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HEIKE KAMERLINGH ONNES

THROUGH MEASUREMENT TO KNOWLEDGE

The Selected Papers of Heike Kamerlingh Onnes 1853–1926

Edited with an Introductory Essay by

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magnetism), we discuss the early work of Diderik van der Waals (especially his equation of state and the law of corresponding states), its relation to the findings of Thomas Andrews and Maxwell's reactions to it. There is also a section about the liquefaction of helium and the properties of liquid helium, where we include some new material that throw some light on the difficulties encountered by Kamerlingh Onnes few months before the liquefaction of helium. The chapter written by Rudolf de Bruyn Ouboter deals with the developments in instrumentation before the liquefaction of helium, and describes the apparatus used for this purpose. The papers are divided in five categories. In the first are those intended for a more general audience, and our notes are much more detailed than for the other papers. The titles of the papers in the other four sections are self-explanatory, and in addition to our overall aims, we try to emphasize the most significant contributions of Kamerlingh Onnes.

The introductory text does not attempt to be a substitute for a biography of Kamerlingh Onnes. Nor do we deal with the exceedingly significant relationship of the developments in low temperature physics with technological developments. It would, indeed, be an interesting undertaking to write the history of refrigeration. It is, rather, an attempt to raise a series of methodological and historical issues concerning the establishment of low temperature physics as a "separate" branch and its development that was so heavily influenced by Leiden's physics culture.

This volume owes its completion to the constant encouragement of Professor Robert S. Cohen of Boston University. His enthusiasm is contegious and we feel lucky to have been caught in its spell. Prof. Rudolf de Bruyn Ouboter and Prof. Hans van Duyneveldt of the Kamerlingh Onnes Laboratory of the University of Leiden have done their utmost to help us with our project. Detailed discussions with Prof. Sam Schweber of Brandeis University and Harvard, and Prof. Peter Harman of Lancaster University helped us clarify many points, and more significantly, they made us more sensitive to a number of historical issues. We also thank Prof. Aristides Baltas of National Technical University, Athens; Professors Erwin Hiebert, Gerald Holton and Everett Mendelsohn of Harvard University; Prof. Nancy Nersessian of Princeton University; Theodore Arabatzis, Maria Yamalidou and Christos Nasiopoulos, graduate students at the Universities of Princeton, Lancaster and Thessaloniki.

We made extensive use of various archives. We thank Dr. A.C. van Helden and H.J.F.M. Leechburch Auwers of Boerhaave Museum, Leiden where the papers of Kamerlingh Onnes are kept; Mrs. I.M. McCabe, Librarian at the Royal Institution, London where the Dewar papers are; Ms. C. Anderson of the Manuscript Division of University College, London where the William Ramsay papers are.

We thank Mrs. Annie Kuipers, acquisition editor in the humanities and social sciences division of Kluwer Academic Publishers, who has been very supportive and always dealt very quickly and effectively with all the difficulties that such an edition has. Mr. Teun de Graaf, of the production department, was kind enough to discuss at length various problems related to the production of the volume.

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Note to the Reader:

The asterisks and numbers indicated in the margins of the original articles correspond to the editors' notes to be found at the end of the volume starting on page 491.

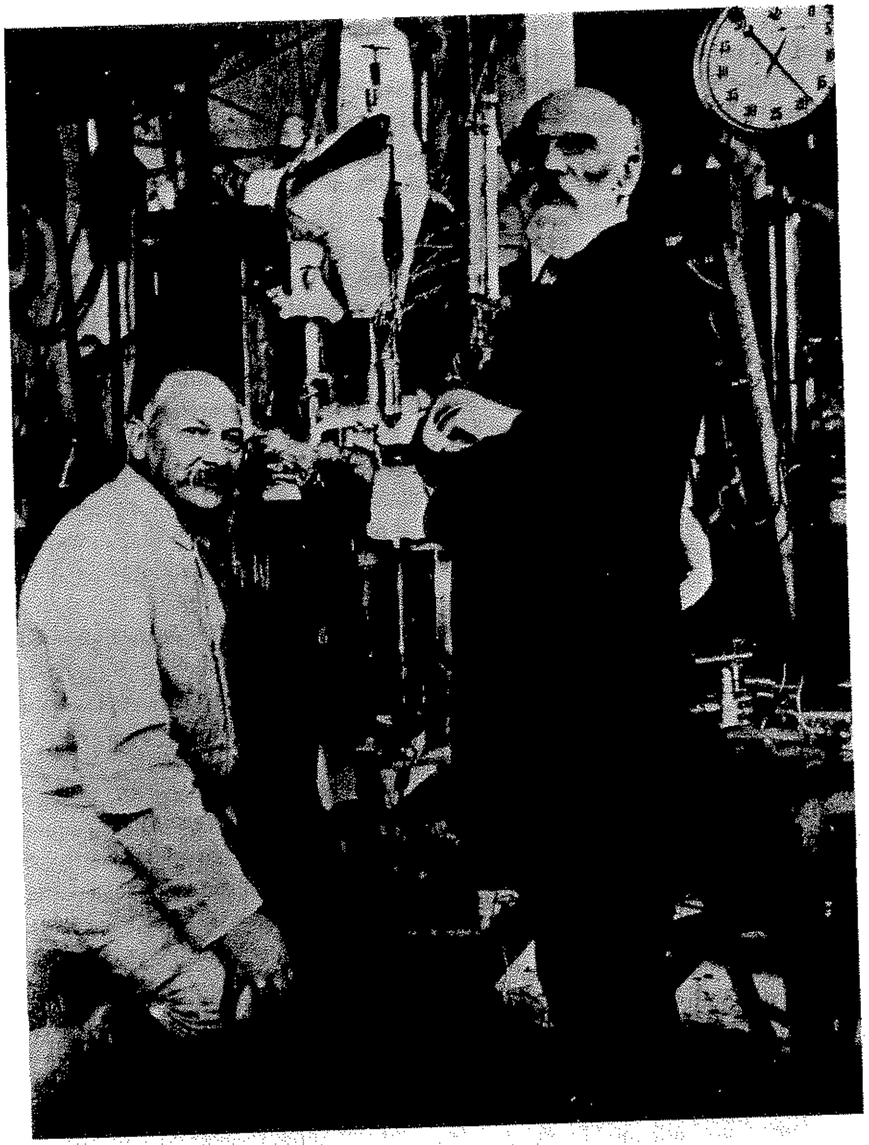
In some of the originals we used the copies we found with the corrections made in handwriting.

The bibliography for both the Introduction and the editors' notes starts on page 539 (except for Kamerlingh Onnes's works which are to be found in the list of his publications starting on page 521).

References to Kamerlingh Onnes's papers reprinted in *CPL* or *CPL Supplement* are indicated by the number of the *Communication* in which they appear.

CPL stands for *Communications from the Physical Laboratory at the University of Leiden*, and *KAWA* for *Proceedings of the Koninklijke Akademie van Wetenschappen te Amsterdam*.

"KAWA" defined



H. Kamerlingh Onnes (left) and J. D. van der Waals (right) before the helium liquefactor (1911)

THE REMARKABLE WORK OF "LE GENTLEMAN DU ZERO ABSOLU"

by K. Gavroglu and Y. Goudaroulis

INTRODUCTION

Cold, colder, coldest, Onnes ... was the beginning of an article in *Everybody's Magazine* in September 1915. The article was about the work in low temperature physics at the University of Leiden and was referring to the Director of the Physical Laboratory there, Heike Kamerlingh Onnes. "Mr. Freezer" as some Dutch cartoonists called him, had already received the Nobel Prize for physics in 1913 and he was in charge of the only laboratory that could produce liquid helium and perform measurements of various physical parameters at the lowest of temperatures – barely a couple of degrees above absolute zero.

The oldest University of Holland, the University of Leiden, was founded by William I the Silent, Prince of Orange in 1575 and though some of the events that marked the history of science were associated with names of people from Leiden, such as Christiaan Huygens and his wave theory of light, or Petrus van Musschenbroek and his electrical condenser, it was during the period of fifty years from 1873 to 1923 that physicists from the University of Leiden contributed to some of the most dramatic developments in physics. In 1873 Johannes Diderik van der Waals defended his thesis where he proposed a theoretical explanation for Thomas Andrews's observations that the transition from the gaseous to the liquid state is a continuous process and formulated the equation of state that bears his name and is still in use. Hendrik Antoon Lorentz in 1875 completed his thesis on the problem of reflection and refraction of electromagnetic waves – a problem not properly treated by Maxwell – and some years later he proposed his theory of electrons. Pieter Zeeman's discovery in 1896, of the splitting of the spectral lines by high magnetic fields, something that Faraday had tried but failed to accomplish, led to the first determination of the ratio of e/m for the electron about a year before its discovery by J.J.Thomson in 1898. In 1908 the last of the inert gases, helium, was liquefied for the first time by Heike Kamerlingh Onnes – a step heralding the "formal" beginning of low temperature physics. He managed it after years of systematic and impressively precise measurements of isotherms that helped him, among other things, to determine the critical point of helium. To the end of his life he continued to perform all kinds of experiments with "this most exceptional liquid"[1] as he wrote to Dewar few days after he liquefied it, and he came to realize that helium was no ordinary liquid. In 1911 he discovered superconductivity. Later he found that the density of liquid helium went through a maximum around 2 degrees, this being the temperature below which helium became superfluid – a phenomenon discovered long after Kamerlingh Onnes's death. Kamerlingh Onnes's programs in molecular physics and on the electric, magnetic and optical properties of various substances were, in effect, a confluence of the work of Lorentz and van der Waals. By the time Kamerlingh Onnes retired in 1922 all four had received a Nobel Prize, together with another Dutch *enfant terrible* Van't Hoff, who had started his career at The Netherlands and continued it at Leipzig with Ostwald.[2]

Heike Kamerlingh Onnes was born on September 21, 1853 at Groningen. His father, Heim Kamerlingh Onnes, owned a tile factory, and by Kamerlingh Onnes's account, the family led an isolated life in this predominantly university town. His mother's, Anna Gerdina Coers's, father was an architect. Values that were in many instances expressed by Kamerlingh Onnes later in his life were, by his own account, also the dominant values in his family

> In my parents' house all was made subservient to *one* central purpose: to become *men*. And only when a deep inner culture goes hand in hand with refined good breeding, so that nothing is neglected, and manifests itself also in neat and careful dress, may we expect that the result of such an education will be to form men, in the best and widest acceptation of the word. Has it not been a blessing that I was educated in a family where such ideas obtained?[3]

He started high school in 1865 and the director of Hoogere Burgerschool was J.M. van Bemmelen who became professor of chemistry at the University of Leiden and whose influence on Kamerlingh Onnes has been repeatedly expressed by Kamerlingh Onnes himself.[4] He matriculated in 1870 and entered the University of Groningen to study science. At the end of his first year, he took part in a competition of the University of Utrecht and won the gold medal with his essay titled "A critical investigation of the methods determining vapor density and the results obtained thereby, with respect to the relation of the nature of the chemical compounds and the density of their vapors". In 1871 he went to the University of Heidelberg where Robert Wilhelm Bunsen and Gustave Robert Kirchhoff were professors. He was also able to win the "Seminarpreis" and become one of the two assistants of Kirchhoff. During his second year there, in 1872, he received the second prize in a competition of the University of Groningen with his essay titled "A critical survey of the methods determining the quantities of heat which are set free by chemical reactions and dissociations and of the results obtained by different investigators". During this year he started working on a topic that would eventually become his doctoral thesis titled "New proofs for the axial rotation of the earth" which he completed in 1879 – even though he had passed the necessary examinations in 1876. In his thesis he displayed an impressive command of mathematics. This work was in fact the first "proper" treatment of Foucault's pendulum and the subsequent experiments that he himself performed did – not unsurprisingly – corroborate his theoretical calculations. In 1878 he was appointed assistant to Bosscha at the Polytechnic School at Delft (later the University of Delft). He gave both the lectures (substituting Snijders during 1880-1881 and Bosscha during 1881–1882) and supervised students in their laboratory work. In 1882 he was appointed to the first chair of experimental physics to be founded in The Netherlands, and succeeded Rijke at the University of Leiden. H.A. Lorentz had been appointed Professor of theoretical physics.[5]

Kamerlingh Onnes was a member of numerous scientific societies in many countries (Germany, Norway, England, Poland, United States, Denmark, Sweden, France, Italy, Spain, Austria) and received a large number of awards. He was one of the founding members of the Association (now Institut) International du Froid and president of its scientific committee for many years. His health was frail and he had chronic bronchial problems. On February 21, 1926, after a short illness he died in Leiden. He was survived by his wife Maria Adriana Wilhelmina Elisabeth Bijleveld, and his son Albert, who was a high-ranking civil servant at The Hague.[Cohen 1927; Mathias 1926; Koopman 1927; Scientific American 1915; Casimir 1983; Gavroglu, Goudaroulis 1988a, 1989].

The detailed discussion of the developments of low temperature physics, and particularly those at Leiden, presents, undoubtedly, an interest for the historians of science. It is not only the case of the establishment and development of a laboratory where so many of the developments of low temperature physics took place. Anything related to the study of the development of low temperature physics is quite significant for understanding issues about the relationship between science and technology, since during the period we are examining, developments in the refrigeration industry brought about lasting changes relating to agriculture, and generally the distribution and availability of perishable goods in the populous industrial cities. But, the detailed discussion of the developments of low temperature physics is also of interest to the philosophers of science, and we would like to concentrate on a rather neglected aspect of these developments: The methodological trends that appear to be particular to this specific branch of physics as it has been established and developed at Leiden. It is our claim that the gradual appearance of a new branch within a particular scientific discipline (in our case, low temperature physics within physics) is accompanied by a series of methodological novelties particular to the specific branch that delineate its autonomous status.

We propose to trace the emergence of these trends in the establishment of low temperature physics at the University of Leiden during the forty years of Kamerlingh Onnes's professorship. This period from 1882 to 1922, for our purposes here, has the following two significant characteristics. First, its beginning overlapped with most of the developments influencing the emergence of physical chemistry (and especially those in chemical thermodynamics). Second, its end was just before the dramatic developments of 1926. The problems of delineation of physical chemistry from molecular physics and the desperate, yet at times promising, attempts to formulate the (old) quantum theory within the classical framework, influenced quite strongly the trends expressed during the foundation of low temperature physics and marked Kamerlingh Onnes's style. It is true that there had been exceedingly significant developments earlier, mainly in the liquefaction of gases. Cailletet in Paris and Pictet in Geneva had both observed oxygen mist in 1877; during 1893–1894 Olszewski and Wroblewski had been able to liquefy nitrogen and oxygen in Cracow; Dewar had liquefied hydrogen in 1898 in London. But it was Kamerlingh Onnes who so strongly articulated the need for experiments in low temperatures as a *necessary* outcome of the study of a series of theoretical issues explicitly expressed or implied by the work of van der Waals and established the first cryogenic laboratory.

Kamerlingh Onnes (re)assessed the role of the equation of state

proposed by van der Waals and the possibilities it offered. This (re)assessment expressed his philosophical preferences, methodological choices and ontological commitments. He regarded the equation of state as providing an underlying organising principle for a framework within which it would become possible to classify, compare and study substances. It can be argued that Kamerlingh Onnes's aim was to achieve a taxonomy of substances (first the gases, then the liquids; first the simple ones, then the mixtures) much in the spirit of the periodic table, but in this case with respect to their *physical* rather than *chemical* behaviour. Numbers, expressing measurements, of course, were of paramount importance for Kamerlingh Onnes. He believed that unless there were many of them, it would not be possible to "read" the underlying patterns and find an explanation for these patterns. Yet one cannot fully appreciate Kamerlingh Onnes's phenomenal work unless his theoretical frames of reference are taken into consideration.

A characteristic feature of Kamerlingh Onnes's researches was the fact that his experimental ingenuity went hand in hand with his theoretical pursuits. In the preface of his thesis he quoted from Helmlotz's memorial lecture on Gustav Magnus:

> It seems to me that nowadays the conviction gains ground that in the present advanced stage of scientific investigation only that man can experiment with success who has a wide knowledge of theory and knows how to apply it; on the other hand, only that man can theorize with success who has a great experience in practical laboratory work.[6]

Kamerlingh Onnes, in his inaugural address in 1882 after he was appointed Professor, put forth the principles that were to guide his researches

> Considering the intricate nature of the laws which govern the connection of physical properties with the nature and motion of the molecules, we may regard it as an important step if we are able to form even approximate laws ... From approximate hypotheses concerning the molecule, theory can provide indespensable guides to experiment, but it is measurement that must decide their validity; this must secure research from being lulled to sleep by the seduction of a rounded off mathematical theory. It is measurement finally, that *in the deviations provides the natural material for new hypotheses regarding the properties of molecules*" (our emphasis)[7]

His inaugural address also contained the dictum that was to have been so faithfully followed by Kamerlingh Onnes

> According to my views, aiming at quantitative investigations, that is at establishing relations between measurements of phenomena, should take first place in the

> experimental practice of physics. By measurement to knowledge [door meten tot weten] I should like to write as the motto above the entrance to every physics laboratory.[8]

And he did, in fact, put such a placat in his laboratory as witnessed by the only surviving photograph of all the people working there and taken by Dana. [Donnelly, Francis, 1985]

Kamerlingh Onnes had a rather idiosyncratic theoretical agenda. He had a firm command of theoretical developments and an ability to contribute to those developments. What should be emphasized, however, is not whether his theoretical contributions were sophisticated or lasting, but rather the fact that he regarded theoretical activity as a necessary ingredient for the planning of his experimental investigations. The planning of experiments was not only guided by the needs of previous experiments or by theories and propositions put forward by others, but also by hypotheses proposed by Kamerlingh Onnes himself. He was, however, remarkably little prejudiced in favour of his own hypotheses. Even when there was sufficient data to claim their confirmation, he was always on the look-out for weaknesses in the measuring process or oversimplification in the proposed hypotheses.[9]

But above all, the experiments were planned and executed as part of a long term program to test and extend the implications of the equation of state proposed by Johannes Diderik van der Waals in his doctoral thesis in 1873. That *problematique* of van der Waals together with the law of corresponding states provided the theoretical framework that, in effect, determined the characteristic themes and trends of low temperature physics at Leiden.[10] As we shall see, this framework provided the possibility for settling many more issues, than simply the different ways to test the particular equation of state.

> For van der Waals' theory the solution of problems like these is of fundamental importance. Investigations of the different models wherever we think most convenient cannot lead us to our goal. The form of the model of one substance must, however much exertion it may cost, be investigated as completely as possible, as well at high as at low reduced temperatures ... Then we shall know for each substance the general law of all quantities [coefficients of compressibility, coefficients of expansion, heat of vaporization ...] which are now known generally only over a limited range. We shall have laid down the equation of state of each substance in one single image which will cover all these quantities – an empirical formula with 25 constants has been tried as such – and it will be this empirical equation of state which will be looked up in tables as we now, for instance, look up the empirical formula of a coefficient of expansion .... When all these equations of state of the various substances, including the abnormal ones ... will the correspondence between these groups of models with their striking deviations still be as great mystery to us as at present, or shall we have succeeded in explaining their correspondence and their deviations by the greater or less similarity in the chemical nature of the substances? We trust that the latter would be the case.[11]

Such a program could be realized because of the particular methodological role Kamerlingh Onnes had ascribed to the equation of state, because of his attitude about the significance of taxonomy via the equation of state, but most importantly, because he adopted a particular interpretation of the ontological implications of the equation of state and the law of corresponding states. Far from considering the equation of state as an "algorithmic device" to calculate observable quantities, he regarded these equations as displaying the "gist" of what was actually going on among the real molecules, expressing their "bare" behaviour. The deviations from the predictions of the original (idealized) equations became corroborating evidence for the truth of the underlying mechanisms rather than an indication of a disagreement as such. These deviations, exactly because of their systematic character, by displaying the "real" behaviour of the substances were at the same time strengthening the role of the law of corresponding states as an *organizing principle.*

But Heike Kamerlingh Onnes was first and foremost a brilliant experimenter, and apart from his numerous discoveries, his contributions to the perfection of various techniques and instruments remain classic to this day. His indifference (abhorrence according to many) towards teaching is well recorded [Casimir 1983; Struik 1980; Burgers 1962].[12] Fortunately for the students, Lorentz did the teaching of Kamerlingh Onnes's courses as well. It is true he ran his laboratory with an iron hand. He demanded the utmost from his staff and assistants and it was not always the case that this hard work was sufficiently acknowledged by Kamerlingh Onnes – a practice not uncommon during the period. He had the fortune of working with one of the ablest technicians, G. Flim[13] and had at his disposal the services of the quite unique school for technicians that he himself established in 1901 [Crommelin 1926; Bloembergen 1983]. Kamerlingh Onnes's results were uniformly accepted by the community and he was not involved in any controversies except in a minor dispute with de Heen concerning the determination of critical points CPL. 68; de Heen 1901; Mathias 1904].[14] Though Kamerlingh Onnes had been universally regarded as the founder of low temperature physics, this recognition did not come till after his receiving the Nobel Prize. His numerous achievements were well known among his colleagues in various countries. But hardly anyone knew of his work outside this relatively small group of people. It is characteristic that the first article for a wider audience was written in the *Scientific American* in 1914 after the announcement that he received the Nobel Prize for 1913. The Leiden laboratory was the only laboratory in the world that could produce liquid helium from 1908 till 1922 (except during the years of the First World War) in sufficient quantities and preserve it for a long enough time so that it was possible to make measurements of physical parameters. And by all accounts, it was a laboratory where a lot of well known and many other younger physicists were welcome to work.

Kamerlingh Onnes's researches could be divided into the following – not necessarily the only possible – categories: researches on thermodynamics and the equation of state, studies of the properties of liquid helium, electrical researches, magnetic researches. In addition to these main divisions, there was also the study of the electrical and magnetic properties of gases and metals at liquid hydrogen and helium temperatures.

One of the aims of this extended introduction to Heike Kamerlingh Onnes's Selected Papers is to show the coherence and interrelationships of the various research programs carried out at Leiden during Kamerlingh Onnes's professorship there. This text cannot be regarded either as a short biography or as the history of the Physical Laboratory of the University of Leiden, and we hope that our work may contribute towards an undertaking of these projects. Hence, there are certain aspects of Kamerlingh Onnes's life that we do not discuss at all. One of those is Kamerlingh Onnes's activities related to applied cryophysics and, particularly, refrigeration, both nationally and internationally. Indicative of these activities was his membership and precidency in numerous Dutch committees[15] and especially those whose purpose was to examine ways for developing refrigerating machines in the large fishing boats as well as his contributions in resolving a series of sensitive issues prior to the foundation of the Institut Internationale du Froid in 1908 as witnessed in the extensive correspondence Kamerlingh Onnes had with Guillaume and his subsequent active participation in the work of the Institute, especially as the president of its international commission on physics, chemistry and thermometry.[16] [Association Internationale du Froid 1908, 1911, 1913; Thevenot 1980; Woolrich 1969].

A systematic study of the research programs undertaken at Leiden during Kamerlingh Onnes's directorship brings to the surface the themes which characterized Leiden's "physics culture" and its strong influence by the positivist prescriptions: Laws or theoretical proposals were systematically tested, and the deviations from the predicted values carefully studied in order to be able to devise (semi-empirical) formulas describing in a satisfactory manner the recorded results. Explanations were then proposed and new experiments were planned to test the proposed explanations. When confronted by a new phenomenon there was a careful examination of the status of various theories, and the emphasis was usually not on providing novel theories or new explanations, but, rather, on bringing forth all the facets of the new phenomenon. Kamerlingh Onnes's motto "to knowledge through measurement" loomed large, especially in those instances when he was confronted by new phenomena. To understand, however, Kamerlingh Onnes's work one has, first, to discuss van der Waals's early work.

VAN DER WAALS AND THE LAW OF CORRESPONDING STATES

In 1873 Johannes Diderik van der Waals, at the age of 36, defended his thesis at the University of Leiden. It bore the same title as Thomas Andrews's celebrated 1869 Bakerian Lecture: "The Continuity of the Gaseous and Liquid State". In it van der Waals presented an improved solution to the capillarity problem and starting from quite general assumptions and the kinetic theory of gases, he proposed an equation of state which incorporated corrections to Boyle's expression of the ideal gas law. Using van der Waals's equation of state it became possible to derive with impressive accuracy Andrews's experimental results that had quite convincingly demonstrated the continuity of the transition from the gaseous to the liquid state.

Maxwell had read van der Waals's thesis right after it was published in 1873, and wrote an article in *Nature* the next year using the opportunity "to explain Clausius's virial theorem a little more fully [since] in this country the importance of this theorem seems hardly to be appreciated".[18] Maxwell was full of praise for van der Waals's contributions and was impressed by his "investigations [which] are conducted in an extremely original and clear manner".[19] He was, however, very critical about two crucial aspects of van der Waals's derivation of his equation of led to a deadlock, and Keesom [1915a, b] attempted to incorporate quantum effects – but it was too late . This was in 1915, and Bohr had already published his papers.

On November 19, 1908 van der Waals and Kamerlingh Onnes were awarded the highest mark of distinction of the Ancient Association of Physics, Medicine and Surgery of The Netherlands for the law of corresponding states for the former, and the liquefaction of helium for the latter. As we have already mentioned, van der Waals interpreted the law of corresponding states as implying that all substances form a single genus

> "Now it was a question whether helium also belongs to this common genus, whether this dwarf also has a well formed shape .... By carrying out measurements of pressure and volume at the lowest possible temperature, you were able to determine the so-called Boyle point i.e. the temperature at which, with very great volume, the substance follows Boyle's law. For all substances, the Boyle point is rather more than three times higher than the critical temperature, according to the equation of state 27/8 times the critical temperature .... Strictly speaking the question was now settled: Helium too pocesses this very same remarkable point"[76]

These were van der Waals's words. They signified the end of an exciting period wrought with rivalries and momentous developments. They also signified the beginning of a new one as well. All gases had been liquefied and there was now a new temperature range to explore. And Kamerlingh Onnes was no less enthusiastic about van der Waals's achievements. Referring to the same meeting in a letter to Dewar he remarks

> Wednesday was a beautiful day. Prof. van der Waals spoke splendidly .... I was happy to be allowed to quote your words.[77] They did give him great satisfaction and I will not forget his beautiful look, as I quoted them. You know van der Waals is not only a master genius, but also a really great man. What you say about there not being given enough honour to him by other countries, is quite my idea. The sole explication is that his work wants time to be seen in its full greatness by the general scientists. How long took it before it came to general notice? .... There was only your Maxwell who appreciated well, Clausius did not grasp the scope of the work at all. When people like Clausius fail who will you think of other one hurrying after the nearest of the new. Boltzman had an adequate idea of van der Waals work. But he himself has not found the appreciation he deserved by his revolutionizing views. It is like you say one have to await the work of time, which sifts – as v.d.Waals once said to me – admirably well that which has real value from the other things.[78]

PROPERTIES OF LIQUID HELIUM

Helium "has always been a most remarkable and entertaining substance. Consider the manner of its discovery. Most of the rare elements have been found by painstaking search and careful chemical isolation, but helium has been discovered almost by accident, not on the earth but on the sun! In fact after the first discovery of helium in the solar atmosphere, nearly thirty years were to elapse before it was found to be present on the earth".[79] In 1895–96 helium was separated in pure form and there were attempts to liquefy it. After thirteen years of unsuccessful attempts by others [Olszewski 1896a, b, Dewar 1901, Travers 1903, Olszewski 1905b] Kamerlingh Onnes managed to liquefy helium on July 10, 1908.

To be able to liquefy the gas, it was necessary to have access to large supplies of helium. The Bath wells were the obvious source, and Kamerlingh Onnes made such a request to Dewar.

> I thought you had occasionally helium containing gas from them [the Bath wells] but now I learn ... that you have put up a plant of machinery there for extracting the gases regularly. The question is that I have advanced so far that I can take seriously to have the determination of the isotherms of helium at low temperatures as well as the magnetic dispersion of the plane of polarization in my large apparatus for compressed gas. I want many liters of pure helium and to get this I will be obliged to distill it from yet larger quantities of impure helium. It seemed most appropriate to me to prepare them out of a great number of cubic meters of the helium containing gas in which you first found this precious element. I realize my will that getting the pure helium in suficient quantities will take some two years of preparatory work and that I will have to sustain many losses before all is arranged in an unobjectionable way. But the more it is necessary that I make a beginning with it. So I have to seek for a copious supply of helium containing gases.[80]

Dewar, of course, was not so obliging

> It is a mistake to suppose the Bath supply is so great. *I have not been able so far to accumulate sufficient for my liquefaction experiments.* If I could make some progress with my own work the time might come when I could give a helping hand which would give me great pleasure.[81] (emphasis in the original)

It was clearly the case that Dewar was squarely in the "race". As mentioned by Kamerlingh Onnes in the paper reporting the liquefaction of helium, "at first the great difficulty was to obtain sufficient quantities of this gas".[82] He was eventually able to isolate the gas from monazite sand found in North Carolina, through the Office of Commercial Intelligence at Amsterdam where his brother was the director.

Kamerlingh Onnes acknowledged in 1904 that Dewar's researches with the resistance of metals at liquid hydrogen temperatures gave credence to Kelvin's proposal that as temperature goes down, the resistance will increase greatly, after passing through a minimum, due to "electron condensation." He was, however, quite ready to abandon this attitude in view of the first measurements with the resistance of mercury in helium temperatures.

In February 1911 there was the measurement of the resistance of platinum and that of pure mercury at helium temperatures in April 1911: It was shown that at 3°K the value of the resistance of pure mercury became 0.0001 times the value of the resistance of solid mercury at 0 degrees C, extrapolated from the melting point.

> The next step was obviously to look for the point at which the resistance first becomes measurable as the temperature is raised. The temperature of this point was found to be slightly more than 4.2°K.[121]

The change in resistance took place faster – and more abruptly – than the rate of change predicted by a formula proposed after the measurements of platinum.

It is interesting to note that Kamerlingh Onnes was very enthusiastic about the prospect of using superconducting wires to pass very intense currents and thus experiment with high magnetic fields, since there would be no heat developed due to the Joule effect, and "with this end in view modified measurements are now being made."[122]

In November 1911 the phenomenon was reaffirmed at 4.19°K, and at the Solvay Congress of 1911 Langevin asked whether there are any changes in other properties of mercury, and further experiments were planned.

> It can well be, however, that should there exist such a new modification (of the properties), it would differ from ordinary mercury at higher temperatures chiefly by the property that the frequency of the vibrators in the new state has become greater, and therefore the conductivity rises to the extremely large value exhibited below 4.19°K.[123]

Experiments to measure the resistance of mercury at helium temperatures were repeated during 1912–1913. The emphasis somehow was not shifted, and what was studied was the potential difference necessary for the electric current through mercury below 4.19°K. The phenomenon of the sudden drop of resistance was firmly established, it was realized that impurities do not play any role – at least in the case of mercury – in

hindering the disappearance of the ordinary resistance, and the phenomenon was for the first time called the "superconductivity of mercury."[124]

We should note that by the beginning of the century, the form of the law correlating electrical resistance to temperatures (even at the liquid hydrogen range) was unknown despite the successful theory of electrical (and thermal) properties of metals proposed by Riecke [1898] and Drude [1900]. They treated the electric current in a metal as a drift of an electron gas under the influence of an electric field. The conduction electrons in such a model move freely in the spaces between the heavy, fixed atoms of the metal, with which they exchange energy by collisions and so they contribute towards the establishment of equilibrium. The electrons were considered to be free, and apart from the collisions with the atoms, they were assumed to behave as an ideal gas, their mutual interaction being neglected. If an electric field is then imposed, the motions of the electrons will no longer be entirely random and an electric current will be set up in the direction of the electric field. Ohm's law, then, for the electrical conductivity γ, was found to be

$$\gamma = \frac{e^2 n\lambda}{2mv} \tag{19}$$

where e and m represent the electronic charge and mass, n the number of free electrons in unit volume, λ the mean free path, and v the root-mean-square electron velocity. If one now replaces the mean kinetic energy $1/2\, mv^2$ by $3KT/2$ – the value ascribed to it by classical kinetic theory – Drude's expression for γ becomes

$$\gamma = \frac{1}{6}\frac{e^2 n\lambda v}{KT} \tag{20}$$

A temperature gradient in a metal will also cause an electron current which is calculable by the same principles. Drude's expression for the coefficient of thermal conduction is $u = (hv\lambda k)/2$ and the ratio of u to γ becomes

$$\frac{u}{\gamma} = 3\frac{K^2}{e^2}T \tag{21}$$

This expression was in agreement with the old empirical law of Wiedemann and Franz (1853): the ratio of thermal to electrical conductivity is the same for all metals at the same temperature. The derivation of

Figure 1: Heike Kamerlingh Onnes, drawing by his nephew Harm Kamerlingh Onnes, 1922.

Kamerlingh Onnes appointment as professor in experimental physics in 1882 was the beginning of low temperature physics in Leiden. His inaugural address was titled: "The significance of quantitative research in physics", and his motto was "To comprehend through measurement". His major achievements in the field of experimental science and technology were the liquefaction of helium in 1908 and the discovery of superconductivity in 1911. A very long preparation was necessary before he succeeded. The guiding theory of Van der Waals, given in his doctoral thesis (1873) with the equation of state, and in his famous article on the law of corresponding states (1880), constituted the basic theoretical foundation on which Kamerlingh Onnes established his experimental program. The underlying technological frame work from his predecessors was mainly formed by the ingenious discoveries of Dewar (1842-1923): the use of silvered vacuum glasses (1892), the liquefaction of hydrogen (1898), and the absorption of gases in charcoal (1905) at low temperatures used to purify helium. By 1908 36 articles had already appeared in his *Leiden Communications* "On the methods and apparatus used in the cryogenic laboratory" and "On the measurement of very low temperatures". In 1906 his liquid hydrogen liquefactor became ready and in *Communication number 102a, b of December 1907* he tells us that he remained convinced that only the determinations of the isotherms could decide how helium could be made liquid. The Boyle point was found to be between 20 and 23 °Kelvin and he estimated *(Communication no.105)* the critical temperature between 5 and 6 °Kelvin.

The final project was to cool compressed helium by means of liquid hydrogen boiling under a pressure of 6 cm of mercury quite near its melting point, and then lead it through a Hampson regenerator spiral which ended in an expansion valve.

The 10th of July 1908 helium was liquefied and on that first day he found that the boiling point was 4.3 °Kelvin, the critical temperature not much over 5 °Kelvin and, when the bath pressure was reduced, a temperature of 1.7 °Kelvin was reached. Thereby he opened up a whole new field of research. The discovery of superconductivity in 1911[1] is ultimately connected with the cryogenic problems of the liquefaction of helium and the separate cryostat attached to the liquefier.

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[1] The author has elsewhere described the discovery of superconductivity (Superconductivity: Discoveries during the early years of low temperature research at Leiden 1908-1914 by R. de Bruyn Ouboter; IEEE transactions on Magnetics MAG-23 (1987) 355-370).

Short biography:

Kamerlingh Onnes was the son of a well-known manufacturer in Groningen. After attending secondary school, he was admitted in 1870 to the University of Groningen, where he studied physics and mathematics. Beginning November 1871 he spent some time at Heidelberg where he studied under Bunsen and Kirchhoff. In April 1873 he returned to Groningen to complete his studies and on 10 July 1879 he defended his dissertation, entitled: New proofs for the axial rotation of the earth. In 1878 he was appointed assistant at the Technical University in Delft. During this time he was already in close contact with Van der Waals, who was then professor in physics in Amsterdam. In 1882 he was appointed to professor in physics at the University of Leiden at the age of twenty-nine. He held this position, which included the Directorship of the Physics Laboratory, for a period of forty-two years. He made his *purpose* to give experimental support to Van der Waals's theory of the behaviour of gases and especially to the "law of corresponding states", which says that all gases behave in exactly the same way and obey the same equation of state, when the units in which pressure, volume and temperature are measured are adapted to the gas under specific consideration. For this purpose he studied the behaviour of gases of simple molecules having low condensation temperature, and consequently it was important to have a large range of temperatures at his disposal and it was desirable to use the lowest temperatures possible. A first necessity was for Kamerlingh Onnes to build an apparatus for the liquefaction of air in large quantities. In 1892 his apparatus for the cascade method for the liquefaction of oxygen and air was ready, in February 1906 the hydrogen liquefier and in July 1908 the helium liquefier. He created a "big" research organization for those days. He did his work with great accuracy and perseverance, systematically, and with attention to all details. In conducting the research and developing the necessary technical facilities he showed an enormous capacity for work, although he had a rather delicate health.

The study of the resistance of metals was his second major field of research. Superconductivity was discovered in 1911.

In 1913 Kamerlingh Onnes received the Nobel prize in physics "for researches on the properties of matter at low temperatures, which researches have among others also led to the liquefaction of helium".

Kamerlingh Onnes was also concerned with the application of low temperatures in every day matters such as food preservation, refrigerated transport, and the production of ice. In 1908, at the first international congress of refrigeration in Paris, he proposed an international organization of refrigeration. He insisted that one of the commissions should be devoted to scientific problems.

The workshops of his laboratory were organized as an instrument makers school. In 1901 he founded at the laboratory the school of instrument makers and glass blowers which he incorporated into a society. This establishment has been of great importance in training instrument makers and glass blowers in the Netherlands. Most of his equipment was built in the laboratory workshops.

His younger brother, Menso, became a well-known painter, whose son Harm became a painter also. Harm Kamerlingh Onnes painted many portraits, for instance of Kamerlingh Onnes, Lorentz, Einstein and Ehrenfest (the latter being in the Municipality Museum at Amsterdam).

Kamerlingh Onnes was in his youth interested in poetry. He provided the cryogenic laboratory with a leaded stained glass window panes memorial tablet made by his nephew Harm to honor the discovery, in the same building, and explanation in 1896 of the magnetic splitting of the sodium spectral lines by Zeeman and Lorentz.

D14.

* Second part of *CPL* No 119. Originally published in *KAWA*, 25 February 1911, pp. 1187–1208. Communicated to the Meeting of December 24, 1910.

1. By 1906 Kamerlingh Onnes had an efficient hydrogen liquefier and, with J. Clay, investigated problems of thermometry at liquid hydrogen temperatures in order to reproduce Dewar's measurements (see *CPL* Nos 95c, d, 99c, d and note 42 for **A2**). Their observations showed that if one wished to take account of the resistance over the whole region of low temperatures, one would have to devise rather intricate formulas. Kamerlingh Onnes and Clay tried to improve their formulas and to extend their investigations by studying the influence of admixtures on the change with temperature of the electrical resistance of pure metals (see *CPL* No 107c and [Clay, 1908]).
2. See §2 of *CPL* No 99c.
3. The investigations by Kamerlingh Onnes and his collaborators between 1904 and 1908 had been at least partly motivated by Lord Kelvin's proposal (see note 43 for **A2**). Kamerlingh Onnes in 1904 (see *CPL* supplement No 9 reprinted as **A2**) did acknowledge that Dewar's researches gave credence to Lord Kelvin's proposal (see note 42 for **A2**).
4. *CPL* Supplement 9; reprinted as **A2**.
5. [Koeningsberger, Reichenheim, 1906]; [Koeningsberger, Schilling, 1910].
6. See *CPL* No 107c, p. 26 where they express "a doubt of Lord Kelvin's opinion".
7. [Einstein, 1907].
8. [Drude, 1900], [Lorentz, 1905; 1909].
9. [Riecke, 1909].
10. [Nernst, 1911].
11. [Einstein, 1911].
12. [E. Madelung, 1909].

D15.

* *CPL* No 120b. Originally published in *KAWA*, 28 April 1911, pp. 1479–1481.

1. *CPL* No 119b reprinted as **D14**.
2. *CPL* No 123.
3. *Ibid.*, Note 1.
4. See notes 18 for **C10**, and 6 for **A3**.
5. See note 47 for **A2**.
6. [Nernst, 1911].
7. [Lindemann, 1911].

D16.

* *CPL* No 122b. Originally published in *KAWA*, 27 May 1911, pp. 81–83.

1. *CPL* No 120b, reprinted as **D15**.
2. *CPL* No 119B reprinted as **D14**.
3. Kamerlingh Onnes gave an account of his work on mercury, as completed in May, to the first Solvay Congress, which met in October 1911 (*CPL* supplement No 29, See also §3 of *CPL* No 124c, reprinted as **D17**).

D17.

* *CPL* No 124c. Originally published in *KAWA*, 30 December 1911, pp. 799–802.

1. Reprinted as **D16**.
2. Reprinted as **D14**.
3. See note 10 for **D18a**.
4. P. Langevin actually asked whether "the very fast variation of the conductivity of mercury near 4°K corresponds to a change of state and whether it may be accompanied by any observable structural modification of mercury" (*CPL* Supplement No 29, p. 10). Two decades later, when the disappearance of resistance was no longer an isolated phenomenon, but was found to be accompanied by other changes, the phenomenon was described, according to Langevin's suggestion, as a transition between two phases: the normal and the superconductive phase.
5. In 1914 Kamerlingh Onnes's investigations on this matter permitted him to conclude that "with respect to the specific heat nothing peculiar happens at the point of discontinuity" and that "there is no reason for speaking of an allotropic modification at the discounuity point of conductivity" (*CPL* No 142c, p. 30. See also *CPL* supplement No 44a).
6. See *CPL* No 133a, b, c, reprinted as **D18a, b, c**.

D18a.

* *CPL* No 133a.Originally published in *KAWA*, 22 February 1913, pp. 1284–1302.
1. Reprinted as **D17**. This paper was communicated in November and published in December 1911.
2. Read *CPL* No 133d (reprinted as **D19**).
3. Reprinted as **D17**.
4. Reprinted as **D16**. This paper was published in May 1911.
5. Reprinted as **D16**.
6. *CPL* No 124c, reprinted as **D17**.

7. *CPL* No 124c, reprinted as **D17**.
8. See note 4.
9. According to the experimentally determined law announced by J.P. Joule, when a current of voltaic electricity is propagated along a metallic conductor, the heat evolved in a given time is proportional to the resistance of the conductor multiplied by the square of the electric intensity.
10. J.C.A. Peltier found in 1834 that at the junction of two dissimilar metals carrying a small current the temperature rises or falls, depending upon the direction of the current. The rate of intake or output of heat is proportional to the magnitude of the current, and an electromotive force resides at the junction. Allowing for the Joule effect (see note 9), the heat that must be either supplied or extracted to restore a junction to its initial temperature is called the Peltier heat. (See §3 of *CPL* No 124c, reprinted as **D17**).
11. Reprinted as **D14**.
12. See also *CPL* Supplement No 34b and Kamerlingh Onnes's Nobel Lecture [Kamerlingh Onnes, 1913].
13. Wien's theory addressed the problem of fitting Planck's formulas to the data on superconductivity. [Wien, 1913]. See also *CPL* No 133c, reprinted as **D18c**.
14. [Lenard, 1913].
15. See *CPL* No 133d, reprinted as **D19**.
16. Reprinted as **D14**.
17. *CPL* No 133c, reprinted as **D18c**.
18. *Ibid.*
19. *CPL* No 124c, reprinted as **D17**.

D18b.

* *CPL* No 133b. Originally published in *KAWA*, 22 March 1913, pp. 1388–1391. Continuation of *CPL* No 133a, reprinted as **D18a**.

1. Reprinted as **D14**.
2. *CPL* No 133c, reprinted as **D18c**.
3. In his report to the Third International Congress of Refrigatation held in Washington and Chicago in September 1913 (*CPL* supplement No 34b), Kamerlingh Onnes still regarded superconductivity as an extreme case of normal conductivity. He held the view that "if gold and platinum could be obtained absolutely pure, they would pass into the superconducting state at helium temperatures", despite his strong evidence that adding impurities does not inhibit the drop to zero resistance.
4. According to "Errata Communication No 133" the following has to be added: If this microresidual resistance is not evenly distributed over the thread (Cf. §11), yet being a property of pure mercury itself, we will call it an "apparent microresidual resistance".
5. *CPL* No 133d, reprinted as **D19**.

6. Here, the new and lasting term for the phenomenon – e.g. "the superconductivity of mercury" – appeared in print for the first time.
7. He means microresidual resistance.
8. *CPL* No 133d, reprinted as **D19**.

D18c.

* *CPL* No 133c. Originally published in *KAWA*, 31 May 1913, pp. 125–137. Continuation of *CPL* Nos 133a and 133b, reprinted as **D18a**, **D18b**.

1. *CPL* No 133a, reprinted as **D18a**.
2. Read: microresidual resistance.
3. *Ibid.*, §3.
4. *CPL* No 133b, reprinted as **D18b**.
5. *CPL* No 133a, reprinted as **D18a**.
6. *Ibid.*, §5 and §8.
7. *Ibid.*
8. *CPL* No 133b, reprinted as **D18b**.
9. Read: real microresidual resistance.
10. *CPL* No 133a, reprinted as **D18a**.
11. The theoretical derivation of the empirical Wiedemann-Franz law (the ratio of thermal to electrical conductivity is the same for all metals at the same temperature) represented one of the striking successes of the Riecke-Drude electron theory of metals. Lorentz refinement of the theory in 1905 did not remove all its weaknesses. The low temperature regions became a fundamental difficulty for the electron theory of electrical conduction. (See notes 8 and 9 for **D14**).
12. *CPL* No 133d, reprinted as **D19**.
13. *CPL* No 133a, reprinted as **D18a**.
14. *Ibid.*
15. See note 10 for **D18a**.
16. Reprinted as **D14**.
17. *CPL* No 133b, reprinted as **D18b**.
18. [Lenard, 1913].
19. J. Stark assumed that each atom in a metal releases a valence electron, and that these electrons form a regular lattice maintaining the atoms in position. An electron in a lattice can be displaced only on certain shearing surfaces of the metal crystal and only in unison with the simultaneous movement of other electrons. See [Stark, 1912].
20. [Reinganum, 1911].
21. Reprinted as **D14**.
22. See note 12 for **D18a**.
23. See note 13 for **D18a**.
24. [Keesom, 1913].
25. Reprinted as **D14**.

106. — and **C. Braak.** Isotherms of diatomic gases and their binary mixtures. VIII. The breaking stress of glass and the use of glass tubes in measurement under high pressure at ordinary and low temperatures. (With a plate).
KAWA, April 1908.

107a. — and **C. Braak.** On the measurement of very low temperatures. XXI. On the standardizing of temperatures by means of boiling points of pure substances. The determination of the vapour pressure of oxygen at three temperatures. (With a plate).
KAWA, May 1908.

107b. — and **J. Clay.** On the measurement of very low temperatures. XXII. The thermoelement gold silver at liquid hydrogen temperatures.
KAWA, May 1908.

107c. — and **J. Clay.** On the change of the resistance of pure metals at very low temperatures and the influence exerted on it by small amounts af admixtures. II.
KAWA, May 1908.

108. —. The liquefaction of helium. (With three plates).
KAWA, August 1908.

109b. —. Methods and apparatus used in the cryogenic laboratory. XV. An apparatus for the purification of gaseus hydrogen by means of liquid hydrogen. (With a plate).
KAWA, March 1909.

110. **Henri** and **Jean Becquerel** and —. On phosphorescence at very low temperatures (with two plates).
KAWA, April 1909.

111. **P. Lenard**, — and **W.H. Pauli.** The behaviour of the phosphorescent sulphides of the alkaline earths at various temperatures, and particularly at very low temperatures.(With a plate).
KAWA, June 1909.

112. —, Isotherms of monatomic gases and their binary mixtures. III. Data concerning neon and helium.
KAWA, June 1909.

114. **Pierre Weiss** and —. Researches on magnetization at very low temperatures. (With two plates).
KAWA, February 1910.

116. — and **Albert Perrier.** Researches on the magnetization of liquid and solid oxygen. (With a plate).
KAWA, April 1910.

117. **E. Mathias** and —. The rectilinear diameter for oxygen. (With three plates).
KAWA, January 1911.

118b. — and **C.A. Crommelin.** Isotherms of monatomic gases and of their binary mixtures. VII. Isotherms of argon between +20°C and −150°C. (With three plates).
KAWA, October 1910.

119. —. Further experiments with liquid helium. A. Isotherms of monatomic gases etc. VIII. Thermal properties of helium. B. On the change in the resistance of pure metals at very low temperatures etc. III. The resistance of platinum at helium temperatures. (With three plates).
KAWA, February 1911.

120a. — and **C.A. Crommelin.** Isotherms of monatomic substances and of their binary mixtures. IX. The behaviour of argon with regard to the law of corresponding states. (With a plate).
KAWA, February 1911.

paper 15 → 120b. —. Further experiments with liquid helium. C. On the change of electric resistance of pure metals at very low temperatures etc. IV. The resistance of pure mercury at helium temperatures.
KAWA, April 1911.

121b. — and **C.A. Crommelin.** Isotherms of monatomic substances and of their binary mixtures. X. The behaviour of argon with respect to the law of corresponding states. (Continued).
KAWA, May 1911.

121c. — and **C.A. Crommelin.** Isotherms of monatomic substances and of their binary mixtures. XI. Remarks upon the critical temperatures of neon and upon the melting point of oxygen.
KAWA, May 1911.

122a. — and **Albert Perrier.** Researches on Magnetism. III. On Para- and Diamagnetism at very low temperatures.
KAWA, May 1911.

paper 16 → 122b. —. Further experiments with liquid helium D. On the change of the electrical resistance of pure metals at very low temperatures, etc. V. The disappearance of the resistance of mercury.
KAWA, May 1911.

123. —. Further experiments with liquid helium. E. A helium cryostat. Remarks on the preceding communications. (With a plate).
KAWA, June 1911.

124a. — and **Albert Perrier.** Researches on magnetism. IV. On paramagnetism at very low temperatures.
KAWA, December 1911.

124b. —. Further experiments with liquid helium. F. Isotherms of monatomic gases etc. IX. Thermal properties of helium. (With a plate).
KAWA, December 1911.

paper 17 → 124c. —. Further experiments with liquid helium. G. On the electrical resistance of pure metals, etc. VI. On the sudden change in the rate at which the resistance of mercury dissappears. (With a plate).
KAWA, December 1911.

126. **Albert Perrier** and —. Magnetic researches. V. The initial susceptibility of nickel at very low temperatures.
KAWA, February 1911.

127c. — and **W.J. de Haas.** Isotherms of diatomic substances and of their binary mixtures. XII. The compressibility of hydrogen vapour at, and below, the boiling point.
KAWA, May 1912.

128. —. Isotherms of monatomic substances and of their binary mixtures. XIII. The empirical reduced equation of state for argon.
KAWA, June 1912.

129a. — and **Bengt Beckman.** On the Hall effect and the change in the resistance in a magnetic field at low temperatures. I. Measurements on the Hall effect and the change in the resistance of metals and alloys in a magnetic field at the boiling point of hydrogen and at lower temperatures.
KAWA, June 1912.

129b. — and **E. Oosterhuis.** Magnetic researches. VI. On paramagnetism at low temperatures.
KAWA, June 1912.

129c. — and **Bengt Beckman.** On the Hall effect and the change in the resistance in a magnetic field at low temperatures. II. The Hall effect and the resistance increase for bismuth in a magnetic field at, and below, the boiling point of hydrogen.
KAWA, September 1912.

130c. — and **Bengt Beckman.** On the Hall effect and the change in the resistance in a magnetic field at low temperatures. V. Measurements on the Hall effect for alloys at the boiling point of hydrogen and at lower temperatures.
KAWA, October 1912.

131a. **E. Mathias,** —and **C.A. Crommelin.** On the rectilinear diameter for argon.
KAWA, October-November 1912.

131c. — and **C.A. Crommelin.** Isotherms of monatomic substances and of their binary mixtures. XIV. Calculation of some thermal quantities for argon.
KAWA, November 1912.

132a. — and **Bengt Beckman.** On the Hall effect and on the change in the resistance in a magnetic field at low temperatures. VI. The Hall effect, for nickel, and the magnetic change in the resistance of nickel, mercury and iron at low temperatures down to the melting point of hydrogen.
KAWA, November 1912.

132b. — and **Bengt Beckman.** On the change induced by pressure in electrical resistance at low temperatures. I. Lead.
KAWA, November 1912.

132d. — and **Bengt Beckman.** On the Hall effect and on the change in the resistance in a magnetic field at low temperatures. VIII. The Hall effect in tellurium and bismuth at low temperatures down to the melting point of hydrogen.
KAWA, December 1912.

132e. — and **E. Oosterhuis.** Magnetic researches. VII. On paramagnetism at low temperatures. (Continued).
KAWA, January 1913.

132f. — and **Mrs Anna Beckman.** On piezo-electric and pyro-electric properties of quartz at low temperatures down to that of liquid hydrogen.
KAWA, February 1913.

133a, b, c. —. Further experiments with liquid helium. H. On the electrical resistance of pure metals etc. VII. The potential difference necessary for the electric current through mercury below 4.19°K.
KAWA, February-March 1913.

Paper "18a" & "18b"

133d. —. Further experiments with liquid helium. H. On the electrical resistance etc. (continued). VIII. The sudden disappearance of the ordinary resistance of tin, and the superconductive state of lead.
KAWA, May 1913.

134a. —, **C. Dorsman** and **Sophus Weber.** Investigation of the viscosity of gases at low temperatures. I. Hydrogen.
KAWA, March 1913.

134b. — and **Sophus Weber.** Investigation of the viscosity of gases at low temperatures. II. Helium.
KAWA, March 1913.

134c. — and **Sophus Weber.** Investigation of the viscosity of gases at low temperatures. III. Comparison of the results obtained with the law of corresponding states.
KAWA, April 1913.

134d. — and **E. Oosterhuis.** Magnetic researches. VIII. On the susceptibility of gaseous oxygen at low temperatures.
KAWA, April 1913.

135. **Madame P. Curie** and —. The radiation of radium at the temperature of liquid hydrogen.
KAWA, April 1913.

137a. — and **C.A. Crommelin.** Isothermals of di-atomic substances and their binary mixtures. XIII. Liquid-densities of hydrogen between the boiling point and the triple point; contraction of hydrogen on freezing.
KAWA, June 1913.

137b. — and **Sophus Weber.** Vapour pressures of substances of low critical temperature at low reduced temperatures. I. Vapour pressures of carbon dioxide between −160°C and −183°C.
KAWA, June 1913.

137d. — and **W.H. Keesom.** On the measurement of very low temperatures. XXIII. The vapour pressures of hydrpogen from the boiling point to near the triple point.
KAWA, September 1913.

139a. — and **Albert Perrier.** Magnetic researches. X. Apparatus for the general cryomagnetic investigation of substances of small susceptibility.
KAWA, October 1913, January 1914.

139c. **Albert Perrier** and —. Magnetic researches. XII. The susceptibility of solid oxygen in two forms.
KAWA, February 1914.

139d. **Albert Perrier** and —. Magnetic investigations. XIII. The susceptibility of liquid mixtures of oxygen and nitrogen, and the influence of the mutual distance of the molecules upon paramagnetism.
KAWA, February 1914.

139e. — and **E. Oosterhuis.** Magnetic researches. XIV. On paramagnetism at low temperatures. (Continuation of VII).