Kammerlingh Onnes, Liquid Helium, and Modern Low Temperature Physics

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September 27, 1908 marks the centennial of a landmark event that has changed the way we live today and is, to a certain degree, responsible for the growing (fat) mass in our body: the first production of the 2.9 liter, 4 cylinder, 20 horsepower Ford Model T. This was the first affordable car that put America on wheels. In the same year, just 80 days before this event, a monumental scientific accomplishment, whose enormous impact to physics would only be fully appreciated in the coming years, was also made in the small Dutch city of Leiden. Heike Kammerlingh Onnes saw 70 cc of transparent liquid helium collected at the bottom of a double-walled vacuum glass flask, called a dewar. It is amusing to realize that these seemingly disconnected events in distance and subject actually stemmed from a common root, *thermodynamics*.

When Sadi Carnot published his thesis *Reflections on the Motive Power of Fire* in 1824, aiming for the general public rather than scientists, it did not draw much attention. In this remarkable work, Carnot laid out logical arguments on the efficiency of heat engines (in terms of the *caloric*), which later became the founding concept of thermodynamics.

It was a triumphant moment for Kammerlingh Onnes. He had been preparing for this day for the past 26 years since his arrival at Leiden. Looking back, he had gone through countless moments of frustration from gas leaks, explosion of glass dewars, and a momentary suspension of lab operations due to safety issues. Furthermore, Kammerlingh Onnes had to stand up against well-established names in this fierce competition such as James Dewar at the Royal Institution in London, who had won in almost every step up to the liquefaction of hydrogen.

When he was appointed to the chair of physics at the University of Leiden in 1882[1], Kammerlingh Onnes had a grand plan for the quest for absolute zero. As reflected in the title of his inaugural address for his professorship, *The Importance of Quantitative Investigation in Physical Science*, he believed that accurate experimental measurements would lead to a deeper knowledge and understanding of nature. He also understood the importance of careful planning and organization of experimental research, realizing that the complexity of modern experiments required excellent technical support. In this spirit, he founded a school of instrument-makers and glass-blowers and started *Communications from the Physical Laboratory of the University of Leiden*, the only English physics publication in the country where all the experimental results from his group (the only experimental group in the Netherlands at that time) were published in a timely fashion.

As most of thermodynamics textbooks start from the ideal gas law uncovered by Boyle and Mariotte independently, it is fair to say that the quest for absolute zero also began from the same place. Studying Boyle-Mariotte's law using air at various temperatures, Guillaume Amonton realized that the pressure of air should reach zero at a lower temperature when extrapolated and proposed the first concept of absolute zero[2] .

At the end of the 18^{th} century, while conducting isotherm measurements with various available gases, van Marum found that ammonia started to deviate from the ideal gas law around 7 bar and finally turned into ammonia liquid. Then, scientists started to liquefy various gases one by one. Michael Faraday chased this route of converting various gases into liquids starting with chlorine. By 1845, Faraday had liquefied all the known gases except for six, which he called permanent gases: oxygen, nitrogen, hydrogen, nitric oxide, methane, and carbon monoxide. In 1848, William Thomson (Lord Kelvin) established the thermodynamic temperature (Kelvin) scale and started to articulate the laws of thermodynamics. The subsequent discovery of the Joule-Thomson effect in 1852 provided another route to produce cooling in gas, which was adopted in the final stage of Kammerlingh Onnes's helium liquefier. It was known then without clear theoretical understanding that temperature should be lower than a certain value (critical temperature) in order to convert gas to liquid by compression. Finally, a theoretical account of this strange behavior of gas at low temperatures was provided by van der Waals in 1872 through his paper, *On the Continuity of the Gaseous and Liquid States*. This theory was especially important since from the measurements of various isotherms one can estimate the critical temperature and pressure. Within 5 years, one of the permanent gases, oxygen, was converted into liquid by Caillete and Pictet only a few days apart from each other, and subsequently nitrogen surrendered. Being able to reach down to 77 K, scientists started to see the realistic possibilities of research in extreme cold near absolute zero, and embarked on an adventure towards *Ultima Thule*[4] as geographic explorers endeavored to reach the North and South Poles.

With only two gases (hydrogen and then newly discovered helium) left to be liquefied, Kammerlingh Onnes set out to reach this goal. Completed in 1894 was the construction of a cascade type liquefaction plant for oxygen which was designed with a foresight to support his research for many good years, and then a 14 liters per hour capacity air liquefier. Despite falling behind Dewar in liquefying hydrogen, the Leiden laboratory was equipped with a large capacity hydrogen liquefier by 1906[5] . Kammerlingh Onnes was convinced that *only the determination of the isotherms could decide how helium could be made liquid*. He carried precise measurements of the isotherms and estimated its critical temperature to be in the 5 to 6 K range, which was *a favorable result for the critical temperature at once serviceable*.

The work of July 10^{th}, 1908 started early at half past five in the morning. 75 liters of liquid air was prepared for the final assault a day before, and 20 liters of liquid hydrogen produced in the morning started to cool down the cascade helium liquefier. As the time passed 6 pm, 20 liters of liquid hydrogen was almost consumed but still no evidence of liquid helium. Everybody in the lab was nervous and started to think about the worst case scenario. Around 6:30 pm, following the suggestion of an observer, Prof. Schreinemakers, when the bottom of the glass dewar was illuminated, history was made as Kammerlingh Onnes recollected that moment later in his Nobel lecture,

"It was a wonderful sight when the liquid, which looked almost unreal, was seen for the first time. It was not noticed when it flowed in. Its presence could not be confirmed until it had already filled up the vessel. Its surface stood sharply against the vessel like the edge of a knife. … The boiling temperature of the helium was found at 4.25 K, the critical temperature assessed

as 5 K. The low critical pressure to which we had to conclude and which fell between 2 and 3 atmospheres was remarkably small."

With liquid helium at hand, it seemed his quest for absolute zero was close to the finish line. In 1910, Kammerlingh Onnes reached 1.15 K by lowering the vapor pressure using the best available pumps. But helium remained liquid without being converted to solid unlike all other liquids. This observation as well as the unusually thin meniscus and low density[6] puzzled him without realizing that he was about to open a new world of quantum fluids. However, his quest for absolute zero and freezing helium had to be interrupted due to technical limitations until he resumed this mission in 1922, using twelve diffusion pumps developed by Langmuir to reach 0.83 K, which made him claim his laboratory as *the coldest place on earth.*

Kammerlingh Onnes decided to attack a problem which could be tackled with the equipment available, low temperature resistance of metals. The first measurement was done with a platinum wire which showed saturating resistance at low temperatures. He attributed the limiting low temperature resistance to the slight impurities in the material, and thought the resistance would disappear at low temperature in absolutely pure platinum. His choice of material with the highest purity was mercury. After the painstaking purification processes, mercury was poured into a series of U-shaped glass capillary tubes and the resistance was measured. The sudden drop in resistance at 4.2 K indicated that it was a new state which he called the state of superconductivity.He envisaged establishing a persistent current in an isolated solenoid by Faraday induction, and tested the possibility of a superconducting magnet which could generate strong magnetic fields without experiencing enormous Joule heating.

The first liquefaction of helium by itself may not belong to an extraordinary ground-breaking scientific discovery that would require a new way of thinking or theoretical framework. However, it was an important technical achievement which extended the limit of attainable temperature, offering in return the possibility of completely unexpected and scintillating discoveries. The discovery of superconductivity immediately followed the technical milestone. Numerous novel phenomena in liquid helium bewildered physicists and were finally understood as properties related to superfluidity. It marked the birth of modern low temperature physics which widened our horizon to the wonderland where the then newly developing quantum theory could be tested.

Persistent efforts to reach even lower temperatures laid the groundwork for the development of new cryogenic techniques (and inevitably thermometry) such as adiabatic demagnetization of paramagnetic salts and nuclear spins, the Pomeranchuk method, and the dilution refrigeration technique.

To date, 11 Nobel Prizes[7] have been awarded in the fields directly related to low temperature physics and superconductivity. Surely, there are more fascinating phenomena waiting to be uncovered at lower temperatures yet to be reached, as we anticipate discoveries of new particles in even higher energy accelerators.

In the future I see all over the Leyden laboratory measurements being made in cryostats, to which liquid helium is transported just as the other liquid gases now are, and in which this gas also, one might say, will be as freely available as water.

Kammerlingh Onnes, Nobel Lecture (1913)

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[1]Another candidate for this faculty position

was Wilhelm Röntgen who received the 1st Nobel Prize in 1901. Although he had lived in Holland except for his first three years, Röntgen had been born in Prussia, and this fact might have played a role in the decision in favor of Kammerlingh Onnes.

[2]His estimation of absolute zero corresponds to around 33 K.

[3]Ammonia has a high critical temperature (405 K) and a high critical pressure (113 bar).

[4]The ancient Greek and Latin name for a land thought to be the most northerly (coldest) region in the world.

[5]Around this time Kammerlingh Onnes was able to secure a large quantity of monazite sand which contains helium on favorable terms through the Office of Commercial Intelligence at Amsterdam under the direction of his brother.

[6]Kammerlingh Onnes observed a maximum in density at 2.2 K which signaled the phase transition to the superfluid state. But the actual identification of the superfluid transition in helium 4 was left to others until 1936.

[7]See the list of Nobel Laureates provided at the end of this article.

References

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[2] T. Shachtmann, Absolute Zero and the Conquest of Cold, Mariner Books, New York (1999).

[3] H. Kammerlingh Onnes, The Liquefaction of Helium, Communication No. 108 from the Physical Laboratory of Leiden, September 8, 1908.

[4] H. Kammerlingh Onnes, Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium, Nobel Lecture, December 11, 1913.

[5] C.W. Seibel, Helium: Child of the Sun, University Press of Kansas, Lawrence/London(1968).

[6] Web Sources :
http://www.knaw.nl/waals/kamerlingh.html,
http://www.geocities.com/neveyaakov/electro_science/kamerlingh-onnes.html.

Timeline of Historic Events Leading to Helium Liquefaction

1662 Robert Boyle publishes a paper titled, *The spring of the air*, on now known as the Boyle's law.

1703 Guillaume Amontons proposes the concept of absolute zero.

1720 The Fahrenheit temperature scale is invented.

1738 Daniel Bernoulli postulates kinetic interpretation of heat based on Newtonian mechanics.

1741 The Celcius temperature scale is invented.

1787 Martinus van Marum liquefies ammonia.

1823 Michael Faraday liquefies chlorine.

1824 Sadi Carnot publishes his thesis, *Reflections on the Motive Power of Fire.*

1848 William Thomson (Lord Kelvin) invents the Kelvin scale.

1852 Discovery of the Joule-Thomson effect.

1850 - 60 The first and second laws of thermodynamics are established by William Thomson and Rudolf Clausius.

1869 Norman Lockyer and Pierre Janssen independently discover a new gaseous element from the sun spectrum taken in 1868 summer. Lockyer gives the name *helium* to this new element.

1872 Johannes Diedrik van der Waals publishes a paper titled, *On the continuity of the gaseous and liquid state.*

1877 Lois-Paul Cailletet liquefies oxygen and subsequently nitrogen. Almost simultaneously Raoul Pictet liquefies oxygen using a different method.

1892 James Dewar (Lord James) invents a double-walled evacuated glass flask, later called a dewar.

1882 Heike Kammerlingh Onnes (HKO) is appointed to the chair of physics of the University of Leiden.

1898 James Dewar liquefies hydrogen at 23 K.

1905 Walther Nernst establishes the third law of thermodynamics.

1908 HKO liquefies helium.

1910 HKO reaches 1.15 K by pumping the chamber and observes lack of solid at this temperature.

1911 HKO discovers superconductivity in mercury.

1913 HKO receives Nobel Prize.

1922 HKO reaches 0.83 K using 12 diffusion pumps and claims his lab *the coldest place on earth.*

List of Nobel Laureates and Citations Related to Low temperature Physics and Superconductivity

1913 Heike Kammerlingh Onnes
"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"

1962 Lev Davidovich Landau
"for his pioneering theories for condensed matter, especially liquid helium"

1972 John Bardeen, Leon N. Cooper, J. Robert Schrieffer
"for their jointly developed theory of superconductivity, usually called the BCS-theory"

1973 Ivar Giaever, (Leo Esaki)
"for their experimental discoveries regarding tunneling phenomena in superconductors"
Brian D. Josephson
"for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"

1978 Pyotr Leonidovich Kapitsa, (Arno Penzias, Robert Woodrow Wilson)
"for his basic inventions and discoveries in the area of low-temperature physics"

1985 Klaus von Klitzing
"for the discovery of the quantized Hall effect"

1987 J. Georg Bednorz, K. Alexader Müller
"for their important break-through in the discovery of superconductivity in ceramic materials"

1996 David M. Lee, Douglas D. Osheroff, Robert C. Richardson
"for their discovery of superfluidity in helium-3"

1998 Robert B. Roughlin, Horst L. Störmer, Daniel C. Tsui
"for their discovery of a new form of quantum fluid with fractionally charged excitations"

2001 Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

2003 Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett
"for pioneering contributions to the theory of superconductors and superfluids"

저자이력

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