12. Impact of the Dutch School

12.1 *Overview.*

There are many and diverse paths leading from the studies of fluid mixture phase separation and fluid criticality of the Dutch School at the turn of the 19th century to present-day science and technology. Some are quite direct and obvious, others are more tortuous and diffuse. Some paths were major excursions: they crossed geographical boundaries, and at their far end, a new scientific endeavor began. Some never evolved, or were forgotten. A new path was created later, and only afterwards it was found to have existed much earlier. From what was initially a strictly scientific enterprise, the emphasis shifted to engineering applications, but the century-old roots of the modern disciplines are still recognizable and traceable.

The effect of Van der Waals's work on molecular science in the 20th century was direct and fundamental, as is well recognized and extremely well documented, due in large part to books by Rowlinson (1988), and by Kipnis *et al.* (1996). This chapter summarizes the achievements of the Dutch School highlighted in previous chapters, as well as insights lost and rediscovered latter. Then, it sketches connections perhaps less known. Three of these have been chosen. First, the history of fluid property and phase equilibrium studies in the Netherlands passes review, including the bifurcation of phase equilibrium and fluid property studies that occurred early in the 20th century. Secondly, we show the impact of the Dutch School on physical chemistry, geology and metallurgy in Russia. Finally, we recall the debt owed to the Dutch School by the 20th-century chemical process industry.

12.2 *Lasting intellectual contributions*

By introducing parameters characterizing molecular size and attraction in constructing his equation of state, Van der Waals set the tone for molecular physics of the 20th century. That molecular aspects such as size, shape, attraction, and multipolar interactions should form the basis for mathematical formulations of the thermodynamic and transport properties of fluids is presently considered an axiom. The Van der Waals forces between molecules, much weaker than chemical bonds but present universally, play a fundamental role in condensed-matter science and in surface science. Elucidation of the nature of the Van der Waals forces between molecules has remained a scientific effort from Van der Waals's days to the present.

The law of corresponding states, first derived by Van der Waals from his equation of state and generalized by Kamerlingh Onnes, was a key concept of lasting significance. This law is still the method of choice for estimating properties of poorly characterized compounds within families of related substances.

The ability of the equation of state to qualitatively describe phase separation in fluid mixtures is another major and lasting achievement. The cubic character simplifies these calculations. This is why, notwithstanding the enormous advances in computer technology, cubic equations retain their niche in the modeling of chemical processes. The virtues of cubic equations for calculation of phase equilibria of multicomponent fluid mixtures are so great that efforts to improve them have lasted through the 20th century. In a sense, the cubic equations are the first and the last word in global phase equilibrium calculations. Any refining of the equation of state due to increased knowledge of intermolecular forces leads to greater complexity. This diminishes the ability to explore the phase behavior fully and may produce phase diagrams not present in real fluid mixtures. There is, as yet, no match for this achievement of the Dutch School a century ago.

The mean-field assumption, another fundamental contribution by Van der Waals, has turned out to be a mixed blessing. Its strength is the major simplification of the conceptual and computational work. For the application to global phase diagram calculations, there is no substitute for the mean-field approach, which is still the method of choice for a first exploration of any theoretical model in statistical mechanics. This method fails, however, when fluctuations become important. The method does not work, for instance, in fluid mixtures of very different molecular attraction and size, in which the surroundings of a chosen molecule differ considerably from the bulk concentration. Chemists and chemical engineers have developed approximations to account for local-composition variation while retaining the character of analyticity of the equation of state.

The neglect of large-scale fluctuations existing near critical points because of the large compressibility of the fluid cannot be repaired this way. Van der Waals and Verschaffelt noted the failure of the Van der Waals equation near the critical point a century ago, and Verschaffelt knew this failure was a general feature of analytic equations of state. It was only in the second half of the 20th century that the critical fluctuations were quantitatively studied, and limited-range scaled fundamental equations, accurately fitting fluid data near the critical point, where proposed to replace those based on the mean-field theory. Crossover theory offers means to repair existing mean-field equations near the critical point. However, an equation of state valid over large ranges of fluid phase behavior, which is accurate in region where fluctuations are large, and which is capable of predicting realistic fluid mixture phase behavior, is still a distant goal.

12.3 *Knowledge lost and rediscovered*

12.3.1 *Important insights that were forgotten*. Much, but not all, of the mathematician Korteweg's work on plaits and plait points was lost and gradually rediscovered. His insight in the origin and development of plaits on analytic surfaces, including the unstable regions, was qualitatively familiar to Van der Waals as well as to Dutch chemists such as Scheffer, who show plots of accessory plait formation in their papers. The Taylor expansion of the Helmholtz energy near critical points (plait points) of pure fluids and fluid mixtures were familiar to the Dutch School, and the criticality conditions formulated by Korteweg for fluid mixtures made it into the modern literature. This was primarily due to Rowlinson's influential book on liquids and liquid mixtures (1958). Physicists in general, and Soviet physicists in particular (see Ch. 12.5), however, were unaware of Korteweg's work. Taylor expansions near critical points, the basis for renormalization-group calculations that incorporate the effect of fluctuations, are universally credited to Landau (1937).

Van der Waals's equation of state lost its luster at an early stage as its many deficiencies and inaccuracies became apparent. By the middle of the 20th century it was considered useless beyond the confines of a freshmen physical chemistry class. The work by Van Konynenburg and Scott (1980) on the global phase diagram of Van der Waals mixtures, however, proved how much valuable qualitative insight can be obtained from this equation. Rowlinson's (1988) translation of Van der Waals's thesis, preceded by an extensive discussion of the impact of this work, has led to a renewed appreciation by the scientific community. Van der Waals's definition of critical exponents for mean-field theory, along with Verschaffelt's discovery of nonclassical critical exponents, was a concept lost and not rediscovered until half a century later.

Van der Waals's fourth major achievement is his theory of capillarity of 1894. Though not discussed in this book, it is another example of historic amnesia. Only after Cahn and Hilliard (1958) completed their influential work on the free energy of nonuniform systems (in which they *did* cite Van der Waals's (1894) value of the experimental surface tension critical exponent) did they discover that Van der Waals had developed the theory of capillarity based on a continuous density profile through the interface more than sixty years earlier.

One wonders what caused this loss of valuable knowledge. There are probably many contributing factors. What presently seems highly significant may not have appeared that way at the time it was first discovered, or was overshadowed by developments considered more important or exciting.

12.3.2 *Language barriers*. Speakers and writers of Dutch are for the most part limited to the native Dutch, Flemish and South-African populations. Due to the foreign-language proficiency of the educated Dutch, however, this should not have been a major impediment to dissemination of the work of the Dutch School. Very few of the relevant papers are available exclusively in the native language. It is very common to find several versions of a paper of the Dutch School in one or more of the foreign languages: German, French and English. The practice of publishing in English took a firm hold in the Netherlands as early as 1900. Before that time, Academy Proceedings appeared in Dutch, while German was the language of preference for publications following these presentations. Kamerlingh Onnes, however, was far ahead of his time, by publishing the Leiden Communications in English from the very beginning.

Korteweg, on the other hand, published his two substantial papers on plaits in the French-language Archives néerlandaises. Only one of these was also published in the German-language proceedings of the Academy of Vienna. Van Laar published part of his work on the geometric-mean Van der Waals model in French in Archives du Musée Teyler. History just might have taken a different course had Van der Waals published his four major works in English instead of German.

12.3.3 *Other impediments to dissemination*. Korteweg the mathematician, even though highly focused on applications and held in high esteem, may have been somewhat of an outsider. The very limited referencing by other members of the Dutch School did not work in his favor. The Leiden colleagues apparently preferred to go by the far less explicit but more accessible results in the appendix of Van der Waals's 1890 paper on mixtures. The esoteric qualities of the Van der Waals symmetric mixture may have been a strike against Korteweg. As we saw in Ch. 7.5.10, Korteweg's model was re-explored in the second half of the 20th century by Meijering (1951), Straley and Fisher (1973), Das and Griffiths (1979) and others in the context of phase separation in three-component liquids or solids and the three-state Potts model. Only Meijering, however, cites Korteweg's work.

Van Laar's work on fluid phase equilibria remains mostly unread. The reasons are obvious to those who have tried. Van Laar, an educated man with strong interest in literary endeavors, did not know how to bring his points across effectively, and significant results drowned in an ocean of formulae. Van Konynenburg and Scott (1980) recognized his contributions to the global phase equilibrium calculations of the geometric-mean Van der Waals equation for mixtures. Meijer *et al.* (1989, 1993), however, were the first to note that Van Laar had actually performed exact calculations for this case.

Van Laar's work did find a place in chemistry. Van Emmerik (1991) discusses his equation for the heat of mixing based on the geometric-mean rule. Hildebrand used and modified it as input to the influential theory of regular solutions. As a consequence of his feud with Van 't Hoff and the osmotic school, Van Laar was the first to introduce what are currently called activity coefficients for non-ideal solutions.

12.3.4 *The new physics.* By the end of the 19th century modern physics was borne. The discovery of radioactivity broke open the indivisible atom of Demokritus, and directed the focus onto the atomic nucleus. Spectroscopy presented electromagnetic and atomic theory with the challenge to explain the spectral lines, characterizing the different elements, in terms of electrons orbiting the nucleus. Early notions of quantization of energy were to blossom into the new discipline of quantum mechanics. The liquefaction of helium opened the field of cryogenics. Superconductivity and superfluidity were discovered and studied intensively. With so much energy and intensity devoted to the new fields of science, interests in phase behavior of fluid mixtures slipped into the background, out of the focus of physicists.

12.4 *Heritage of Van der Waals and Kamerlingh Onnes in the Netherlands*

The universities of Leiden and Amsterdam were the centers of study of fluid phase behavior around 1900. In the Leiden physics department, Kamerlingh Onnes held the reins. Fluid mixture phase equilibria were a topic of active interest, with the liquefaction of helium marking the end of this period. The mysterious properties of the coldest liquid on earth, and the many new research opportunities offered by the then-ultimate cryogenic coolant, set new directions for the laboratory. Nevertheless, some members of the staff, supplemented by visitors such as Mathias, continued work on P-V-T properties of fluids until the 1920s. They worked mostly on one-component cryogenic fluids such as argon, and the work no longer had the novelty and vibrancy prevalent in the days of Kuenen and the early Keesom. After the Second World War, however, fine experimental work on the molecular physics of fluids, in particular the effect of magnetic fields on transport properties of molecular fluids, was carried out in Jan Beenakker's group.

In Amsterdam around 1900, Van der Waals not only was involved in his theoretical work on fluid mixtures, but also ran a modest-scale laboratory in the Physics Department, where he studied fluid phase equilibria in mixtures at elevated pressures. In 1898, at the occasion of the 25th anniversary of his doctorate, Van der Waals's friends established a fund allowing him to expand his laboratory. Van der Waals decided to use this opportunity to extend the pressure range. Up to that time, experimental pressures in the Amsterdam and Leiden laboratories were limited by the strength of glass.

Van der Waals purchased a press and several deadweight gages in 1900. In 1911, Van der Waals retired and Philipp Kohnstamm, his closest pupil, took over his laboratory. Capabilities for *P-V* and phase equilibrium measurements were put into place. The pressure limit was set at 3000 atmospheres, following Amagat, the leading French high-pressure expert. Kohnstamm is mainly remembered for his co-authorship with Van der Waals (1912) of a two-volume text on thermodynamics. This is a compendium of Van der Waals's lecture notes on the thermodynamics of fluids and fluid mixtures. It is clearly written, in a somewhat elaborate and flowery style, and was still an obligatory text for physics and chemistry students in Amsterdam in the 1920s.

After 1915, Kohnstamm's interest took a different direction, and the laboratory was moribund by the end of the First World War. The laboratory was rescued from oblivion by Anthonius M.J.F. Michels (*1891-1969*), Kohnstamm's assistant and later his successor. He shaped the Van der Waals laboratory into a premier high-pressure institute, where the thermophysical properties of fluid were measured with unsurpassed accuracy. During that period, relatively few studies were carried out in fluid mixtures and the pressure limit remained at 3000 atmospheres. In the last part of the 20th century, however, Schouten and collaborators expanded the pressure range in a major way, and pioneered the observation of phase separation in fluid mixtures in diamond anvil pressure cells, work that was referred to in Ch. 8. For more details on the history of the Van der Waals Laboratory, see Levelt Sengers (1993, 2001).

The chemistry department in Amsterdam became a world-renown center of phase studies under the direction of Bakhuis Roozeboom, who succeeded Van 't Hoff in 1897. Van der Waals had triggered the interest in the phase rule when Bakhuis Roozeboom was still a student in Leiden. Until his death in 1907, Bakhuis Roozeboom directed an active experimental group, with the study of phase equilibria in chemically active systems including solid phases as a primary objective. He, too, carried out these studies at elevated pressures, and to rather high temperatures. Phase theory became the principal focus of the department. Van 't Hoff characterized Bakhuis Roozeboom in a memorial speech shortly after the death of this very devout man: 'To the Almighty in his [BR's] philosophy of life, corresponded the phase rule in chemistry.' See Cohen's (1913) biography of Van 't Hoff.

Bakhuis Roozeboom (1901) wrote the first two books in the series 'Heterogeneous Equilibria from the Perspective of the Phase Rule.' Over the years, his former pupils F.A.H. Schreinemakers, A.H.W. Aten and E.H. Büchner added volumes. By that time, they were all professors of chemistry. This book was highly influential. It introduced Gibbs's phase rule as a foundation for disciplines such as metallurgy, mineralogy and geophysics. Schreinemakers was a professor of chemistry in Leiden, and is well known for 'Schreinemaker's rule,' which sets limits on the angles at which phase boundaries can meet in a phase diagram.

Van Laar could have been a natural mediator between the scientific interests of the physicist Van der Waals and the chemist Bakhuis Roozeboom, but Van der Waals resisted. Thus, early in the 20th century, the two groups diverged, with the chemists becoming the world's experts on phase theory including solid phases, and the Van der Waals laboratory turning to accurate property measurements at high pressures, mostly in pure fluids.

The Delft Polytechnic Institute was only a minor player in this field in the early 1900s. Notwithstanding the difference in curricula between the Polytechnic Institute and the academic institutions, however, there was always an exchange of graduate students and professors. Kamerlingh Onnes, for instance, was an assistant to physics professor Bosscha in Delft from 1878 to 1882. Korteweg began his studies at the Delft Polytechnic and then transferred to Amsterdam. The Polytechnic Institute firmly entered the field of fluid phase equilibria studies in 1917, when it appointed the chemist Scheffer as a professor of analytical and organic chemistry. Scheffer was a research assistant at Van der Waals's Laboratory, having obtained his doctorate with Bakhuis Roozeboom. Scheffer was a professor at Delft from 1917 to 1953, and created a bridge from the work of Van der Waals and Bakhuis Roozeboom to the modern age. He also aided the transfer of the purely scientific knowledge acquired in the early part of the 20th century to chemical process technology. The impact of his textbook on this topic could have been larger, had it been written in English instead of Dutch.

The textbook by the industrial chemist J. Zernike (1955) is a practical, English-language compilation of the work of the Dutch School.

The phase equilibria studies in fluid mixtures on the basis of the method of the Cailletet tube continue to the present day. The Delft group of De Swaan Arons, Peters, and De Loos has made numerous contributions to chemical process technology, in particular to the natural gas industry, polymer processing, and processing by means of supercritical solvents.

In addition to the work in these experimental groups, a high degree of expertise in statistical mechanics, kinetic theory, non-equilibrium thermodynamics and molecular physics accumulated at several of the Dutch universities and science institutes, growing naturally from the foundations laid by Van der Waals and Kamerlingh Onnes. Ornstein and Zernike's (1914) influential treatment of fluctuations was mentioned in Ch. 9. Theorists such as Ehrenfest, Kramers and Uhlenbeck in Leiden, De Boer in Amsterdam (Ch. 3.7.4), and Van Hove and Van Kampen in Utrecht, all built strong theory groups, entertaining a steady stream of foreign visitors and lecturers. De Groot and Mazur's (1962) book on nonequilibrium thermodynamics is a classic.

The chemists Kruyt and Overbeek at the University of Utrecht founded modern colloid science in the early part of the 20th century, in strong interaction with industry. Kruyt raised Casimir's interest in the role of Van der Waals forces between colloid particles, resulting in the calculation of what is presently known as the Casimir effect. Experiments by Vrij and by Lekkerkerker on solutions of colloidal particles of controlled shape and charge in the later part of the 20th century have demonstrated a variety of novel phase separations.

Koningsveld and Kleintjens at the laboratory of the Dutch State Mines pioneered the use of lattice models for modeling phase separation in polymeric fluids. Meijering at Philips Laboratories adapted Korteweg's methods to phase separation in solids. The ground prepared by the Dutch School around the turn of the 19th century has indeed proved its fertility throughout the 20th century.

12.5 *The Dutch School and physical chemistry in Russia*

Kipnis et al. (1996) describe in detail the influence of the Dutch School of fluid phase behavior on Russian scientists. Since two of the authors are Russian, their story is a treasure-trove of interesting facts not well known in the West. A summary relevant to this book follows, supplemented by additional information.

The cosmopolitan physicist A.G. Stoletov (*1839-1896*), who studied at several major universities in Germany before becoming a professor at Moscow University, taught his students about the Van der Waals equation shortly after the German translation of Van der Waals's thesis appeared in print in 1881. Famous Russian chemists D.I Mendeleev and D.P. Konovalov also studied the thesis. As early as 1886, Konovalov took a stand in favor of Van der Waals and against the view that molecules in the liquid are compounds different from those in the vapor. Konovalov became an expert on the properties of coexisting phases in liquid mixtures and a strong force in carrying over Van der Waals's ideas to Russian physical chemistry. M.P. Avenarius, a professor of physics at the University of Kiev, was the first to publish an account of critical opalescence in 1873. We encountered Golotsin (Galitzine) in Ch. 10, one of many scientists reporting experiments that disagreed with Andrews and Van der Waals's view of criticality. Stoletov was one of the first to criticize Galitzine's work. In Ch. 9, we introduced a pupil of Stoletov, D.A. Goldhammer, who, as early as 1910, formulated a corresponding-states coexistence curve equation for pure fluids with a non-classical critical exponent of 1/3.

N.M. Vittorf (*1869-1929*), an organic chemist at the Artillery Academy, spent the year 1903/04 in Göttingen, where he met Bakhuis Roozeboom. In 1909, Vittorf published a detailed account of the geometric approach to phase diagrams, as developed by Bakhuis Roozeboom, and used it to construct and classify phase diagrams of alloys. He defined nine classes, five of which had been found by Bakhuis Roozeboom. Thanks to Vittorf's translation, the series of books by Bakhuis Roozeboom and his pupils has had a major and well recognized influence on the development of metallurgy and mineralogy in Russia.

Between 1910 and 1960, the interest of physicists in phase behavior of fluids waned in Russia just as it did in the West, but physical chemists kept the tradition alive. One of these, A.V. Rakovskii (*1879-1941*) at Moscow University, edited the Russian translation of the book by Van der Waals and Kohnstamm in 1927.

Physical chemist I.R. Krichevskii (*1901-1993*), whose long life spanned most of the twentieth century, formed a key conduit between the Dutch School and the modern age. At the Institute of the Nitrogen Industry in Moscow, he built a large-scale laboratory for the study of phase equilibria under high pressure. Krichevskii was thoroughly familiar with the work of the Dutch School, and always displayed the two volumes by Van der Waals and Kohnstamm on his desk. He and his group of mostly female researchers were the first to measure gas-gas equilibrium in the strict sense, namely, above the critical temperatures of both components (Ch. 8). They also were the first to study an asymmetric tricritical point (Ch. 7.2.4). They criticized the work on the derby-hat region by Mayer and Maas (Ch. 10) and studied dilute-mixture properties near critical points (Ch. 11.3.6, 11.4.5). In the 1960s, Krichevskii hosted a seminar at his Institute attracting many external speakers and visitors.

It is well known that Russian physicists such as Landau and Voronel lead the revival of interest in fluid criticality in the Soviet Union and in the world. Curiously, the work of physical chemists and physicists had diverged to such an extent that the knowledge passed from the Dutch School to Russian physical chemists was completely unfamiliar to physicists. Thus, Landau's work on the Taylor expansion of the free energy at the critical point, mentioned above, did not build on the foundation laid by Korteweg, but was developed independently. The physics community in Moscow, very active in the field of critical phenomena, kept itself aloof from physical chemistry in general, and from Krichevskii in particular. Physicist Alexander Voronel was an exception. His discovery of the divergence of the isochoric heat capacity in argon near its critical point in 1962 (Ch. 9) brought fluid criticality back to the center of interest. Voronel was a regular participant at the seminar and fully appreciated Krichevskii's knowledge and expertise. Krichevskii, on the other hand, immediately recognized the importance of Voronel's experiment. The physical chemist Mikhail Anisimov, at that time postdoctoral researcher with Voronel and another regular at Krichevskii's seminar, helped bridge the gap separating Soviet physicists and physical chemists, and contributed to the generalization of the modern ideas on critical-point universality to fluid mixtures. Thus, by a circuitous route, the Dutch School seeded Russian physical chemistry and ultimately cross-fertilized Russian physics.

12.6 *The Dutch School and the chemical process industry*

In the Netherlands, phase equilibria studies shifted to the Delft Polytechnic Institute, and a similar change of direction took place in other countries.

In the United States, a prolonged silence followed Gibbs's pioneering work on the equilibrium of heterogeneous substances. After the First World War, however, chemical engineers and physical chemists set up the scaffolding for the modern approach to fluid phase equilibria. Lewis and Randall, in a classic textbook first published in 1923, introduced the universally adopted characterization of fluid mixtures by means of activity coefficients and partial molar properties. Between the two World Wars, studies of the properties and phase equilibria of hydrocarbon and their mixtures flourished in the United States, driven by the practical needs of the explosively growing petroleum industry. As oil and gas drilling extended to greater depth and higher pressures, the phenomenon of retrograde condensation was rediscovered, rekindling interest in Kuenen and the Dutch School. During the Second World War, a study of several years took place at the University of Michigan, collecting all material on the behavior of hydrocarbons under pressure in records dating back to 1860. The report by Katz and Rzasa (1946) contains literature references and reprints of the most important papers by European scientists in this field from 1875 to 1910. A large part of this report is taken up by the work of the Dutch School presented in this book.

In the United Kingdom, Rowlinson served as an effective conduit between the Dutch School and the chemical process industry. Rowlinsons's

(1958) book extensively references work of the Dutch School on fluid mixtures, and introduces Korteweg's equations for fluid mixture criticality in terms of the Helmholtz energy. Rowlinson enlightened engineers drilling for gas in the North Sea on Kuenen's retrograde condensation. Freeman and Rowlinson (1960) studied lower critical end points in polymeric solutions, and drew attention to the fact that Kuenen and Robson first observed this type of phase behavior.

Thus, the fundamental contributions by the Dutch School, although perhaps not always explicitly recognized, permeate the modern chemical process industry, providing the framework for understanding and modeling the phase behavior of multicomponent fluid mixtures.

Notes on referencing

Conventions used. The year following the author's name in the text is printed boldface, again in parentheses, in the corresponding reference in the following list. The references are listed alphabetically by last name of the first author. If an author has more than one paper referred to in a given year, these papers are ordered chronologically to the extent possible, and distinguished by lower-case letters a, b, *etc.*

In frequent cases of multiple versions of a particular paper, the version quoted in the text corresponds with the one carrying the boldface year in the reference list.

Most papers by the Dutch School were published in more than one language. Not all versions of a given paper are given in the reference to it. In case an English-language version is available, this is the primary, and often only reference given. If no English version is available, or if the English version appeared considerably later than the original version, the bold-face version quoted, and referred to in the text, has been chosen in the following order of preference: German, French, or Dutch.

*Referencing to the periodicals of the Royal Netherlands Academy of Sciences***.** The 'Verslagen' and 'Proceedings' of the Academy are printed as issues, each covering a monthly session. The issues are bundled in volumes, which are numbered in chronological order and usually cover an academic year. Within a volume, pages are numbered consecutively. At the beginning of each volume, the starting page numbers for the individual session issues are prominently displayed. Each session issue, in turn, is preceded by a one-page detailed listing of all the communications in the session. Therefore, in this book the references to 'Verslagen' and 'Proceedings' are given for the session under which the particular article is published. This date may occasionally differ from that of the session in which the article was actually communicated. If this is the case, the date of communication is added to the reference. Since the date of print of the session is, at best, indicated inconspicuously in a hard-to-find place at the end of the session issue, this date is not given in this book.

From 1898 onwards, an English version of the Academy presentations, the *Proceedings*, was published. For Academy presentations from 1898 onwards, only the English version is given in the reference.

The 'Verhandelingen' of the Academy are usually more substantial papers, which may or may not have been presented in individual sessions. Roughly half a dozen 'Verhandelingen' are published in a volume, in which each 'Verhandeling' is numbered starting with page 1. A listing of the papers appearing in a volume is included in the Volume, but the papers are not always numbered. They are therefore somewhat awkward to find or to refer to. In this book, the volume number, year, and page numbers (1-X) are given, and, if it is known, the session in which the paper was presented.

Referencing to the Communications of the Physical Laboratory at Leiden. The Leiden Communications bundle all of the publications of the Physical Laboratory starting around 1890. They were printed in English almost exclusively, and are numbered sequentially. For almost all Dutch-language Academy presentations published by Kamerlingh Onnes and his laboratory, a corresponding English-language Communication exists. If it does, it serves as the prime reference. In the case of the English-language Academy Proceedings, the Leiden Communications number, if known, is included in the reference.

Particular usages. Dutch last names are alphabetized while skipping definite articles and propositions such as De, Den, Van, Van de, Van der, Van ’t. Examples: Van ’t Hoff is found under H, and Van der Waals is found under W. Note that, following present-day custom in the Netherlands, the first of the articles or prepositions that are part of the last name are capitalized in the text and references as long as only the last name is stated. If the first name or first initial is included, the articles/propositions are not capitalized. In the case of a double last name, the reference is alphabetized according to the first letter of the first of these two names. Thus, Kamerlingh Onnes is found under K, and Levelt Sengers is found under L.

Frequently used sources for biography and bibliography. The Dictionary of Scientific Biography has been a major source of biographical information given in this book. The *Dictionary* is an 18-volume series published, under various editors, by Scribner’s Sons, New York, from 1970 to 1990. In addition, the following biographies have been consulted. Each of these contains a complete bibiliography. For Van der Waals, that by Kipnis *et al.* (1996) – for Van ’t Hoff, that by Cohen (1912) – for Van Laar, that by Van Emmerik (1991) – and for Verschaffelt, that by Henriot (1957).

Journal Abbreviations

Ann. Acad. Roy. Belg.	Annuaire de l’Académie Royale de la Belgique
Ann. Chim. et Phys.	Annales de Chimie et de Physique
Ann. Physik	Annalen der Physik
Ann. Physik und Chem.	Annalen der Physik und Chemie
Ann. Rev. Phys. Chem.	Annual Review of Physical Chemistry
Arch. Musée Teyler	Archives du Musée Teyler
Arch. néerl.	Archives néerlandaises des sciences exactes et naturelles

Ber. Bunsenges. Physik. Chem.	Berichte der Bunsengesellschaft für Physikalische Chemie.
Bull. Acad. Roy. Sci. Belg.	Bulletin de l'Academie Royale des Sciences de la Belgique
Bull. Inst. Liège	Bulletin de l'Institut de Liège
Can. J. Res.	Canadian Journal of Research
Chem. Rev.	Chemical Reviews
Chem. Weekblad	Chemisch Weekblad
Comm. Phys. Lab. Leiden	Communications of the Physical Laboratory at Leiden.
Comptes Rendus Acad. Sci. Paris	Comptes rendus hebdomaires des séances de l'Academie des Sciences (Paris)
Fluid Phase Equil.	Fluid Phase Equilibria
J. Am. Chem. Soc.	Journal of the American Chemical Society
J. Chem. Phys.	Journal of Chemical Physics
J. de Phys.	Journal de Physique et le Radium
J. Math. Phys.	Journal of Mathematical Physics
J. Phys.	Journal of Physics
J. Phys. Chem.	Journal of Physical Chemistry
J. Stat. Phys.	Journal of Statistical Physics
Philips Res. Rep.	Philips Research Reports
Phil. Mag.	Philosophical Magazine
Phil. Trans. Roy. Soc. London	Philosophical Transactions of the Royal Society of London
Physik. Z.	Physikalische Zeitschrift
Phys. Rev.	Physical Review
Phys. Rev. Lett.	Physical Review Letters
Proc. Roy. Soc. London	Proceedings of the Royal Society of London
Proc. Kon. Akad.	Koninklijke Nederlandse Akademie van Wetenschappen. Proceedings of the Section of Sciences.
Pure and Appl. Chem.	Pure and Applied Chemistry
Rep. Progr. Phys.	Reports on Progress in Physics
Russ. J. Phys. Chem.	Russian Journal of Physical Chemistry. Translation of. Zhurnal Fizichevkoi Khimii
Sitzungsber. Akad. Wissensch. Wien	Sitzungsberichte der mathematischnaturwissenschaftlichen Klasse der Königliche Akademie der Wissenschaften zu Wien.
Soviet Phys. JETP	Soviet Physics, JETP. Translation of Zhurnal Eksperimentalnoi i Teoreteschkoi Fizika
Trans. Connecticut Acad.	Transactions of the Connecticut Academy
Trans. Farad. Soc.	Transactions of the Faraday Society
Verh. Kon. Akad.	Verhandelingen van de Koninklijke Nederlandse Akademie van Wetenschappen

Versl. Kon. Akad.	Koninklijke Nederlandse Akademie van Wetenschappen. Verslagen van de gewone vergaderingen der Wis- en Natuurkundige Afdeling.
Z. Anorg. Algem. Chem.	Zeitschrift für Anorganische und Algemeine Chemie
Z. Anorg. Chem.	Zeitschrift für Anorganische Chemie
Z. Physik. Chem.	Zeitschrift für Physikalische Chemie

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Name index

Page numbers in bold indicate the principal entry among multiple entries for a topic

Subject index