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## August Kekulé—The Architect of Chemistry Commemorating the 150th Anniversary of His Birth<sup>[\*\*]</sup>

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Imagination, daring, and critical understanding are the sources of the impulses still felt today which chemistry received from the theoretical studies of *Kekulé*. "Let us learn to dream, gentlemen, then perhaps we shall discover the truth; but let us beware of publishing our dreams abroad before they have been scrutinized by our vigilant intellect ... Let us always allow the fruit to hang until it is ripe. Unripe fruit brings even the grower but little profit; it damages the health of those who consume it; it endangers particularly the youth which cannot yet distinguish between ripe and unripe." (*Kekulé* 1890).

*"Eine Geschichte zu schreiben, ist immer eine bedenkliche Sache. Denn bei dem redlichsten Vorsatz kommt man in Gefahr, unredlich zu sein; ja, wer eine solche Darstellung unternimmt, erklärt im voraus, daß er manches in Licht, manches in Schatten setzen werde."* (*J. W. von Goethe, Introduction to the didactic part of the theory of colors*)

Many scientific discoveries of bygone centuries have meanwhile become so commonplace that the achievement of their discoverer is often underestimated in spite of all the appreciation it receives. Yesterday's genius becomes today's banality. Pertinent examples are the foundation of organic structural chemistry and the proposal of the benzene formula by *August Kekulé* who, although of comparable genius with *Justus Liebig*, likewise born at Darmstadt, received far less recognition than the latter. The 150th anniversary of his birth provides an opportunity to call to mind his importance in the history of chemistry and for development of the chemical industry, and his part in the teaching of chemistry as viewed from a modern standpoint, and thus to reflect upon a great, almost unique scientific tradition, extending far into

the present century, which is hardly known to the present generation.

When *Kekulé* published his paper on the isomerization of *n*-propyl bromide to isopropyl bromide in the presence of aluminum bromide<sup>[1]</sup> a hundred years ago and therein, without knowing it, provided one of the first experimental proofs of the existence of carbenium ion intermediates, he had

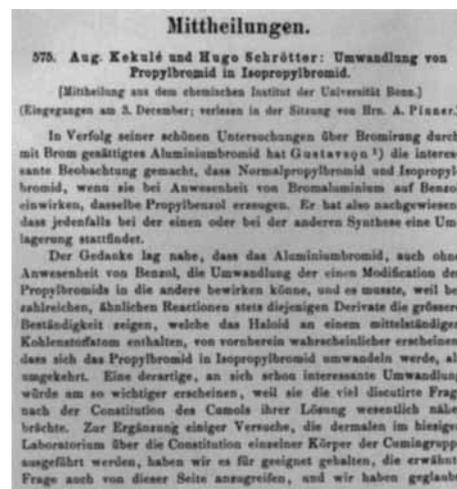


Fig. 1. Title page of publication by *Kekulé et al.* on the isomerization of *n*-propyl bromide [1].

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already—hardly fifty years old—completed his major life's work. It was left to *Hans Meerwein* (1879—1965), born in the same year, to introduce the then revolutionary concept of ionic reactions into organic chemistry more than four decades later<sup>[2]</sup>.

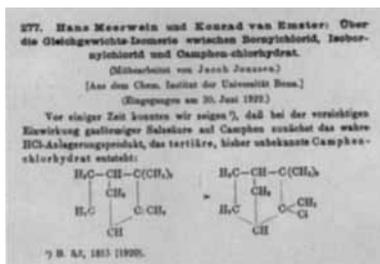


Fig. 2. Title page of the first publication, by *H. Meerwein*, on ionic reactions in organic chemistry [2].

*August Kekulé* lived in a century between the world-shaking events of Napoleon's Hundred Days and the First World War. This was an age of scientific revolutions, ranging from the disproof of spontaneous generation and the discovery of microorganisms to the description of viruses and enzymes, from *Faraday's* laws of electrolysis to the discovery of X-rays and that of the radioactivity of uranium compounds. It was also an age of engineering, ranging from the first railway to

#### Life of August Kekulé

- 1829 Born at Darmstadt, Neckarstrasse 19, on September 7
- 1835 to 1847 Pupil at the private school run by *Heinrich Schmitz* and at the Ludwig-Georgs-Gymnasium, Darmstadt
- 1847 to 1848 Study of architecture at Giessen
- 1848 to 1849 Semester at Darmstadt Polytechnic
- 1849 to 1851 Study of chemistry at Giessen
- 1851 to 1852 Period of study at Paris
- 1852 Awarded degree of Dr. phil.
- 1852 to 1853 Private assistant to *A. von Planta* at Reichenau Castle, Chur
- 1854 to 1855 Private assistant to Professor *J. Stenhouse* at St. Bartholomew's Hospital, London
- 1855 to 1858 *Privatdozent* at Heidelberg University
- 1856 Habilitation for chemistry, physics, and geognosy
- 1857 to 1858 Publication of fundamental papers on the theory of valency
- 1858 to 1867 Professor of chemistry at the State University of Ghent, Belgium
- 1859 Publication of the first instalment of *Kekulé's* textbook of organic chemistry
- 1860 Participation in the first international congress on chemistry at Karlsruhe September 3 to 5, 1860
- 1862 Marriage to *Stephanie Drory*
- 1863 Birth of son *Stephan*; death of *Stephanie Kekulé, née Drory*
- 1865 Proposal of formula of benzene
- 1867 Call to Bonn University
- 1868 Award of honorary degree of Dr. med. at 50th anniversary of the foundation of Bonn University
- 1875 Call to Munich University as successor to *J. von Liebig*—not accepted
- 1876 Marriage to *Luise Högel*
- 1877 to 1878 Chancellor of Bonn University
- 1878 Birth of son *Fritz*
- 1878, 1886, 1891 President of German Chemical Society
- 1882 Birth of daughter *Louise*
- 1885 Birth of daughter *Auguste*
- Award of Copley medal
- 1889 Award of Huyghens medal
- 1890 Benzene festival of German Chemical Society held in the City Hall of Berlin
- Award of the "Kronenorden II. Klasse" and election to "Ritter des Maximilian-Ordens für Wissenschaft und Kunst in Bayern"
- 1893 Nomination as "Ritter des Ordens pour le mérite für Wissenschaften und Künste"
- 1895 Prussian title of nobility (*Kekulé von Stradonitz*)
- 1896 Died at Bonn on July 13

the discovery of the Diesel engine, and from the first electromagnetic telegraph to wireless telegraphy.

*Kekulé's* birth—on September 7, 1829—coincided with the actual beginning of organic chemistry. Just one year earlier, *Friedrich Wöhler* (1800—1882) had disproved the concept of vitalism<sup>[4]</sup> by synthesizing urea from ammonium cyanate<sup>[3]</sup>. Thus was initiated an incredibly productive and lively development of organic chemistry. *Michael Faraday* (1791—1867) obtained "bicarbuuretted hydrogen"<sup>[5]</sup> from compressed illu-

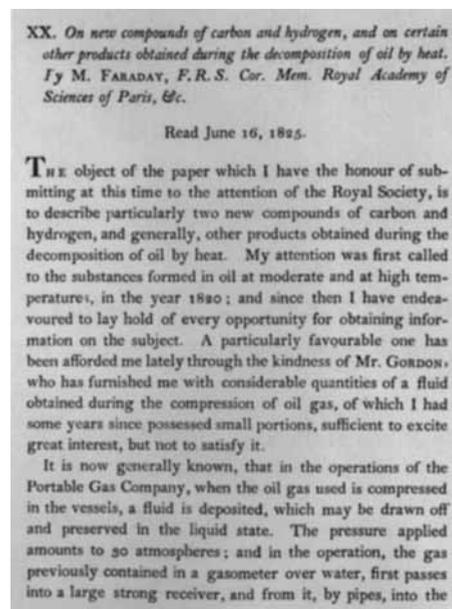


Fig. 3. *Faraday's* publication [5a] on the first isolation of benzene from illuminating gas (1825).

minating gas; shortly afterwards the same compound was obtained by *Eilhard Mitscherlich* (1794—1863) when benzoic acid was heated with quicklime<sup>[6]</sup>, and was called benzene in accord with its mode of formation. 30 years later, its structural elucidation was destined to crown *Kekulé's* life's work and

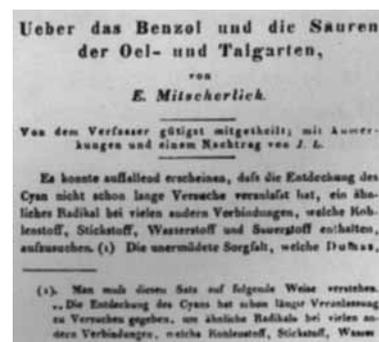


Fig. 4. *Mitscherlich's* publication [6] on the production of benzene from benzoic acid (1834).

also to initiate a tremendous upswing of the chemical industry. During the first years of *Kekulé's* life, *Friedlieb Ferdinand Runge* (1795—1867) discovered aniline and phenol in coal tar<sup>[7]</sup>, and *Jöns Jacob Berzelius* (1779—1848) introduced the concepts of catalysis<sup>[8]</sup> and of isomerism<sup>[9]</sup>. *Justus Liebig's* (1803—1873) and *Wöhler's* studies on benzoyl compounds<sup>[10]</sup> laid the foundations of the radical theory of carbon com-

pounds which was welcomed by *Berzelius*, the father of the then generally accepted electrochemical-dualistic concepts which were so very fruitful for inorganic chemistry, as the “dawn of a new day in vegetable chemistry”<sup>[11]</sup>.



Fig. 5. From left to right: J. J. Berzelius, M. Faraday, E. Mitscherlich, F. Wöhler.

At this time, *Friedrich August Kekulé* grew up as the youngest child of the “Grossherzoglicher Oberkriegsrat” *Ludwig Karl Emil Kekulé* (1773—1847)<sup>[12]</sup> in Darmstadt. Although highly gifted and very interested in all scientific phenomena, the schoolboy showed no pronounced interest in chemistry. Like *Georg Christian Lichtenberg* (1742—1799), *Johann Heinrich Merck* (1741—1791), and *Georg Büchner* (1813—1837) before him, and like *Stefan George* (1868—1933) and *Friedrich Gundolf* (1880—1931) after him, he was a pupil of the Grossherzogliches Gymnasium<sup>[13]</sup> of his home town which he left in 1847 with a distinguished leaving certificate<sup>[14]</sup>.

A gift of rapid comprehension coupled with an exceptionally good memory guaranteed his success, as did a vivid imagination which became almost visionary in later life. “His thoughts turned into pictures and at times he could visually observe his thoughts”<sup>[15]</sup>. Remarkable graphic and mathematical ability and several designs for houses in the old part of Darmstadt drawn while he was still at school predestined him for the study of architecture at the Hessian University at Giessen. At that seat of learning, it was his fellow Hessian *Liebig*, then at the zenith of his scientific career, who inspired him by his lectures and persuaded him to change over to chemistry in which he was soon to develop his constructive bent in such magnificent manner. Philology and classics were then, and later, the main props of German education and it is hardly surprising that *Kekulé*’s family, strongly influenced by such ideals, were reluctant to condone this change. Instead, a time of deliberation was prescribed at the Darmstadt Polytechnic, the forerunner of the Technical University<sup>[16]</sup>. He spent that winter-semester of 1848/49—far away from the political unrest of the time—performing analytical work in the laboratory of *Friedrich Moldenhauer* (1797—1866). He did not return to architecture, but instead to *Liebig*’s laboratory at Giessen, where he pursued analytical studies with enthusiasm, carefulness, and persistence, a dedication without haste, which was to characterize him throughout his life. “It was not practical chemistry which attracted him, but the philosophy of chemistry”<sup>[17]</sup>. He participated briefly in *Liebig*’s physiological work on plants and animals with an analytical study on gluten and wheat bran<sup>[18]</sup>; *Liebig* had already turned his attention away from pure organic chemistry. *Kekulé* was awarded his doctorate for an experimental thesis “Über die Amyloxydschwefelsäure und einige ihrer Salze”<sup>[19]</sup> completed under the supervision of *Heinrich Will* (1812—1890)<sup>[20]</sup>, one of *Liebig*’s students.

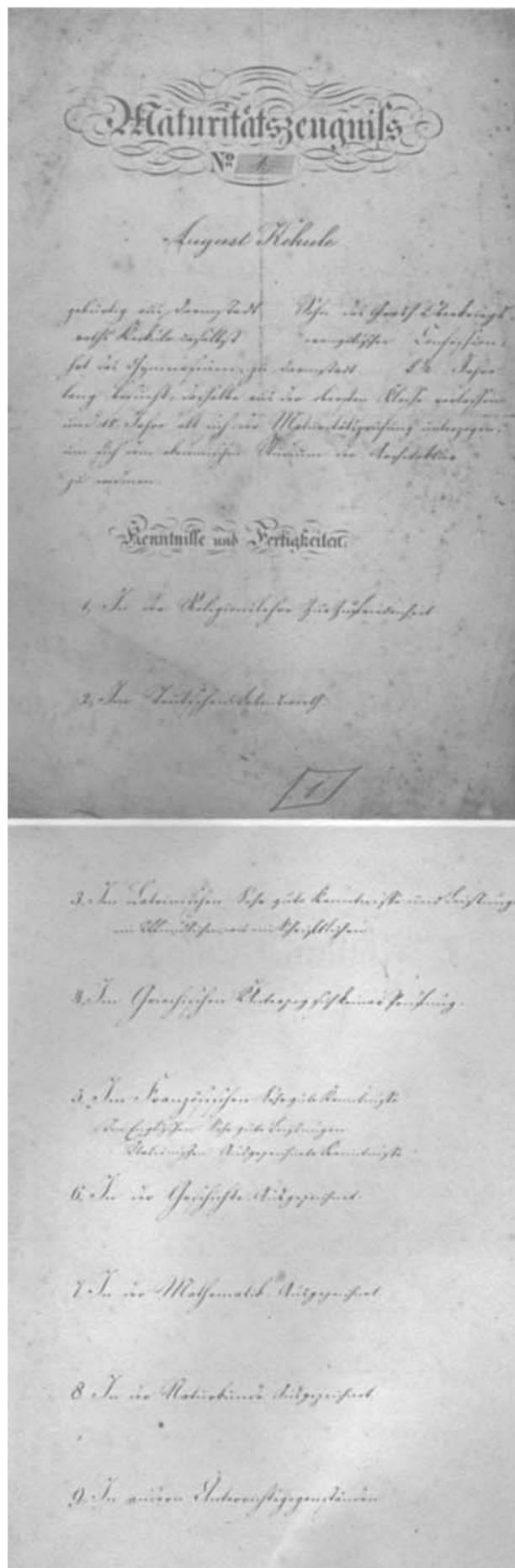


Fig. 6. *Kekulé*’s school leaving certificate.



Fig. 7. Drawing by Kekulé at age 13.



Fig. 8. Drawing by Kekulé at age 18.

It was an ingenious turn of history which took the young Kekulé from his studies at Giessen to meet Charles Gerhardt (1816—1856) in Paris and Alexander William Williamson (1824—1904) in London. Both of these contacts were to prove crucial for his intellectual work.



Fig. 9. Left: Justus von Liebig ca. 1850. Right: H. Will.

When Kekulé entered the scientific arena the first steps had just been taken towards a clearer understanding of the linkage between atoms of the simplest nitrogen and oxygen compounds. The nature of hydrocarbon “radicals” was still shrouded in mystery. They appeared, as aptly stated by Jean Baptiste Dumas (1800—1884), “as planetary systems, held together by a force resembling gravitation but acting in accord with much more complicated laws”<sup>[21]</sup>. Even concepts such as atom, molecule, and equivalent were used in different ways. Confusion surrounded both the significance and the

magnitude of atomic weights, and molecular weights were not employed, although Amedeo Avogadro (1776—1856) and John Dalton (1766—1844) had already prepared the ground

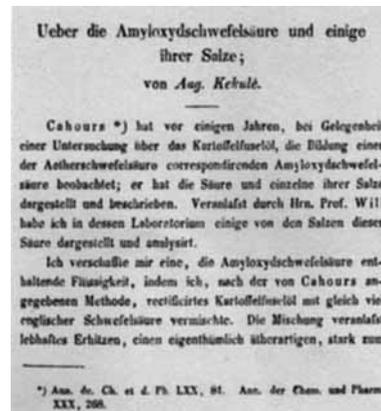


Fig. 10. Kekulé's first publication (doctoral dissertation).

for their use at the beginning of the century. Kekulé later described the situation thus<sup>[22]</sup>: “At that time a general feeling of discouragement had just overcome the most influential chemists. Because whole categories of facts could be reconciled neither with one another nor with the general theoretical views of the time, it was believed that all speculations had to be banned from chemistry and all atomistic considerations relinquished.”

A reasonable classification of the known organic compounds whose number had grown beyond comprehension was beyond the scope of the dualistic radical theory. The concept of building up chemical compounds from an electropositive and an electronegative partner was incompatible, in the realm of carbon compounds, with the feasibility of replacing electropositive elements such as hydrogen by electronegative ones such as chlorine without any great change in chemical character of a compound. Dumas and Auguste Laurent (1807—1853) attempted to explain these findings in terms of their unitary substitution theory, freed from the constraints of “dipolarity”; this theory provided preparative chemistry with fruitful stimulation but failed to supply a key to the understanding of the structure of carbon compounds. The “radicals” associated with an electric charge were replaced by “types” or “nuclei” susceptible to both substitution and addition. The desire for some kind of understanding of the complex phenomena, even if only in formal terms, prompted Gerhardt to propose his theory of types, which was a comprehensive classification destined to assume an intermediary role between the radical and substitution theory and the theory of valency soon to be developed by Kekulé. From a formal point of view, a satisfactory relationship was seen to exist in the case of simple substances by assigning a key role to simple parent compounds, *i. e.* “types” such as water or ammonia, in which hydrogen is replaced by various groups, *e. g.* of carbon compounds. However, an understanding of more complicated substances required the assumption of complex units, called “paired types”, which were confusing and did not further the understanding of the mode of reaction. The sheer wealth of experimental data stood in the way of their correlation, and of a systematic overall classification.



Fig. 11. From left to right: J. B. Dumas, A. Wurtz, C. Gerhardt.

This was the time of *Kekulé's* sojourn in Paris, then the stronghold of chemistry, and his meeting with *Dumas* and *Adolphe Wurtz* (1817—1884), the discoverer of the amines<sup>[23]</sup>, which were so important for further development of theoretical concepts. Above all, however, a bond of friendship grew out of the innumerable discussions he had with the highly intellectual and quickwitted theoretician *Gerhardt*. The combination of *Gerhardt's* principle of classification with the results of chemical reactions, paying due attention to *Avogadro's* law and the concepts of equivalent and atomic and molecular weight, paved *Kekulé's* way to his structural theory. Gifted with a vivid imagination which strove for visualization, with a critical intellect, and with an unusual memory, *Kekulé* could not have been better equipped to absorb all the available facts of his science and to collate them from a fresh angle. An interlude lasting one and a half years as private assistant to *Adolf von Planta* (1820—1895), another former student of *Liebig*, at Reichenau Castle near Chur gave him sufficient opportunity for contemplation to digest the multitude of impressions and stimulation gained in Paris<sup>[24]</sup>.

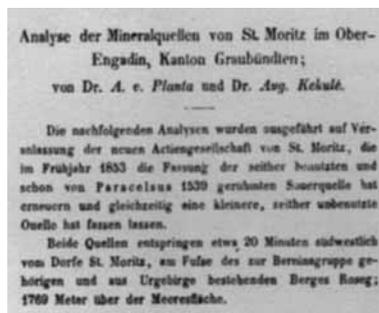


Fig. 12. One of *Kekulé's* publications on work performed in Switzerland [24].

During a subsequent year of comparable importance for his life's work spent with *John Stenhouse* (1809—1880) in London he made the acquaintance of *Williamson*, who had just obtained further confirmation of the theory of types with his synthesis of ether<sup>[25]</sup>; he modified the theory by placing greater emphasis on atomic weights. While in London, *Kekulé* also met *Edward Frankland* (1825—1899), the discoverer of the first organometallic compounds<sup>[26]</sup> which underscored the significance of the concept of valency, and *William Odling* (1829—1921), a gifted young theoretician.

"Originally a scholar of *Liebig*", remarked *Kekulé* not without pride on a later occasion, "I became a scholar of *Dumas*, *Gerhardt*, and *Williamson*; I no longer belonged to any one school"<sup>[27]</sup>. In the course of his own experimental work

"on a series of sulfur-containing organic acids"<sup>[28]</sup> and joint intellectual studies with *Williamson* the concept of the theory of valency took on shape. The parent "types" water and ammonia were supplemented by hydrogen sulfide<sup>[29]</sup> and ultimately by marsh gas<sup>[30]</sup>, *i. e.* methane.



Fig. 13. From left to right: A. W. Williamson, E. Frankland, W. Odling.

In the winter of 1856, the 27-year-old *Kekulé* went to Heidelberg to work under *Robert Wilhelm Bunsen* (1811—1899) as Privatdozent. A confined apartment which he had to rent for himself became his work-place, with the kitchen serving as laboratory for experiments on mercury fulminate<sup>[30]</sup> and

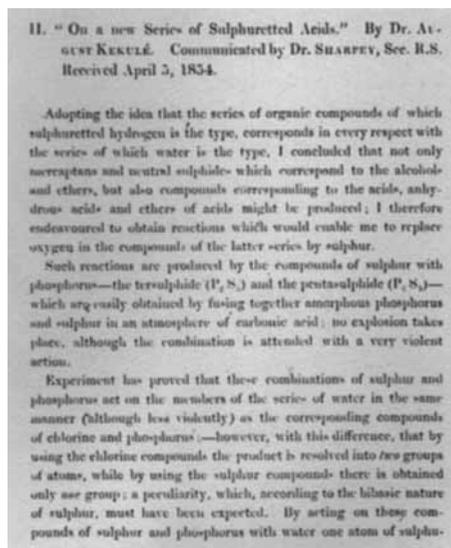


Fig. 14. Publication of *Kekulé* at the age of 25 during his sojourn in England [28].

cacodyl compounds<sup>[31]</sup>; cleaning of the room used as lecture hall was the duty of the young Privatdozent. He soon gathered a large following of enthusiastic friends and students,



Fig. 15. Left: *August Kekulé* 1857. Right: *R. W. Bunsen*.

including *Emil Erlenmeyer* (1825—1909), *Hans Landolt* (1831—1910), *Lothar Meyer* (1830—1895), as well as *Friedrich Conrad Beilstein* (1838—1906) and *Adolf Baeyer* (1835—1917), who later reported: “In a theoretical context, a

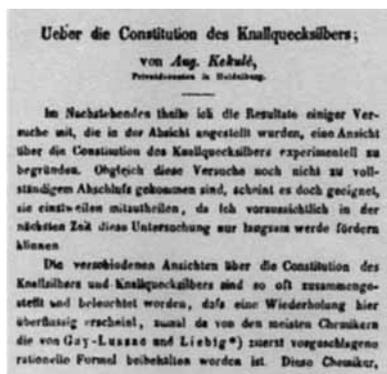


Fig. 16. *Kekulé's* studies on mercury(II) fulminate  $\text{Hg}(\text{OCN})_2$  [30].

new world opened up to me in his lectures and in personal contact with him. Young chemists cannot gain an adequate idea from the literature of the influence exerted by the young *Kekulé* on his contemporaries. His textbook, in which he was frequently unfaithful to his own views, gives but an incomplete picture. His lectures were completely different. Captivated by the logical consistency of the new theory which was later known as structural theory, he constructed, before his enthusiastic listeners, the edifice of theoretical chemistry in which we still reside today<sup>[32]</sup>.



Fig. 17. From left to right: *E. Erlenmeyer*, *H. Landolt*, *F. C. Beilstein*, *A. Baeyer*.

For *Kekulé* the years spent in Heidelberg were a time of scientific maturation and the acquisition of complete independence. He developed his creative activity from the interaction between intuition and critical intellect. After the discovery of the methane type and of numerous other “radicals” derived therefrom, as well as the further development of the “mixed and double types” suggested by *Williamson* on the basis of the existence of dibasic acids, and the recognition of the significance of “atomicity”, *i.e.* the valency of the elements themselves, the final step was taken with the discovery of the tetravalency of carbon and of its ability to join to itself. After years of hesitation, reconsideration, and repeated critical examination, he reported, in two papers published in 1857 and 1858<sup>[33,34]</sup>, his brilliant and at the time daring ideas which were to bring about such a dramatic turn of events, perhaps the most decisive in the whole history of chemistry. The break with the old classification of chemical compounds was complete.

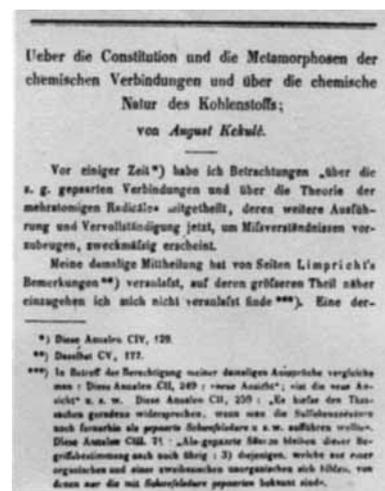


Fig. 18. Title page of *Kekulé's* famous publication on the theory of valency [34].

*Kekulé* wrote<sup>[34]</sup>: “I consider it necessary and, at the present state of chemical knowledge, feasible in many cases to go back to the elements themselves which make up a compound in explaining the properties of chemical compounds. I no longer consider it the primary task of our time to detect groups of atoms which can be regarded as radicals owing to certain properties and thus to ascribe the compounds to various types which have hardly any significance other than that of a typical formula. I rather believe that one should also extend the consideration to include the constitution of the radicals themselves, determine the relationship of the radicals with one another, and derive the nature of the radicals and that of their compounds from the nature of the elements. The considerations of the nature of the elements and of the basicity of atoms formerly compiled by myself are the starting point. The simplest combinations of the elements, as they are caused by the unequal basicity, are the simplest types. The compounds can be ascribed to certain types so long as the compound is attacked, during the reaction under consideration, in such a way that it shows the reaction characteristic of the type. I call that group a radical which is not attacked in the reaction concerned, and about whose composition one therefore need not concern oneself for the moment.”

No sooner had *Baeyer*—still under the influence of *Bunsen*—attempted to establish the difference between methyl chloride and chloromethane<sup>[35]</sup>, than *Kekulé* postulated the equivalence of the four hydrogen atoms of methane. He recognized that the endless variety of the carbon compounds is attributable to the ability of carbon to form single and multiple bonds with itself and other elements. He was the first to propose “rational formulae” for many of the more simple organic compounds. The theory of valency became the first classifying principle of far-reaching validity for the whole of chemistry. Time was ripe for publication of the new theory; the basic ideas were, so to speak, in the air after years of public discussion. Only a few months later, a treatise was published by the Scotsman *Archibald Scott Couper* (1831—1892) who was working with *Wurtz* at Paris but who was condemned all too soon to inactivity by illness, which likewise recognized the tetravalency of carbon and assumed the existence of carbon chains<sup>[36]</sup>. *Couper* was the first to symbolize

bonds in a manner resembling subsequent convention, *viz.* by dotted lines. In contrast, Kekulé initially continued to use “rational formulae”, which—as he said—were intended only as “reaction but not constitutional formulae”<sup>[37]</sup> and in which the symbol for the element merely expressed the magnitude of the valency. They were jokingly called “sausages” by *Otto Nikolaus Witt* (1853—1915)<sup>[38]</sup>, and “bread rolls” by the everbellicose *Hermann Kolbe* (1818—1884)<sup>[39]</sup>. *Alexander Michailowitsch Butlerow* (1846—1886), on the other hand, already considered it feasible to describe unequivocally the structure of a molecule<sup>[40]</sup>.



Fig. 19. Left: A. S. Couper. Right: A. M. Butlerow.

This idea was also to gain *Kekulé's* acceptance; he ultimately adopted the simpler formula notation of *Alexander Crum Brown* (1838—1922)<sup>[41]</sup>, *Wurtz*<sup>[42]</sup>, and *Hofmann*<sup>[43]</sup>. Meanwhile appointed professor of chemistry at the University of Ghent<sup>[44]</sup>, he devoted his energy to the extension of structural theory, as is impressively documented in his four-volume textbook<sup>[45]</sup>, which remained unfinished, and continued to exert a strong influence on his contemporaries.

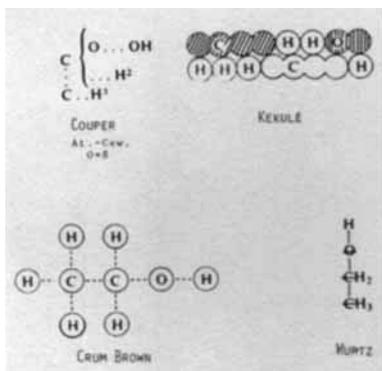


Fig. 20. Development of the notation of chemical formulae as illustrated for ethanol.

Various passages in *Kekulé's* publications and particularly his lecture “Über die Constitution der Salze”<sup>[46]</sup> presented to the “Naturforschertagung” held at Innsbruck in 1869 bear witness to his early concepts of the three-dimensional arrangement of atoms. In 1867 he wrote in his important treatise “Über die Constitution des Mesitylens”<sup>[47]</sup>: “This imperfection”—of the older models—“can be avoided if the four relationship units of carbon instead of being located in a plane are allowed to project from the sphere of the atom in the direction of hexahedral axes such that they terminate in tetrahedral planes.” He thus transferred the realm of the chemical bond out of the plane into three-dimensional space.

All that his student *Jacobus Henricus van't Hoff* (1852—1911) was to add to this idea seven years later was actually already present in *Kekulé's* models. The 22-year-old *van't Hoff*<sup>[48]</sup> and the 27-year-old *Joseph Achille LeBel* (1847—1930)<sup>[49]</sup> however drew the ultimate consequences from the discoveries of *Jean-Baptiste Biot* (1774—1862)<sup>[50]</sup> and *Louis Pasteur* (1822—1895)<sup>[51]</sup> and thus laid the foundation of stereochemistry which has lost none of its topicality to this day<sup>[52]</sup>. A logical development took place from *Kekulé's* structural chemistry and *van't Hoff* and *LeBel's* hypothesis via *Baeyer's* strain theory<sup>[53]</sup> and the geometrical isomerism of *Johannes Wislicenus* (1835—1902)<sup>[54]</sup> to *Emil Fischer's* (1852—1919) studies on relative configuration<sup>[55]</sup>, and thence via the isomerism of nitrogen compounds observed by *Arthur Hantzsch* (1857—1935)<sup>[56]</sup> and the coordination chemistry of *Alfred Werner* (1866—1919)<sup>[57]</sup>, the steric hindrance of chemical reactions<sup>[58]</sup> discovered by *Victor Meyer*<sup>[59]</sup> (1848—1897), the Walden inversion [*Paul Walden* (1863—1957)], and the Sachse-Mohr theory<sup>[60]</sup> [*H. Sachse, Ernst Mohr* (1873—1926)] up to the study of conformation as introduced by *N Kenneth S. Pitzer* (born 1914)<sup>[61]</sup>, *Odd Hassel* (born 1897)<sup>[62]</sup>, and



Fig. 21. From left to right: J. H. van't Hoff, J. A. LeBel, J. Wislicenus, E. Fischer.

above all *Sir Derek H. R. Barton* (born 1918)<sup>[63]</sup>. Experimental proof of the validity of the tetrahedral model was provided by X-ray structure analysis as performed by *Sir William Henry Bragg* (1862—1942) and *Sir William Lawrence Bragg* (1890—1971)<sup>[64]</sup>; the theoretical foundation was laid by *Linus Pauling* (born 1901)<sup>[65]</sup> and *Erich Hückel* (born 1896)<sup>[66]</sup> with the aid of quantum chemistry.

Structural chemistry provided a basis for the explanation of the composition and mode of reaction of aliphatic compounds, not least after clear conventions had been agreed upon concerning the terms atom, molecule, equivalent, *etc.*, at the first international congress on chemistry at Karlsruhe in 1860<sup>[67]</sup> instigated by *Kekulé*, and thanks mainly to *Stanislao Cannizzaro's* (1826—1910) convincing statements concerning *Avogadro's* law and the significance of atomic weights for chemical formulae. However, the large class of aromatic compounds still defied understanding, in spite of *Peter Griess's* (1829—1888) discovery of diazonium salts<sup>[68]</sup> and *Kolbe's* synthesis of salicylic acid<sup>[69]</sup>, as well as that of the first organic dyestuff mauvine<sup>[70]</sup>, whose color resembles that of the mallow flower, by *William Henry Perkins* (1838—1907) in 1856.

Once more *Kekulé's* efforts were crowned with success. His irrepressible striving for visual clarity and his exceptionally powerful imagination were again instrumental in this achievement. Derivation of the formula of benzene is basically a logical consequence of his structural theory—an ob-

vious step when viewed from the vantage point of present-day knowledge but a great leap more than a century ago, comparable perhaps with the intellectual effort once required for man to replace the sled by the wheel. Appreciation of the fact that carbon compounds could have cyclic



Fig. 22. Left: S. Cannizzaro. Right: A. W. von Hofmann.

structures was withheld from the chemists of that epoch. The circle was the symbol for the indivisible, the atom. August Wilhelm von Hofmann (1818—1892) remarked on a later occasion “I would forfeit all my discoveries for that thought of Kekulé’s”<sup>[71]</sup>.

In his paper “Sur la Constitution des Substances Aromatiques”<sup>[72]</sup> submitted to the Paris Academy in 1865, once again after several years of deliberation and examination, and in the following contribution to Liebig’s *Annalen* entitled “Untersuchungen über aromatische Verbindungen”<sup>[73]</sup> he refined his theory of the structure of benzene, *inter alia*, with the

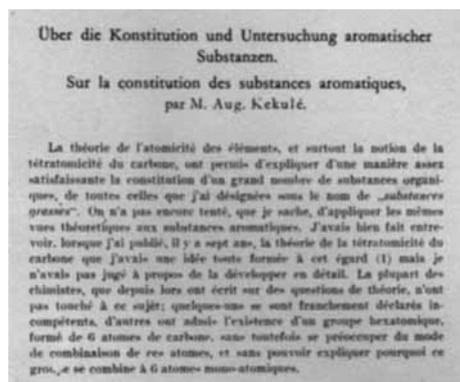


Fig. 23. Titel page of Kekulé's first publication on the structure of benzene [72].

striking sentence “These facts apparently justify the conclusion that in all aromatic substances one and the same atomic group, or, if one will, a common nucleus is present which is made up of six carbon atoms.” This idea was also present in considerations of Joseph Loschmidt (1821—1895)<sup>[74]</sup> although he had no clear idea of the structure of this nucleus.

Even Kekulé's first publications on benzene contain the symmetrical hexagonal formula and mention the equivalence of the six hydrogen atoms. Not long afterwards he and his students Wilhelm Körner (1839—1925)<sup>[75]</sup> and Albert Ladenburg (1842—1911)<sup>[76]</sup> were able to substantiate this idea experimentally. Kekulé supplemented his static concept of bonding by introduction of the hypothesis of oscillation<sup>[77]</sup>.

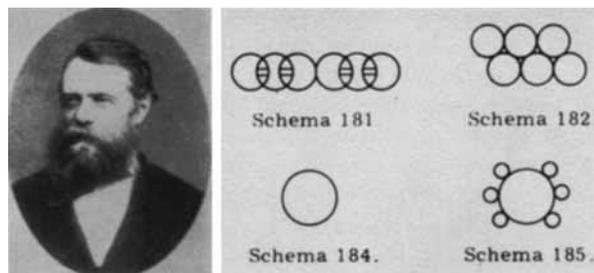


Fig. 24. Left: J. Loschmidt. Right: Loschmidt's benzene formulae.

The discovery of the benzene formula was recounted in all developed countries 100 years later—14 years ago—and the significance of a theory which has retained its full validity for more than a century and the consequences of this theory were emphasized by qualified commentators<sup>[15]</sup>. Kekulé's proposed structure of benzene also initiated a development



Fig. 25. Left: W. Körner. Right: A. Ladenburg.

that has continued to this day, and which has been especially promoted by quantum mechanics which provides all the necessary requirements for a “mechanical approach”<sup>[78]</sup> to

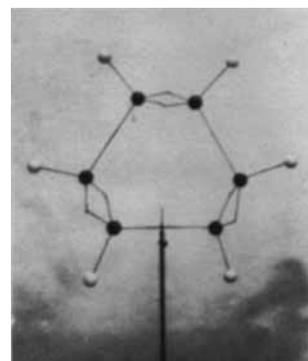


Fig. 26. Kekulé's benzene model of 1866 (original).

chemistry as already demanded by Kekulé. It acquired a new dimension in Erich Hückel's theory of cyclic  $\pi$ -electron systems<sup>[79]</sup>.

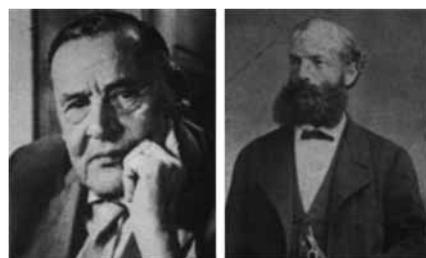


Fig. 27. Left: E. Hückel. Right: August Kekulé 1867.

After nine years of restless activity at Ghent, which made *Kekulé* the reformer of organic chemistry, he accepted a call to Bonn<sup>[80]</sup> in 1867. This was the last stage in the career of this truly European scholar and teacher whose years of international travel as apprentice and scientist call for emulation on the part of the younger generation, more urgently than ever before!

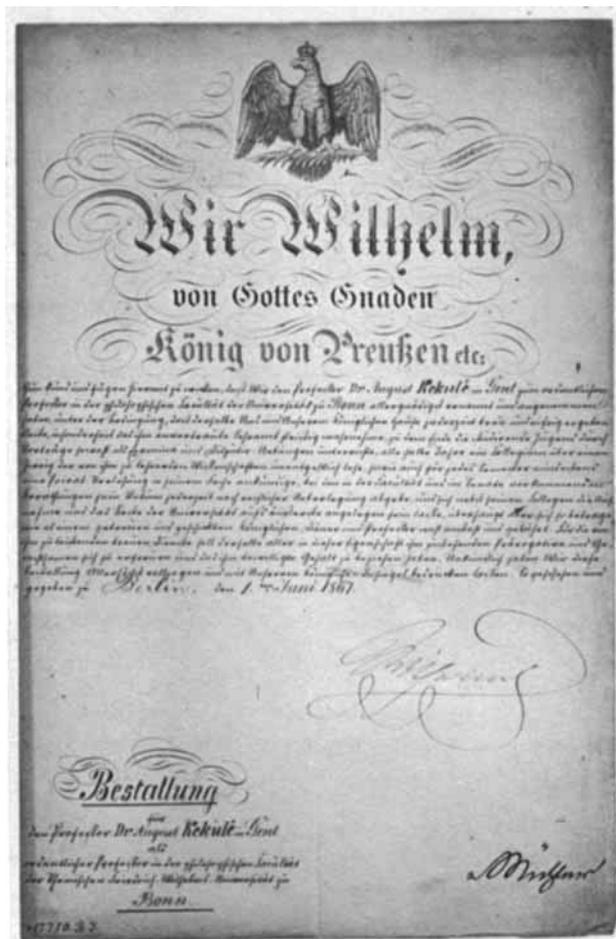


Fig. 28. *Kekulé's* certificate of appointment at Bonn (bearing the signature of *Wilhelm I*) [80].

The three decades left to him were mainly devoted to further testing and confirmation of the benzene theory. Together with numerous students, including *Theodor Zincke* (1843—1928), *Ludwig Claisen* (1851—1930), and *Julius Bredt* (1855—1937), as well as *Richard Anschütz* (1847—1937) and *Otto Wallach* (1847—1931), many of whom were to become pioneers of chemistry in the closing 19th and early 20th century, he refuted other views and structural proposals of his colleagues by pointing out errors and false conclusions<sup>[81]</sup>. His sole motivation was the quest for knowledge of the true scientist, far removed from all striving after technical perfection and immediate utility. Views such as that propounded by his adversary *Kolbe*, “It is not so much a matter of explaining everything but of how things are interpreted”<sup>[82]</sup> contradicted the critical intellect of the seeker after truth<sup>[83]</sup>.

During the years spent at Bonn, *Kekulé* saw the dramatic effect of his ideas on the expanding chemical industry. He was awarded the highest honors<sup>[84]</sup>. His benzene theory had made possible the directed synthesis of dyestuffs, initiated



Fig. 29. Above, from left to right: *H. Kolbe*, *Th. Zincke*, *L. Claisen*. Below: *J. Bredt*, *R. Anschütz*, *O. Wallach*.

the rise of the entire organic chemical industry—especially coal tar chemistry—and had an enduring stimulating effect on the imagination of chemists. Industry and chemical science drew closer together and adopted a symbiotic relationship<sup>[85]</sup>. This is compelling confirmation of the known fact that fundamental research, however abstract or “unpractical” its aims may appear, is indispensable and can crucially influence the development of technology sooner or later. “The depths of knowledge are never explored by him who seeks profit but by him who, motivated by a vital urge for inquiry, deploys his entire personality”. Research is not just a matter for civil servants, neither does it thrive under the direction of bureaucracy and ideologies or the requirement of “relevance” of science. *Kekulé's* fruitful work demonstrates convincingly that highly qualified fundamental research can be neither planned nor forced and can only rarely be assessed according to its immediate utility. This is a timely warning for the state and university administrations to reinstate research to its central position in universities and to give preferential consideration to conditions necessary for the development of the personalities required for such work rather than to formal aspects and matters of university politics.

In his famous, psychologically interesting address to the “Benzene Festival” of the German Chemical Society at Berlin in 1890<sup>[86]</sup> celebrated on the 25th anniversary of the benzene formula—probably one of the most ostentatious conferences ever held by a learned society—*Kekulé* himself contributed to the legends associated with his person. His great achievements will hardly have come to him merely in a dream on a London bus<sup>[87]</sup> or by his fireplace in Ghent<sup>[88]</sup>. Rather, they were the fruit of decades of hard work by day and often by night, loyal to the advice of his teacher *Liebig* “... whoever fails to ruin his health by study will not make his way in chemistry today”<sup>[89]</sup>, or as expressed by *Max von Pettenkofer* (1818—1901): “The man who wishes to be superior to an animal must be prepared to sacrifice life and health for higher things”<sup>[90]</sup>. This condition is certainly not so rigorous in today's laboratories, but utter commitment and renunciation for the sake of increasing knowledge are still

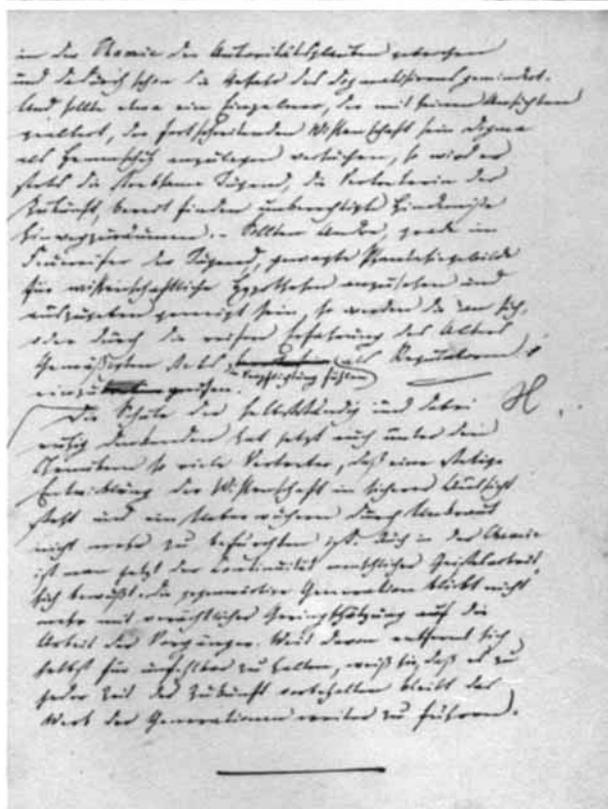
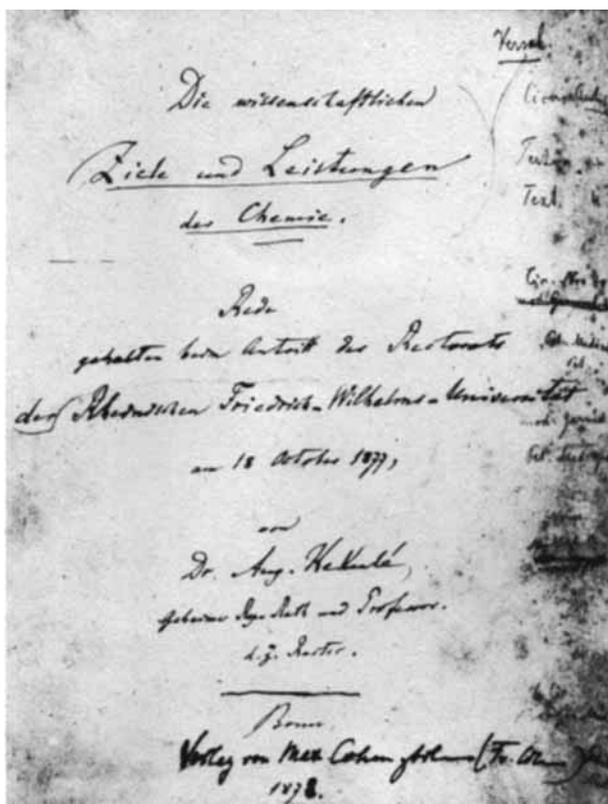


Fig. 30. Handwritten title page and last page of manuscript of Kekulé's speech as University Chancellor in 1877 [14].

just as essential. Above all, however, we see Kekulé, the architect of chemistry, as an ideal researcher by virtue of his rare combination of daring and caution, his pronounced critical powers (also with regard to himself), his polite reserved-

ness, always avoiding aggressive irony, conflicts, and polemics, in particular his great modesty which grew out of the recognition that all his ideas and practical work were only the extension of the achievements of his predecessors and teachers. That inner greatness which creates modesty moved him to say: "Something completely new has never been thought of, certainly not in chemistry"<sup>[19]</sup>. The warning and encouragement of the closing lines of his important speech as University Chancellor in 1877<sup>[22]</sup> still appear valid a century later: "As in all areas of knowledge in chemistry, too, faith in authority has been broken and the danger of dogmatization thus reduced. Should an individual who has aged with his ideas attempt to apply his dogma as a brake to an advancing science, he will always find zealous youth, as representative of the future, ready to clear away unjustified obstacles. Should others, in the ardor of youth, be inclined to regard and propound bold flights of fancy as scientific hypotheses, then those who are more moderate by nature or through the maturing experience of age will always feel obliged to intervene as regulators."

The school of independently and calmly reasoning people has now gained so many representatives among chemists that a constant development of this science is ensured and a takeover by weeds need no longer be feared. In chemistry too, the continuity of human intellectual work is recognized; the present generation no longer looks upon the work of its predecessors with scornful contempt; far removed from considering itself infallible, it knows that at any time it is the prerogative of the future to continue the work of generations."

July 13, 1896, was the last day in the life of this giant among men, who was privileged to know that his theories never led anybody astray but instead opened the way for innumerable discoveries.

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- [83] See "Cassirer Kapitel aus der Abhandlung: Ueber die Carboxylartronsäure und die Constitution des Benzols". At the advice of *Volhard*, *Kekulé* did not publish them. A facsimile reprint of the unpublished manuscript [14] of August 12, 1883, was published by Verlag Chemie, Weinheim, in 1965.
- [84] *A. Kekulé* was a member of most of the European Academies. In addition to other honors, he was awarded the Copley medal in 1885, the Huyghens medal in 1889, and the "Kronenorden II. Klasse" and the Bavarian "Maximilian-Orden für Kunst und Wissenschaft" in 1890. He was nominated as voting "Ritter des Ordens pour le mérite für Wissenschaft und Künste" in 1893 by *Wilhelm II* of Prussia.
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- [88] Concerning the enunciation of the benzene formula, *Kekulé* said, in the same speech (cf. [86], p. 1306): "It was a similar matter with the benzene theory. During my time at Ghent in Belgium, I lived in elegant bachelors' rooms in the main street. However, my study looked onto a dark side-alley and was without light during the day. That was no disadvantage for a chemist who spends the daylight hours in the laboratory. There I sat and wrote for my textbook; but things did not go well; my mind was occupied with other matters. I turned the chair towards the fireplace and began to doze. Once again the atoms danced before my eyes. This time smaller groups modestly remained in the background. My mental eye, sharpened by repeated apparitions of similar kind, now distinguished larger units of various shapes. Long rows, frequently joined more densely; everything in motion, twisting and turning like snakes. And behold, what was that? One of the snakes caught hold of its own tail and mockingly whirled round before my eyes. I awoke, as if by lightning; this time, too, I spent the rest of the night working out the consequences of this hypothesis".
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