 1835 he awarded him a baronetcy as a wedding gift.

A commemorative meeting was held in 1898 in Stockholm on the occasion of the 50th anniversary of Berzelius's death. The meeting was sponsored by the Swedish Academy of Science, Karolinska Institutet, the Royal Academy of Agriculture, and the Swedish Medical Society. The speakers included famous scientists, such as Jacobus van't Hoff (1852–1911), Svante Arrhenius (1859–1927), Johan Kjeldahl (1849–1900), and Peter Waage (1833–1900). The Berzelius museum was inaugurated on the same opportunity. It is housed in the building of the Academy of Science, Stockholm, and it contains a large number of chemical compounds and mineral samples, as well as instruments used by Berzelius. The 100th anniversary of Berzelius's death was celebrated on September 20, 1948, by the above institutions in the presence of representatives of 36 foreign universities and learned societies.

Scientific Achievements

Discovery of New Elements. Berzelius is just one of many Swedish scientists that made a significant contribution in the area of discovering new elements. Of the 68 elements that were known in 1880, not less than 22 (or about 40%) were discovered in Sweden.

Selenium. Through his knowledge of chemistry, Berzelius became deeply involved in practical life. He accepted a number of different assignments as a consultant, and he became a partner with some friends in a factory near Gripsholm Castle, manufacturing vinegar, soap, white lead, and sulfuric acid (by the Gay-Lussac chamber process). Originally, the plant used imported pyrites to produce the sulfur needed in the manufacture of sulfuric acid and then switched to a local raw material known as "Swedish tellurium ore" that came from a mine at Falun, Dalecarlia.

In 1817 Berzelius was asked to investigate worker illnesses at the plant in Gripsholm. The occurrence of the problem fit the period in which the company had switched from imported pyrites to locally obtained ones. Berzelius speculated, correctly, that some impurity in this sulfur source was causing the trouble, and he suspected that the impurity might be arsenic, whose toxic properties were well known, or tellurium, an element that he had recently isolated. However, when Berzelius analyzed the golden-brown sediment present in the mud from the bottom of the lead chamber, he found it to be a compound of copper, silver, and other elements. From it Berzelius isolated the pure element selenium, prepared many new compounds of selenium, and examined their properties exhaustively. Having tellurium (*tellus*, the earth) in mind, Berzelius named the new element *selenium* (after the moon or moon goddess *selene*, moon).

We can add also that in honor of the discoverer of selenium, a mineral, the selenide Cu_2Se, has been named *berzelianite*.

Cerium. During a visit to his friend Hisinger in 1803, Berzelius was shown a sample of a rare mineral, Bastnäs tungsten, from nearby Riddarhyttan. His host was particularly interested in it, for he suspected that it might contain the same yttria earth that Johan Gadolin (1760–1852) had found in 1794. Berzelius and Hisinger analyzed the mineral and in 1803 concluded that it contained an unknown metal element bound to silica earth. This metal was named *cerium* after the recently discovered asteroid Ceres. The discovery of cerium was accompanied by some controversy. Berzelius and Hisinger learned that the noted German chemist Martin Heinrich Klaproth (1743–1817) had simultaneously analyzed a sample of the same ore and had made the same discovery, calling the new metal *ochroit earth.* To complicate matters further, Professor Johan Afzelius from the University of Uppsala declared that cerium did not exist, and the mineral from which it was isolated was a mixture of yttria, manganese, and beryllium earth.

Thorium. In 1815 Berzelius thought that he had discovered a new element in the mineral thorjord (thorium earth) near Falun, but later he realized his mistake and found the material to be basic yttrium phosphate. Eventually he did isolate the new element in a mineral he had collected in Brevik, Norway. Berzelius analyzed the mineral and found it to contain 57.91% thorium oxide. The pure element, which was obtained by treating the ore with metallic potassium, was named *thorium* by Berzelius after the Norse god Thor.

Before closing this subject, it is of interest to mention that the number of substances that have mistakenly been taken as new elements is about 100, a number almost equal to that of the true elements.

Some of Berzelius's research related to the discovery of new elements resulted in resounding failures, which affected his scientific reputation. Of particular importance was his discussion witth Humphry Davy (1778–1829) regarding the nature of chlorine, discovered in 1774 by Carl Wilhelm Scheele (1742–1786). Davy had announced that he could not find oxygen in oxymuriatic acid (chlorine), and inferred that the latter must be an element. This discovery led eventually to the recognition that muriatic acid was hydrogen chloride, an acid without oxygen. Berzelius considered chlorine to be oxidized hydrochloric (muriatic) acid because an aqueous solution of it released oxygen when exposed to sunlight, while hydrochloric acid, assumed to be its second component, remained in solution. In addition, Davy's results struck at the roots of Berzelius's dual theory (see below). The discovery in

1811 of iodine, which was regarded an element from the beginning, further supported Davy's view on chlorine. A conflict followed, during which Berzelius's reputation suffered greatly. In addition, Berzelius considered iodine as a superoxide of an iodic acid, and he continued to write new papers in the same spirit as before.

Electrolysis. In 1803 Hisinger and Berzelius reported on a series of experiments that proved "that the discharge of the galvanic pile exerts on the majority of salts dissolved in water an effect similar to that in water,; whereby the different components are separated, each to its pole, acids in the one direction and alkalies in the other [4]." Some fifteen experiments were performed with a variety of solutions and metal conductors using several types of cells, including U- and V-tubes [4, 5].

Berzelius, with the help of his school friend Court-Physician Magnus Martin de Pontin (1781–1858) developed the idea of a mercury cathode, today an indispensable feature in areas like polarographic analysis and production of sodium hydroxide by electrolysis [6]. Hisinger and Berzelius had learned from Davy that the basic component in potash dissolves in mercury to form an amalgam. With their own technique, they succeeded in obtaining a crystalline amalgam of potassium as well as amalgams of the basic components of calcium and barium hydroxide. Davy extended the experiment, and in the same year by distilling the mercury off the amalgam, succeeded in isolating barium metal. Calcium, strontium, magnesium, and lithium were similarly isolated [1].

In the early 1800s, there were two opinions on the causes of electrolysis. Contact theories accounted for the different voltages observed at the poles. Chemical theories tried to show how chemical phenomena provided the driving force for the electrical processes, a force that came from differences in the chemicals present in the liquid. According to the contact theory endorsed by Alessandro Volta (1745–1827), contact between metals was enough to generate electricity. Davy's theory of electrolysis tried to account for the fact that the conducting liquid was always decomposed, an effect for which Volta's theory could not account. According to Davy, decomposition in the liquid was the source of the electrical current.

Disagreement over these two theories continued throughout the nineteenth century. Standardizing cells became a major preoccupation resulting in the production (in Germany) of *Normalelementen* that contained a particular substance in solution, the electrolytic conductivity of which could be determined and then used as a basis for comparison with solutions of unknown conductivity. Eventually these Normalelementen, as they were called, became very complicated, involving not only containers of solution but stirrers, stoppers, and multiple layers of fluid [1].

The Dualistic Theory (Two-Component Chemistry)

In 1813 Berzelius proposed a classification of matter according to behavior in electrolysis. The two major categories were imponderable and ponderable. Imponderable included phenomena such as positive and negative electricity, light, caloric, and magnetism. Ponderable bodies were first divided into simple and composite bodies and then into two classes, electropositive and electronegative, according to whether during electrolysis they appeared at the negative or positive pole, respectively; here, Berzelius followed Davy's convention of designating electropositive substances as those attracted to the negative pole, and vice versa. Berzelius assumed that every atom had both positive and negative charges, that is, it was polarized. The only exception was oxygen, the most electronegative element. All others could be arranged in such a way that they were electropositive to those above them and electronegative to those below. By 1819, Berzelius had correlated this polarity to affinities. Against the opinion of John Dalton (1766–1844), a British chemist and physicist, he claimed that atoms had neither shape nor dimension and that what characterized them most definitively were their electrical properties.

The results of his electrochemical experiments led Berzelius to believe that a chemical process was the same as an electrical one. His starting point was the series in which Volta had arranged the metals according to the electric tension, which they exhibited after contact with each other. In his own words, "bodies that are likely to combine show free, opposite electricities, which increase in force as they approach the temperature at which combination occurs, until, at the instant of union, the electricity disappears with an elevation of temperature, which is often so great that they burst into flames. Similarly, combined bodies exposed in a suitable form to the action of the electric fluid produced by the discharge of a pile are separated again and regain their original chemical and electrical properties at the same time that the electricity that acted on them disappears. The most probable explanation for the combustion and ignition is that in all chemical combinations there is neutralization of opposing electricities, and this neutralization produces fire in the same manner it produces it in the discharge of the electric jar and the electric pile." [7, 8]. In other words, Berzelius was postulating that in the formation of chemical compounds, there was neutralization of positive and negative charges, often with liberation of light or heat, analogous to sparking across a condenser, but the resulting compound was not necessarily neutral, because the unequal charges did not have to neutralize each other exactly.

As mentioned before, Berzelius used these arguments to divide bodies into two classes: electropositive and electronegative. All bodies could then be arranged in the order of their electrical nature, forming an electrochemical system that could be used to give an idea of chemistry. He went on to say, "if his electrochemical views are correct, then all chemical combination depends solely on two opposing forces, positive and negative electricity, and that thus each combination should be composed of two parts united by the effect of their electrochemical reaction, provided that there exists no third force. Whence it follows that each compound substance, regardless of the number of its constituent principles, may be divided into two parts, of which one is electrically positive and the other negative. Thus, for example, sulfate of soda is not composed of sulfur, oxygen, and sodium, but of sulfuric acid and soda that both may again be divided into two elements, one positive and the other negative. Similarly alum cannot be considered as directly composed of its elements but should be regarded as the product of the reaction of sulfate of aluminum, a negative element, and sulfate of potash, a positive element" [7].

Berzelius arranged the elements according to their charges in a series that began with the absolutely negative oxygen: "oxygen is, of all bodies, the most electronegative. As it is never positive relative to any other we recognize in it an absolute negative. Also, in the electrochemical system, it is the only body whose electrical relations are invariable" [7]. The series led, with the gradual decrease of negative charges and increase of the positive ones, to the metals, of which alkalis seemed to be the most strongly positive. Every member of the series, with hydrogen approximately in the center, was positive about the preceding one and negative in relation to the following one. The oxides of the first half formed strong acids, those of the second half formed bases. Compounds formed by the union of oxides of acidic nature with those of basic characteristics produced salts. At the bottom of the table stood potassium, the most electropositive element.

Lavoisier's oxygen theory of acidity, his theory of neutral salts, and his theory of organic chemistry were the immediate predecessors of Berzelius's ideas. According to Lavoisier, oxygen was both necessary and sufficient for the production of acidity. The belief that oxygen was necessary was later undermined by the discovery of acids that did not contain oxygen and that the presence of oxygen was not sufficient to lead to acidity. According to Lavoisier, all substances, not merely metals, were capable of forming nonacidic compounds, oxides with small quantities of oxygen.

Berzelius developed and completed the dualistic theory of Lavoisier with his own electrochemical hypothesis. He was led to assume that the atoms, whilst separate in simple bodies, should unite to form the atoms of a compound of the first order, and these in turn, uniting in simple proportions, should form composite atoms of the second order. He did not accept that if two substances reacted in a 1:1 ratio they could produce two molecules of the same nature instead of a single molecule; that is, his theory contradicted the hypothesis of Avogadro and of Ampère, which in many cases lead to the conclusion just indicated.

Berzelius emphasized that acids owed their acidity to the characteristic of their radicals, not to their possession of oxygen. Acidity was a specific property and basicity an equivalent, opposing one. For Berzelius the specificity of the acid and basic oxides was established by two facts: the identity of the radical of the oxide and the quantity of oxygen with which it was combined.

Electrochemistry served to generalize the concepts of acidity and basicity. Acidity, as usually understood, was extreme electronegativity; basicity was extreme electropositivity. By calling less markedly reactive oxides weakly electropositive or electronegative, Berzelius was asserting that they could serve as acids or bases, even though they lacked the usual characteristics of acids and bases, and he was maintaining that the compounds of these weakly reactive compounds could be considered saline, even though they shared few of the properties common to salts of strong acids and bases. Accordingly, electrochemical characterization not only distinguished substances from one another qualitatively, it also labeled substances lacking in saline character (e.g., the chlorides of sulfur) as saline and thus subject to Berzelius's stoichiometric laws for the composition of salts [9].

The apparently simplicity of the dualistic theory and its easy explanation of many chemical facts gave it first place in the thinking of chemists.

According to Berzelius's theoretical views, the quantity of electricity collected at the point of union of two atoms ought to increase with the strength of their affinity. Faraday demonstrated by experiment that, insofar as this electricity came forth in electrolytic decomposition, its quantity did not at all depend on the degree of affinity. This was a fatal blow to Berzelius's theory.

Berzelius developed the radical theory of chemical combination, which held that reactions occurred as stable groups of atoms called radicals that were exchanged between molecules. Berzelius coined the term *radical* (or radicle, from the Latin radix, a root), a term that was used during the nineteenth century for the part of a compound that remains unchanged during a reaction. He believed that salts are compounds of an acid and a base, and he discovered that the anions in acids would be attracted to a positive electrode whereas the cations would be to a negative electrode. The electrochemical properties of oxidized substances depended always exclusively on the unipolarity of their electropositive element, that is to say, of their *radical*. The oxide was ordinarily negative regarding other oxides when its radical was negative toward their radicals, and vice versa. The term radical still remains part of the organic chemist's vocabulary today, although it is now used in a different sense than originally intended. The original meaning can still be traced, however, to the use of the generic symbol R to designate the unchanging part of an organic compound undergoing a reaction.

Looking today at Berzelius's theory, we can say that the most serious theoretical objection to it is purely physical: Berzelius made the error of confusing the roles of electrical *potential* and electrical *charge*.

Atomic Structure, Chemical Weights, and Chemical Bonds. To understand Berzelius's contribution in these areas, we must consider what was the status of the atomic theory in his time. The idea that matter is composed of atoms goes back to the Greek philosophers, particularly Democritus (469 B.C.E.–370 B.C.E.). By the end of the 18th century many experimenters were already accepting the idea that every chemical compound contains fixed and constant proportions (by weight) of its constituent elements (the law of definite proportions). In 1797 the French chemist Joseph-Louis Proust (1754–1826) first reported conclusive evidence for this principle in a series of researches on the composition of many substances, especially the oxides of iron. Claude Louis Berthollet (1748–1822) sustained the idea of indefinite proportions; Thomas Thomson (1753–1852) confirmed some of Proust's results and claimed that the latter had definitely proved that "metals are not capable of indefinite degrees of oxidation." Dalton converted the atomic Greek philosophy into a scientific theory and in his book *New System of Chemical Philosophy* (1808–1810) made the first application of atomic theory to chemistry. Dalton proposed that the elements were composed of atoms that were indestructible, that atoms of different elements differed in their masses, and that a compound was a characteristic grouping of atoms. He also proposed that atoms were not infinite in variety as had been supposed and that they were limited to one of a kind for each element. He considered the law of definite proportions a postulate and he expressed the law of multiple proportions as a corollary to it: when two elements combined in a series of compounds, the ratios of the masses of one element that combined with a fixed mass of the second were reducible to small whole numbers.

Joseph Louis Gay-Lussac (1778–1850) extended the relationship between chemical masses implied by Dalton to volumetric relationships of gases. He illustrated his statements by considering the combination of carbon monoxide and oxygen to form carbon dioxide and claimed that the volume of the carbon dioxide produced is equal to the volume of carbon monoxide and is twice the volume of the required oxygen.

We have mentioned already that Berzelius believed that the chemical bond was caused by electrostatic attraction between the atoms; a bond was established between two atoms only if one of the atoms was charged positively and the other negatively; thus, Berzelius was able to explain the bonding conditions for a great number of inorganic substances, contributing to a greater clarity in this field.

Berzelius was, at first, very dubious about Dalton's atomic theory, but after examining it he became one of its foremost supporters. He published his first table of atomic weights in 1814 at Stockholm. When he edited it again (1825–1831), augmented and improved, it listed 46 elements and about 2000 compounds, all of which he himself had analyzed.

In 1819 Eilhard Mitscherlich (1794–1863) announced the discovery of isomorphism and Pierre Louis Dulong (1785–1838) and Alexis Thérèse Petit (1791–1820) published their law stating that the product of the atomic weight and specific heat for an element is a constant. These results led Berzelius to revise his calculations on atomic weights. He published a new chart in 1826 in which he changed most of the values he had determined before. To make them conform to Dulong–Petit's law as well as to Mitscherlich's isomorphism; he divided most of the atomic weights he had determined before by two or four. His results then deviated very little from those commonly used today; only for sodium, potassium, and silver did Berzelius use values double those of today. As a basis of comparison Berzelius chose oxygen, which he considered the "cardinal point of chemistry." He rejected hydrogen as an unsuitable basis because it combines with only a few elements. In addition, the low weight of hydrogen made a precise analysis of hydrogen compounds very difficult.

Berzelius's hypothesis presented some difficulties in interpreting known phenomena. For example, how is it possible to explain that two hydrogen atoms can unite to become a hydrogen molecule? Attraction between two atoms required that one of them be positive and the other negative, but why should two atoms of the same kind possess charges with opposite sign? When the knowledge of organic compounds increased, new difficulties arose. Berzelius, for example, found it necessary to assume that the hydrogen atom was always positive and the chlorine atom always negative. It was already known that in organic molecules a hydrogen atom could often be exchanged for a chlorine atom, which should be impossible if one was positive and the other negative [9].

In 1811 Amedeo Avogadro (1776–1856) analyzed the laws of Gay-Lussac and Dalton's position with respect the structure of the elements and came to the conclusion that the only way to reconcile both was to accept that the number of integral molecules of any gas contained in a given volume is always the same for equal volumes. In addition, he clearly drew the distinction between a molecule and parts of it (today, atoms) and pointed out that Dalton had confused the two concepts. Until the early 1860s, however, the allegiance of chemists to Berzelius's concepts blocked acceptance of Avogadro's ideas.

With increased knowledge, problems that could not be explained by Berzelius's theory became increasingly numerous, and the theory became discredited. Already by the end of the 19th century it had become obvious that the only way to explain certain phenomena was to accept that there were *different kinds* of chemical bonds; thus, the difficulties of Berzelius's theory were also explained. Berzelius's interpretation was, in principle, correct concerning a very important type of bond, but he had made the mistake of applying it also to bonds of a different type. After Bohr had introduced his atomic theory, it was possible to give a fairly satisfactory explanation of the Berzelius bond. As this bond occurs between electrically charged atoms (ions), this bond type has often been called the *ionic bond*.

The bond, which above all others had prevented a general application of Berzelius's theory is now commonly known as the *covalent bond*. The bond between the two hydrogen atoms in a hydrogen molecule, which, as was said before, could not be explained by Berzelius's theory, is covalent.

Chemical Nomenclature [10, 11]

In 1782 Louis Bernard Guyton de Morveau (1737–1816) suggested the present-day chemical nomenclature with its terminology for describing and characterizing chemical compounds. Most of the traditional names for chemical substances owed their origin to accident, as for example, *sal mirabile Glauberi* (sodium sulfate), others united substances that in reality had no relation to each other, such as *spiritus salis* (hydrogen chloride). Guyton proposed instead that the simplest chemical substances (i.e., elements) should be given the simplest names, and that the names of compounds should recall their chemical components. His suggestions were widely adopted throughout Europe. Guyton de Morveau's nomenclature was further developed by Lavoisier and the group around him. The terms *oxides* and *acides* were created, acides being less saturated with oxygen. The endings *ate* and *ite* made a similar distinction [10].

Because the symbols for the various elements were not uniform, it was almost impossible for scientists to communicate intelligibly. Some symbols had been used by the Greeks, others had been added by the Egyptians, while other still mysterious markings had been conjured up by the ancient alchemists. In one book, thirty-five different names and twenty distinct symbols were used to identify mercury. A new and authoritative scientific language had to be established to replace the chaotic nomenclature that was stunting chemistry's growth [11].

The idea of using letters to abbreviate the names of the elements was already present. The French group around Lavoisier had applied signs suggested by Jean Henri Hassenfratz (1755–1827) and Pierre August Adet (1763–1832) in 1787. Letters were used not only for the elements but also for groups like sulfate, phosphate, citrate, etc. Oxygenation of an element was indicated by an attached straight line, sulfate, phosphate, and other groups by curved lines. The unsuitability of such a system is evident. Hardly more useful, especially for the expression of complicated chemical structures, was Dalton's system using dotted and crossed circles as signs for the elements.

Dalton devised a set of symbols to express his theory. Their graphic nature probably helped in his theory becoming accepted. They were circles, because his atoms were spherical, and they contained several lines, dots, or letters to represent the atoms of different elements. Erroneous though Dalton's theory was in many respects, chiefly because of its rigid, arbitrary assumptions (detailed in the previous section), it presented to chemists a number of new and important concepts. It gave a precise, quantitative basis to the older, vague ideas of atoms; it gave to the concept of elements a specificity that had been previously lacking; it explained the discontinuity in the proportions of elements in compounds as expressed in the laws of constant and multiple proportions. Finally, it suggested that the arrangement of the atoms in a compound could be represented schematically in such a way to indicate the actual structure of the compound. The theory gave no indication of any single standard for determining atomic weights, because the relative weights of the atoms varied, depending on whether the compound in which they were found was binary, ternary, or some other degree of complexity. There was no distinction between atoms and molecules in the modern sense [9, 11].

Towards the end of the 18th century the Swedish Government had ordered a revision of the country's Pharmacopoeia, a fact that pressed in Berzelius the urgent need for a reform in nomenclature, which he and his fellow chemists hoped to incorporate in the new Pharmacopoeia. He stipulated that he would make no other changes in words than those which it could not do without, and that he was particularly eager to establish Latin "which is indispensably necessary to chemists to give direction and determination to the nomenclature of each country and to place one in a position to compare and understand fully nomenclatures in different languages." This fifth edition of the Pharmacopoeia was planned as early as 1793, but not completed until 1817 because of war and political unrest; its chemical part is Berzelius's work.

Berzelius's system of nomenclature was first presented to the scientific world in French [12]. Along with the use of letters as symbols for the elements, Berzelius started to use numbers to designate the proportions between the atoms in a molecule, an idea that developed out of his emphasis on the degree of oxygen saturation in the compounds that he studied.

In the years 1813–1814, Berzelius went further and proposed that each element be given a distinctive letter symbol and that this be used to represent the atom of the element in a chemical combination [13, 14]. For convenience in chemical writing and the printing of books, he suggested that the letters of the symbols be set in ordinary type. He proposed also that the symbol be a single capital letter or a combination of two letters, the first of which would be a capital. Berzelius's code was simple. Each element was to be given its own capital letter; for example, carbon would be C. If another element started with a similar letter, Berzelius proposed that a second letter in the word be used next to the initial capital letter; hence, cobalt would be represented as Co, calcium as Ca, and cadmium as Cd. Because several metals that had been used for centuries had names that differed from one European country to another, he suggested that the Latin name be used in forming the symbols. Included in this list were the names and symbols: argentum (silver), Ag; aurum (gold), Au; cuprum (copper), Cu; ferrum (iron), Fe; hydrargyrum (mercury), Hg; plumbum (lead), Pb; stannum (tin), Sn; and stibium (antimony), Sb. In compound particles, Berzelius suggested that the atomic symbols be written next to each other as formulas. The atoms in water, for example, would be represented as 2H+O (now (H_2O), while C+2O (now CO_2) would represent the atoms in carbon dioxide. The chemical sign expressed always one volume of the substance. To present the combination of atoms in a compound he suggested that the symbols for the atoms in the compound particle be put down side by side. He called these *formulas*.

Because the names in themselves failed to indicate the quantitative proportions of their constituents, Berzelius created a language of signs that was to be quantitative throughout. For this chemical shorthand he did not choose geometrical figures, such as had been used previously, but letters, to which he assigned a quantitative value. The reform in chemical symbols proposed by Berzelius permitted a visualization of chemical reactions in the simplest and most effective way. Berzelius's formulas were a great improvement over those previously proposed, not only because of their simplicity and because they could be set in ordinary type, but also because they stood for a definite weight of the elements.

Scientists who had mastered the old symbols were not all eager to learn the new language. Dalton, in a letter to Thomas Graham (1805–1869) in 1837, referred to Berzelius's proposal as "horrifying" and compared it with Hebrew letters; other chemists were openly hostile. Despite these reactions, Berzelius's work began to make ground, and soon influential scientists were using the Latin letters and establishing Berzelius's nomenclature as chemistry's international language.

Dalton also opposed Berzelius's nomenclature because it neglected "allocation," that is, the arrangement of the atoms [11]. This was one advantage possessed by Dalton's symbols; anyone using them thoughtfully could not help considering the relative position of the atoms. Dalton was able to use this advantage to the full in organic chemistry, and he expressed clearly by means of his symbols the concept of isomerism.

In spite of the tremendous improvement involved, Berzelius's notation system had several weaknesses that reflected Berzelius's ideas. Apart from errors due to faulty analysis, it did not consider the halogens and nitrogen as elements but as oxides and denoted them as such in the symbols. Second, he also made a misleading analogy between salts containing water of crystallization and what we now call hydroxides, denoting both by the symbol Aq.

By the middle of the 19th century, in spite of Berzelius's contribution, the conflicting opinions on the structure of matter and the indivisibility of molecules had resulted in a chaotic situation. To try to solve these and other problems, August Kekulé (1829–1896) suggested an international meeting of chemists, and in September 1860 the First International Congress of Chemists met in Karlsruhe, Germany. The organizing committee included distinguished scientists, such as Robert Bunsen (1811–1899), Stanislao Cannizzaro (1826–1910), Jean-Baptiste Dumas (1800–1884), Hermann von Fehling (1811–1885), Hermann Kopp (1817–1892), Justus von Liebig (1803–1873), Louis Pasteur (1822–1895), Victor Regnault (1810–1878), Friedrich Wöhler (1800–1882), and Charles Wurtz (1817–1884). The first session of the congress debated the notions of molecule and atom with Cannizzaro and Kekulé as main speakers. Cannizzaro repeated the arguments that he had published two years before [15], offering for the first time in the history of the physical sciences a very clear definition of atoms as distinguished from molecules. To him the atom was the "smallest quantity of each element that enters as a whole into the molecules that contain it," and to determine this quantity one must know the weights of all or most of such molecules and their composition. Furthermore, by comparing the composition of equal volumes of gaseous substances under the same physical conditions, it might be established that "the different amounts of the same element contained in equal volumes, either of an element or its compounds, are whole multiples of a same amount." This statement represented a most remarkable contribution to the clarification of the issues debated at the time concerning the relations between volumes, atoms, and molecules in both organic and inorganic compounds; in fact, the molecular weights were identified for every substance with the weights of equal volumes under the same physical condition. With his system of formulas, Cannizzaro emphasized the absolute validity of Avogadro's hypothesis and that it could be used to determine not only molecular masses but also, indirectly, atomic masses.

Catalysis

In his 1835 Annual Survey [16] Berzelius summarized the findings of different scientists on the formation of ether from alcohols; the enhanced conversion of starch to sugar by acids; the hastening of gas combustion by platinum; the stability of hydrogen peroxide in acid solution but its decomposition in the presence of alkali and such metals as manganese, silver, platinum, and gold; and the observation that the oxidation of alcohol to acetic acid was accomplished in the presence of finely divided platinum. In a brilliant stroke of logic he was able to understand that all these processes, although seemingly different, had a common denominator, which he called catalysis (either catalysis of inorganic reactions by metals or of biological reactions by enzymes). In the Annual Survey he wrote, "In inorganic nature when compounds arise through the interaction of several substances, the available combining units strive for a state of better satisfaction. Thus, the substances endowed with strong affinities combine readily on the one hand, while those more weakly endowed form combinations among themselves on the other. The agent causing the conversion of substances does not participate in the new compounds formed but remains unchanged, thus operating by means of an internal power, the nature of which is still unknown, although it was in this way that it revealed its existence. Thus it is certain that substances, both simple and compounds, in solid form as well as in solution, have the property of exerting an effect on compound bodies which is quite different from ordinary affinity in that they promote the conversion without necessarily participating in the process. This is a new power to produce chemical activity belonging to both inorganic and organic natures. It will also make it easier for us to refer to it if it possesses a name of its own. I shall call it the catalytic power of substances, and decomposition by means of this power catalysis (from the Greek kata, down, and lyein, loosen)."

The observant reader will realize that the concepts about catalysis developed by Berzelius 170 years ago are not very different from those that are taught today in an introductory lecture about the subject.

During Berzelius's lifetime, his ideas about this new principle of catalysis were bitterly contested and attacked, but in the 20th century they became an indispensable part of both the theoretical and applied fields of chemistry and chemical engineering.

Other Contributions

In 1834, while performing experiments on the distillation of tartaric acid and racemic acid, Berzelius noted that a substance sublimed and sometimes crystallized, but more often polymerized. Berzelius analyzed this substance and found it to be pyruvic acid. Berzelius wrote an exhaustive description of the acid as well as of the method of preparation and properties of twenty different metal salts of the new acid. He interpreted the composition of pyruvic acid according to the concepts in vogue then, claiming that it was an oxide of an organic radical (the ethyl radical C_2H_2), assumed to be common to a series of organic acids.

In 1838, Berzelius corresponded with the Dutch chemist Gerardus Mulder (1802–1880) [17] and proposed the name protein for a supposedly new radical that the latter had isolated from fibrin, casein, and egg white and that was assumed to be present in all animal and plant material. In one of his letters to Mulder, Berzelius considered that, because of the alleged general occurrence of this radical, it was necessary to give it a specific name, suggesting *protein* for this purpose. He picked the name because the material seemed to be the primitive substance of animal nutrition that plants prepare for the herbivores.

In his early days Berzelius had shown that the lactic acid of fermentation that Scheele had discovered in 1780 and the lactic acid that he himself had discovered in muscle in 1808 behaved differently towards polarized light when dissolved in water. Berzelius found that the lactic acid in muscle is what we call today optically active, being dextrorotatory. The lactic acid that Scheele produced by fermentation was the optically inactive racemic form. To determine this property Berzelius used a polarimeter that he had bought from Jean Baptiste Biot (1774–1862) during a trip to Paris. In a later series of experiments about the optical activity of tartaric and racemic acids, Berzelius concluded that these acids had the same elementary composition, and that the difference in properties originated from a different internal distribution of the atoms in the molecule. Berzelius then suggested the word *isomerism* for this phenomenon. He later differentiated between isomorphism (or metamerism) and polymerism by stating that substances are isomorphous when they possess different properties although their chemical composition and molecular weight are alike. In the case of polymerism the substances have different molecular weights, mostly multiples of each other, but the same percentage composition [18, 19].

Application of the concept of isomorphism to the elements led him to define *allotropism*. Berzelius gave as examples "the allotropic modification of carbon in diamonds and graphite."

In 1814 Berzelius published a system of mineralogy offering a comprehensive classification of minerals based on their chemistry. Berzelius recognized silica as an acid and introduced into mineralogy the group known as silicates. The first heteropolymeric compound, $(NH_4)_3[PMo_{12}O_{40}]$, was obtained by Berzelius in 1826 as a yellow, crystalline precipitate, the formation of which is still used for the classical qualitative detection and quantitative estimation of phosphorus (after conversion to phosphate). Besides their use in analytical chemistry, heteropolymeric compounds have found use as catalysts, molecular sieves, corrosion inhibitors, photographic fixing agents, and precipitants for basic dyes.

In Berzelius's studies on animal fluids, he demonstrated that the coloring matter of blood did not derive from an iron salt, but that the iron was contained in the coloring matter in a manner not understood. Among the proofs of this claim was a series of chemical tests with aqueous inorganic reagents that would have detected the iron oxide as a saline constituent.

Berzelius's influence was further strengthened by extensive correspondence and through students that included among others Friedrich Wöhler (who synthesized urea from ammonium cyanate), Eilhard Mitscherlich (1794–1863, discoverer of isomorphism) and the brothers Heinrich (1795–1864) and Gustav (1798–1873) Rose.

Scientific writings

Berzelius published more than 250 original papers and many textbooks; the first was *Förelänsningar i Djurkemien* (*Lectures on Animal Chemistry*, 1806–1808) in two volumes with about 750 pages, followed by his monumental *Lärbok i Kemien* (Textbook of Chemistry) in six volumes with over 6000 pages. Berzelius's *Textbook of Chemistry* contained the entire body of chemical knowledge of that time and it he discussed the opinions and teachings regarding the elements and the known chemical compounds. The textbook analyzed and synthesized all that was new in chemical theory: current views of the nature of the elements and the compounds they could form, chemical nomenclature, the new system of classifying the minerals, and the radical and substitution theories of organic chemistry, as well as the many new compounds which had been identified and produced in the laboratory along with methods developed for their analysis. For many years Berzelius's textbook was the primary source of knowledge for chemists and pharmacists around the world. There were many French, German, Dutch, Italian, and Spanish translations of the book, proof of outstanding popularity over a number of decades.

Soon after Berzelius became secretary of the Academy of Sciences, he began publishing his *Arsberättelser öfver Vetenskapernas Framsteg* (*Annual Surveys of the Progress in the Sciences*), probably his most influential publication. The *Annual Surveys* appeared annually from 1821 until 1848, the year Berzelius died. They amount to 27 volumes with a total of about 12,000 pages. Complete with Berzelius's commentaries, his *Annual Surveys* were the quintessence of the chemical discussion of the time. In them, Berzelius reviewed all the literature of the preceding year and discussed all sorts of the questions related to the elements, their valences, and their compounds. It was through these discussions that he came into constantly recurring conflicts with Dumas and Liebig. Berzelius's comments on the literature were anxiously examined by the authors of the papers in question, for his prestige was such that his opinion could influence their scientific career [1].

Conclusion

Berzelius was one of the most prominent chemists of the 19th century. Although many of his ideas are now outdated, at his time they set the stage for the further development of chemistry. He set the basis for the present-day system of chemical nomenclature, determined accurately the atomic weight of most of the elements known in his time, and introduced the concepts of catalysis, isomerism, allotropy, and protein. His *Annual Reviews* were known as the most comprehensive report on the progress of chemistry and physics and may be considered the forefather of present day journals such as Chemical Reviews.

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