Heike Kamerlingh Onnes and the Road to Liquid Helium

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***Abstract* – I sketch here the scientific biography of Heike Kamerlingh Onnes, who in 1908 was the first to liquefy helium and in 1911 discovered superconductivity. A son of a factory owner, he grew familiar with industrial approaches, which he adopted and implemented in his scientific career. This, together with a great talent for physics, solid education in the modern sense (unifying experiment and theory) proved indispensable for his ultimate successes.**

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I. INTRODUCTION

This paper is based on my talk about Heike Kamerlingh Onnes (HKO) and his cryogenic laboratory, which I gave in Leiden at the Symposium "Hundred Years of Superconductivity", held on April 8th, 2011, the centennial anniversary of the discovery. Figure 1 is a painting of HKO from 1905, by his brother Menso, while Figure 2 shows his historically first helium liquefier, now on display in Museum Boerhaave of Leiden University.

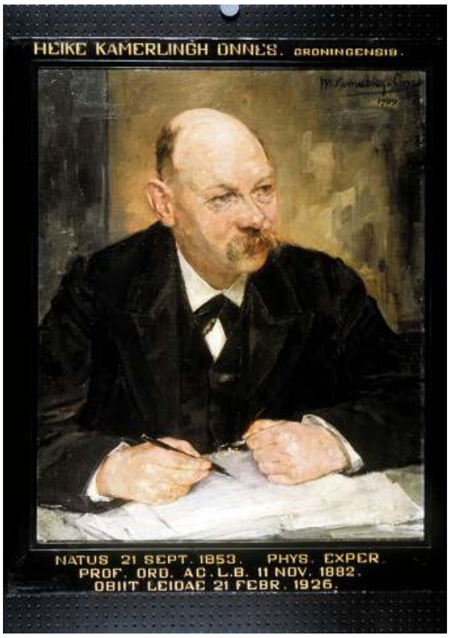


Fig. 1. Heike Kamerling Onnes (HKO), 1905 painting by his brother Menso.

Fig. 2. HKO's historical helium liquefier (last stage), now in Museum Boerhaave, Leiden.

I will address HKO's formative years, his scientific mission, the buiding up of a cryogenic laboratory as a direct consequence of this mission, add some words about the famous Leiden school of instrument makers, the role of the Leiden physics laboratory as an international centre of low temperature research, to end with a conclusion.

II. FORMATIVE YEARS

Our story starts in the province of Groningen, in the northern part of the Netherlands. Heike Kamerlingh Onnes was born in the city of Groningen in 1853. His father owned a tile factory in a small village nearby. As a boy, Heike wandered with his father around the factory site, and learned how bricks and roofing tiles were manufactured and how a company was run. This was an important experience. In his career as an experimental scientist and a managing director of a Physics Laboratory, Heike operated a kind of industrial approach. While his father was a manufacturer of tiles and bricks, he became a manufacturer of cold.

Heike studied at the University of Groningen. At the age of 16, he started with chemistry, his favourite topic at high school. As the chemistry department of Groningen University lacked proper facilities those days, after passing his propaedeutic exam Heike decided to go to Germany for a so called *Wanderjahr* (year of peregrination), and so he moved to Heidelberg, then famous for its international academic environment. Why Heidelberg? Because of Robert Bunsen, who in those days was the most famous chemist of Europe. Bunsen was a very competent experimenter, with fireproof fingers and hands like hams. His most famous invention was the Bunsen burner. He hated theory. His maxim was: "one correct and precise experimental fact has more value than all theories together".

In his first semester, Heike enjoyed the chemistry lab very much. However, when the time was there to start some own research, Bunsen's conservatism and aversion to mathematics got Heike to switch to physics. This was a wise decision. The Heidelberg physics department was led by a man almost as famous as Bunsen: Gustav Kirchhoff.

Important for Heike was that Kirchhoff was a *modern* physicist, in the sense that he propagated the fruitful exchange between theory and experiment. Heike, who had a strong interest in theory, was very much in favour of doing science this way.

After winning the Seminar Prize for his outstanding performance at the physics lab, Heike got one of the two assistant posts at Kirchhoff's Physics Laboratory. There, Kirchhoff asked him to build a table top Foucault pendulum, to be used as a demonstration experiment during lectures. Léon Foucault demonstrated his sensational 67 meter pendulum in 1851 in a crowded and delighted Pantheon in Paris. The pendulum (another one) is still there. The direct proof of the earth rotation impressed the public, the future Emperor Napoleon III included[1].

Building a short pendulum by way of an accurate scientific instrument turned out to be a very complicated experimental *and* a very complicated theoretical task. Heike took it as his doctoral project in Groningen. Because of the need for a vibration free suspension, the experimental set up was built in the basement of the Groningen Academy Building, where the custodian kept his dogs. Heike named the cellar "the Cyclops Cave" and it was in this uncomfortable, poorly illuminated room where he struggled hard with his cursed pendulum. In 1879 he came up with a full blown theoretical treatment of his subject and the accuracy of his experimental results was astonishing too. So he earned his doctorate *magna cum laude*. Figure 3 shows a photo of Heike in his first year at Groningen University, seventeen years old.

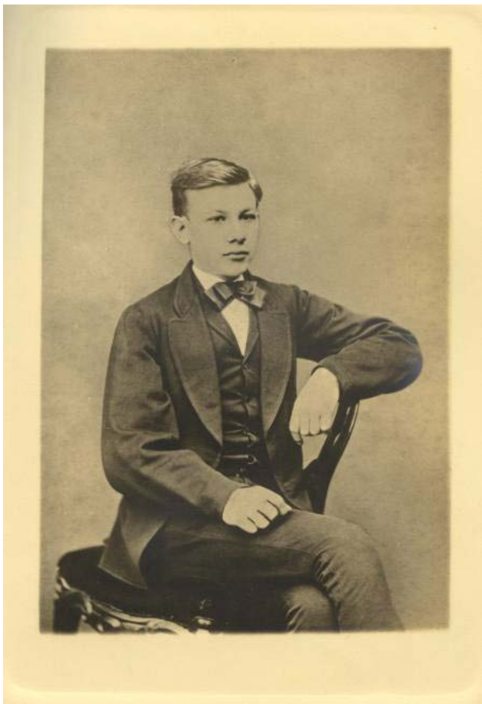


Fig. 3. Photo of HKO in his first year at Groningen University, 1870

[1] In 1851, the future Napoleon III was still an elected President (then the Dictator) of France.

III. SCIENTIFIC MISSION AND LIQUEFACTION OF OXYGEN

In 1882, Kamerlingh Onnes was appointed as a professor in experimental physics in Leiden. The physics department at that time was located in the right wing of the then new building shown in Figure 4. The left wing was occupied by the chemists. His direct colleague in Leiden was the theoretical physicist Hendrik Antoon Lorentz. They became close friends.

Fig. 4. Physics and chemistry department building of Leiden University in 1882.

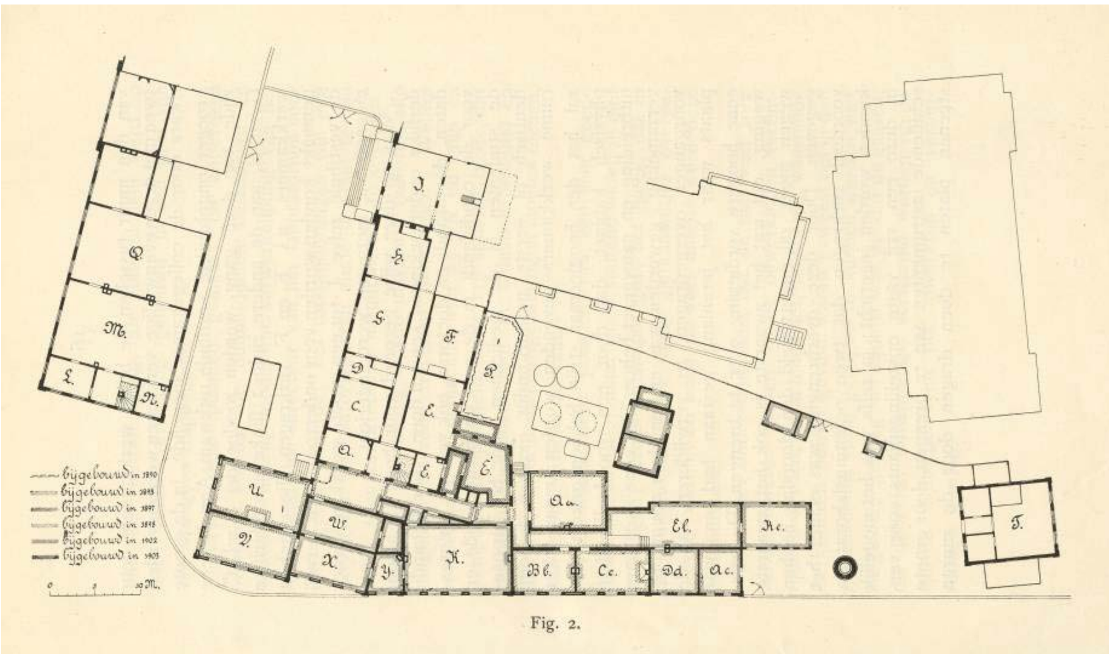


Fig. 5. Historical drawing of the laboratory extensions realised in the years 1882-1903.

As soon as he got started, HKO decided to reorganise the laboratory to suit his plans. After a structural alteration of the main building and creating some extensions, the physics laboratory was transformed from an institute of education into a research laboratory. Kamerlingh Onnes had a talent to persuade the authorities to invest big amounts of money in the physics department. Figure 5 shows the drawing of planned and executed extension.

Why this big effort? Because of his scientific mission: to test the molecular laws of Johannes Diderik van der Waals and in doing so, to give international prestige to Dutch physics. Here we have his equation of state on a stamp. Van der Waals had published his thesis on the continuity of the liquid and gas phase in 1873, a milestone in molecular physics – notice that molecules were not yet generally accepted those days. As a student in Groningen, Kamerlingh Onnes had been attracted to Van der Waals's results and to the kinetic theory of Clausius, Maxwell and Boltzmann.

A consequence of the Van der Waals equation of state is the existence of a critical temperature for each gas. Above the critical temperature, condensation of the gas is impossible, even at the highest pressures. Of course, as a physicist he would prefer simple substances. Monatomic gases like helium and argon were not yet available: they were discovered by William Ramsay in London only in 1895. So HKO started with diatomic gases: oxygen, nitrogen and hydrogen. However, the problem was these gases had very low critical temperatures: more then a hundred degrees Celsius below zero. The boiling temperatures were even lower: -183 °C for oxygen and -253 °C hydrogen. So that's why Kamerlingh Onnes got involved in building from scratch a cryogenic laboratory.

A major piece of apparatus in Kamerlingh Onnes's cryogenic laboratory was the Cailletet compressor, acquired in 1884 and transformed radically to suit the Leiden needs. The problem was that industrial standards were not good enough for scientific use. So Kamerlingh Onnes and his technicians spend lots of time to dismantle the pumps, improve parts, even change essential parts of the construction. In the first ten years of his professorship, KHO did not publish a single article. All that time, he was busy with the construction of his cryogenic installations; living in a world of grease, oil and fat. Nowadays, in the "publish or perish" era, to take a run up like that of HKO would amount to an academic suicide.

The installation for liquid oxygen was completed in 1894. Anyone who entered the cryogenic laboratory, and beheld the profusion of tubes, taps, gas flasks, gas holders, liquefiers, Dewar flasks, cryostats, clattering pumps and droning engines, glass-blowing and other workshops, instruments and appliances for scientific research, would have felt as if he had come to a factory; a cold factory. The cascade had three cycles. Each cycle was a refrigerator with a closed loop consisting of a compressor, an expansion tank and pumps. The end temperature of the first cycle was the starting point for the second one, *etc.* In the first cycle chloromethane was used, the second one consisted of ethylene and the third one had oxygen. In 1892 the Leiden cascade produced its first drops of liquid oxygen, while in 1894 it produced already a few litres per hour. Figure 6 is the photo of the oxygen liquefaction laboratory installation while Figure 7 shows the historical drawing of the cascade (a) and its modern schematic representation (b).

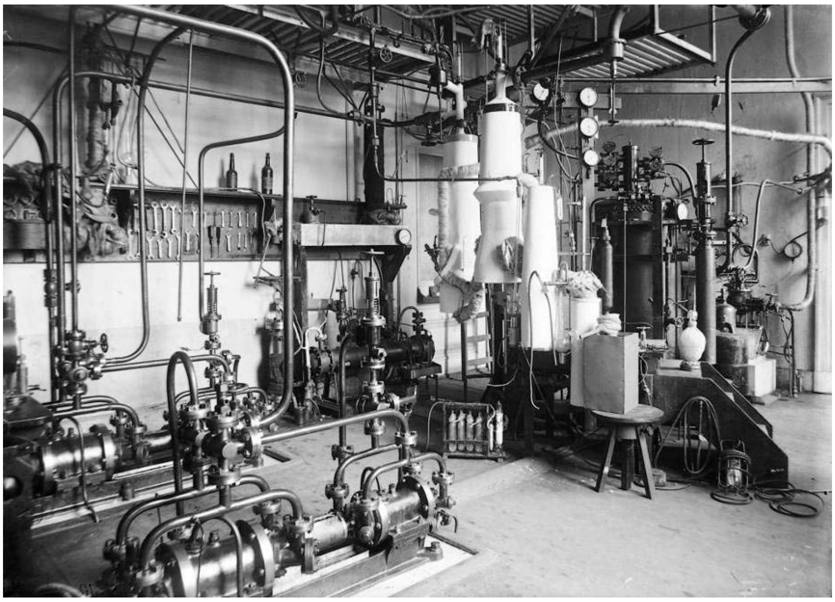
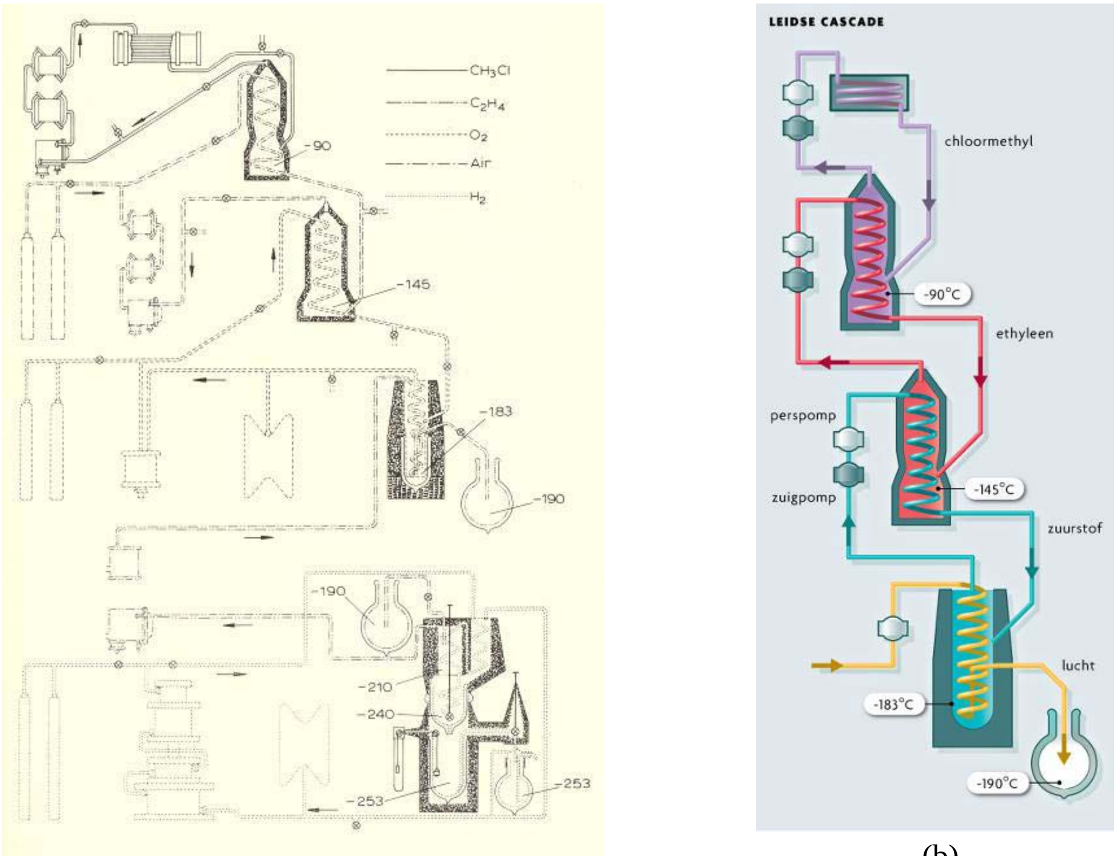


Fig. 6. Photo of the Leiden oxygen liquefaction laboratory, 1894.



(a) (b)

Fig. 7. The oxygen liquefaction cascade: (a) the historical drawing, (b) modern schematic representation. In the first cycle methylchloride was used (top), in the second one ethylene and oxygen was liquefied in the final one (bottom).

IV. SCHOOL OF INSTRUMENT MAKERS

Managing a cryogenic laboratory required an industrial approach. Of course, HKO had a coherent theoretical program, perseverance and a talent to persuade the right people. However, also such an industrial approach couldn't do without a strong technical support. The way he organized this support, by creating in 1901 a school of instrument makers as an integral part of his laboratory, is a unique feature of his cryogenic work and a decisive factor in its success.

Starting with one technician in 1882, HKO soon opened the doors of his simple workshop for a few 14 till 18 year old boys, who were trained as technicians. These "blue collar boys" – the name referred to the work clothes they had to wear – were obliged to visit a local technical school in the evening, where they were taught theoretical subjects. In 1898 there were 16 of them, in 1904 there were 32 blue collar boys. Kamerlingh Onnes used this small army of cheap technicians for building up his laboratory and performing measurements. However, the blue collar boys themselves profited too: after a few years of hard training they could get a job anywhere. HKO employed the best trainees himself. He always wanted the best people, so he got his glassblower, Oskar Kesselring, from Thüringen in Germany. Together with the chief instrument maker, Gerrit Flim, they formed the backbone of the Leiden technical staff. Figure 8 shows a historical photo of the machine shop with trainees, Figure 9 the glassblower shop.

Fig. 8. The machine shop with trainees, 1896.

Fig. 9. The glass blower shop. Standing at the left is Oskar Kesselring, 1902.

V. LIQUEFACTION OF HYDROGEN

In 1894, when the Leiden cascade produced liquid oxygen very efficiently and was described by *Nature* as an ‘extremely high performance apparatus” and as a “model cryogenic laboratory”[2], there was only one, so called, “permanent gas” to go: hydrogen[3]. However, the cascade method was inadequate for the purpose of obtaining liquid hydrogen. With pumped-on liquid oxygen, 54 K could be attained – any lower and the oxygen would freeze. Since the critical temperature of hydrogen was 33 K, a gap of over 20° had to be bridged before any liquid hydrogen could start to form. This gap was bridged by the Joule-Thomson effect. In 1852, James Joule and William Thomson (the later Lord Kelvin) had experimented with air passing through a tube and encountering a porous plug, behind which it expands. As it passes the plug, there is a small temperature reduction effect. In 1895, Carl von Linde and William Hampson independently designed refrigerators for liquid air based on the Joule-Thomson effect. The one devised by Linde, a successful German refrigerator manufacturer, was the first to be made operational.

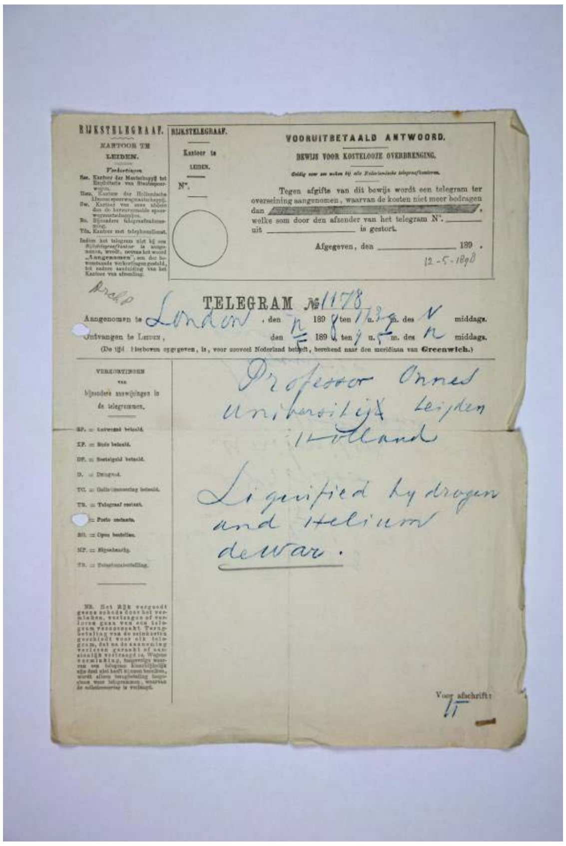
The race for liquid hydrogen was still undecided in 1895. Kamerlingh Onnes had developed ideas about building a hydrogen liquefier, but the problem was he couldn’t get started. The Leiden Physics Laboratory was built on the very spot where in 1807 a gunpowder ship had exploded, with a devastating effect. There were tens of casualties. In January 1895 HKO received a letter from the Leiden municipality that proved to be the opening move in a

[2] ‘The Physical Laboratory at Leiden (Holland)’, *Nature* **54** 345-347 (1896).

[3] Note that in 1894, helium still had to be discovered on Earth; this happened only in 1995.

long drawn out sparring match with the authorities. The neighbourhood had been alerted about "explosive substances" used by the physics professor and they wanted the laboratory moved out of town before another disaster could happen. Kamerlingh Onnes had to apply for a licence and to shut down his cryogenic laboratory for the time being. It was only after a three years struggle with the authorities that he could resume his cryogenic work.

At that moment the race to liquefy hydrogen had just produced a winner: James Dewar in London. Dewar said, he had collected 20 cc of liquid hydrogen in a double-walled insulated glass flask in the basement laboratory of the Royal Institution[4]. The liquid was clear and colourless and had a relatively high refractive index. Dewar had hoped to collect more, but after five minutes his installation had become clogged with air freezing in the pipes. He had succeeded, however, in immersing two thin tubes into the liquid hydrogen. One was open at the top, and the air at the level of the liquid hydrogen froze immediately. The second tube was connected to a spherical vessel containing helium gas, and its immersion triggered a process of condensation. And so on May 12, 1898 he sent a telegram to Leiden (Figure 10): "liquefied hydrogen and helium". It was a semi-triumph. A few days later Dewar had to admit it was not the helium that had been condensed but an impurity it contained.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Aangenomen te London
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University Leiden
Holland
Liquified hydrogen
and Helium
dewar.

Fig. 10. Dewar's telegram to HKO, May 12, 1998.

[4] This double-walled flask or cryostat is still named "dewar" after its designer.

The Leiden hydrogen liquefier was fully operational in 1906. It took so many years, largely because Kamerlingh Onnes wanted his liquefier to meet stringent standards. There was no point, since Dewar's achievement in 1898, in quickly putting together a piece of equipment that could produce a little liquid hydrogen, which would at best be useful for some small, orienting experiments. Leiden had lost that race anyhow. What HKO wanted was a liquefier that produced several litres of liquid hydrogen per hour in a continuous process, with maximum economy. This goal he finally attained.

VI. LIQUEFACTION OF HELIUM

There was still one gas to go: helium. It was discovered on Earth in 1895 by William Ramsay. Since then, all immediate attempts to liquefy the new gas by a single expansion, had failed. The two Scotsmen Dewar and Ramsay could have constituted a golden couple, but instead of joining forces – Ramsay the gas, Dewar the liquefaction – they were fighting each other. In fact, Dewar was fighting with everyone. So in 1895 Ramsay didn't supply Dewar with helium, but sent it to Karol Olszewski, Dewar's enemy in Cracow[5].

In 1906, when Kamerlingh Onnes finally had his hydrogen liquefier, the race for liquid helium was still undecided. The biggest problem was to collect enough helium gas and to purify it. Kamerlingh Onnes first got some litres of gas, collected from wells, from Ramsay. Later on, HKO's brother Onno mediated in a shipping of tens of sacks of monazite sand from the US, a mineral that contained helium (a product of radioactivity). It was a hell of a job to extract the helium from the sand and to purify it. Purification was extremely important because impurities like argon, neon or hydrogen froze in the cooling process and blocked pipes and valves.

On the 10th of Juli in 1908, after a hard day's work, the helium was liquefied. Early in the morning the work started with liquefying hydrogen. At half past one they had stored 20 litres in dewar vessels. In the afternoon the helium gas started to circulate, being compressed by the Cailletet compressor to keep the gas pure. Kamerlingh Onnes had no time for lunch so his wife Betsy came along to feed him pieces of bread. I quote here from Onnes's report "The liquefaction of helium" to the Dutch Academy of Sciences:

> In the construction of the apparatus it had been foreseen that it might fill with liquid, without our observing of the increase of the liquid. And the first time the appearance of the liquid had really escaped our observation. Perhaps the observation of the liquid surface, which is difficult for the first time under any circumstance, had become the more difficult because of the temperature reservoir. However this may be, later on we clearly saw the liquid level get hollow by the blowing of the gas from the valve and rise in consequence of influx of liquid on applying accelerated expansion. […]

[5] Olszewski, in collaboration with Z. Wróblewski, was the first to liquefy oxygen (on April 19, 1883) and nitrogen.

> The surface of the liquid was soon made clearly visible by reflection of light from below and that unmistakably, because it was clearly pierced by the two wires of the thermo-element.
> This was at 7.30 p.m. After the surface had once been seen, the sight of it was no more lost. It stood out sharply defined like the edge of a knife against the glass wall.

The temperature of the liquid helium – about 60 millilitres of it, a little teacup – was 4.2 kelvin. By decreasing the pressure with a vacuum pump, the temperature was lowered until 1.8 kelvin, but helium refused to solidify.

Dewar lost the contest for liquid helium. Why? Decisive for Kamerlingh Onnes's success was his industrial approach. Dewar struggled with impurities in his helium and a shortage of liquid hydrogen. He quarrelled with everybody and lacked the technical support HKO had organized for himself. Dewar once wrote in a letter to Onnes "At the forefront of science assistants are a waste". HKO proved this to be wrong. Figure 11 shows the historical photo of the HKO installation in which the first liquefaction occurred. The heart of it, preserved in our Museum, is shown in Figure 2 above.

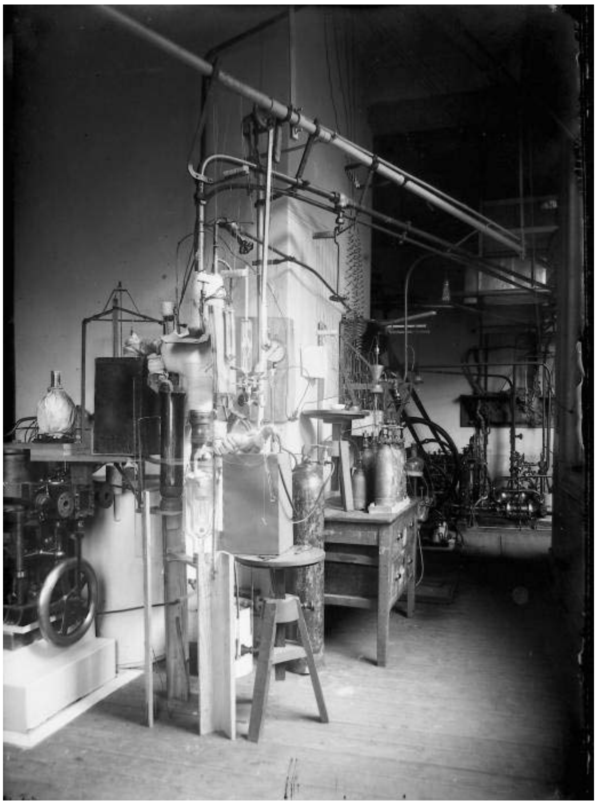

Fig. 12. Historical photo of the installation, in which He was liquefied for the first time

In 1913 Kamerlingh Onnes won the Nobel Prize for his low-temperature work, resulting in the production of liquid helium. There was no mention of superconductivity. Figure 13 is HKO's photo taken not long after the telegram from Stockholm arrived.

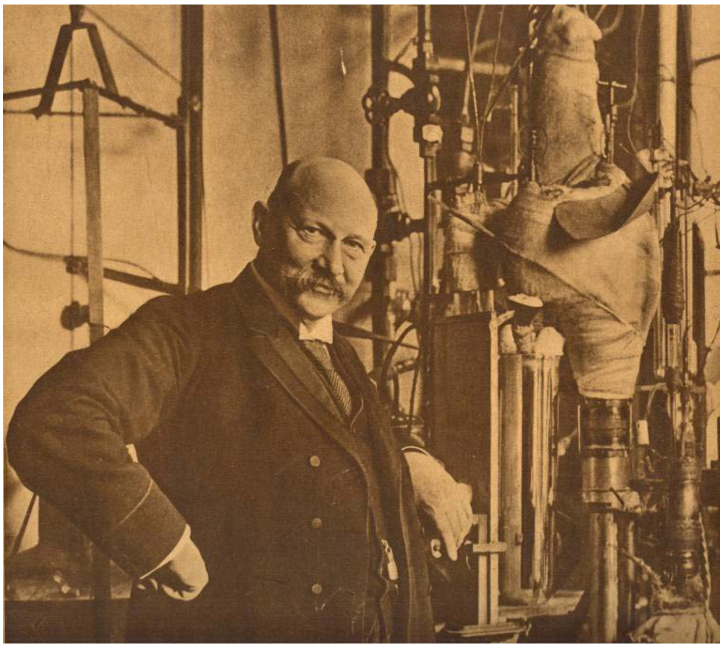

Fig. 13. Photo of Kamerligh Onnes with his He liquefier (1913).

VII. INTERNATIONAL CENTRE FOR LOW TEMPERATURE RESEARCH

After the liquefaction of helium, the Leiden physics laboratory developed into an international facility for low temperature research. It attracted a lot of visitors and researchers from abroad. Kamerlingh Onnes was famous for his hospitality. Many great physicists – Einstein, Madame Curie, Bohr, Lenard, Ramsay, etc., etc., –stayed in his home 'Huize ter Wetering', just outside Leiden. Figure 14 shows a photo of HKO with Paul Ehrenfest, Lorentz and Niels Bohr taken in 1919, while Figure 15 is a sketch of Einstein with Kamerlingh Onnes drawn in1920 by Harm, HKO's nephew. Einstein was a regular visitor of the Onnes family.

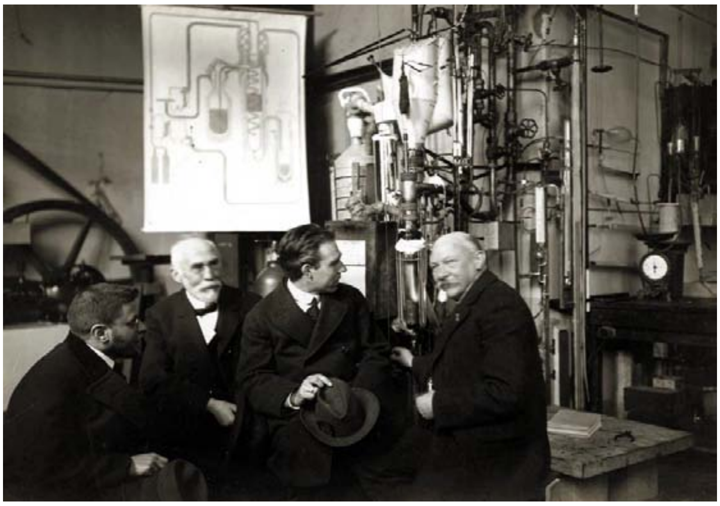

Fig. 14. Visitors at the He liquefaction laboratory.
From left to right: Ehrenfest, Lorentz, Bohr and HKO (1919).

Fig. 15. Albert Einstein with HKO. A 1920 sketch by Harm, son of Menso Kamerlingh Onnes (HKO's brother).

By the time of HKO retirement in 1924, the Leiden Physics Laboratory had expanded enormously when compared with the stand of 1880s (Figure 5). A layout drawing of the laboratory rooms, dating from about 1925, is shown in Figure 16.

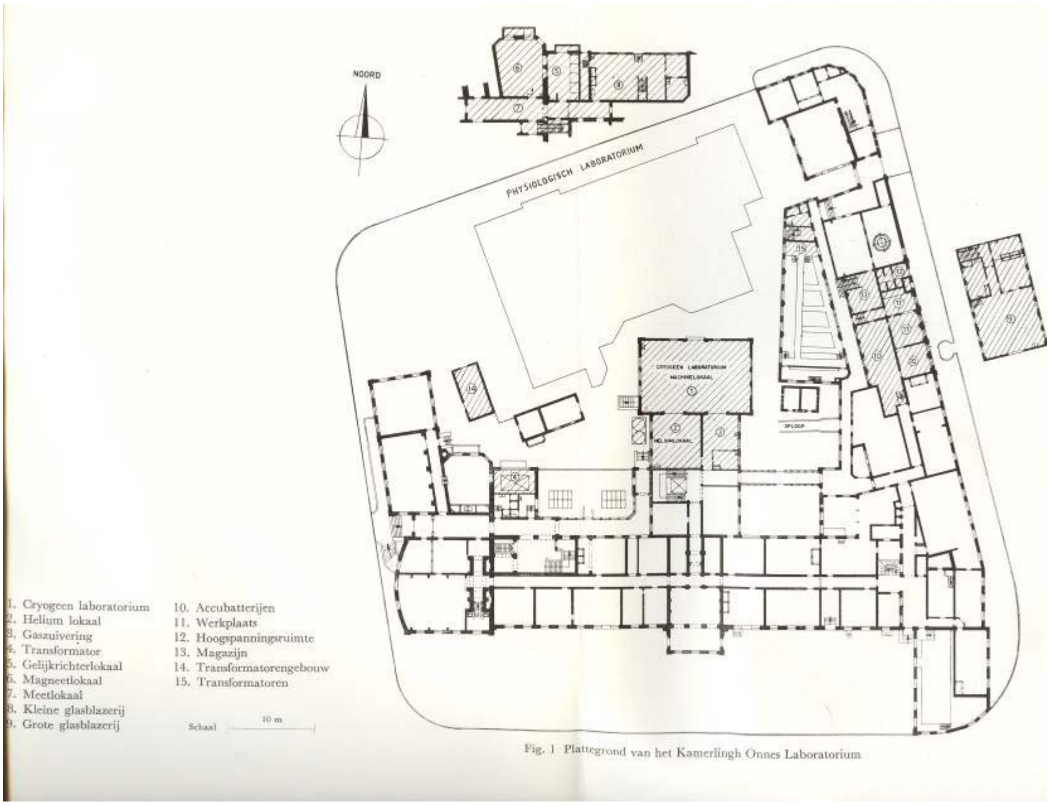

Fig. 16. The Leiden Physics laboratory layout of rooms, ca. 1925.

VIII. CONCLUSION

My conclusion is, HKO's entrepreneurial abilities proved invaluable. Building up a cryogenic laboratory of international status, of a size and personnel unequalled anywhere in the world, called for more than a great talent for physics. Anyone who entered the Steenschuur premises, especially the lab E and its surrounding area, would have felt as if he had come to a "cold factory", with Professor Kamerlingh Onnes as its director, determining policy and exercising tight overall control. As the director of an enterprise, he also set up a well-oiled organisation presided over by an administrative supervisor, a research team including assistants and postgraduate students, a manager, instrument-makers, glass-blowers, laboratory assistants, technicians, an engineer, an assistant supervisor, not to mention a small army of trainee instrument-makers to perform any number of odd jobs. HKO's project was, indeed, Big Science.

With this Big Science approach, his carefully orchestrated research programme, in which, instead of working individually, everyone contributed to a team effort in pursuit of a well-defined goal, Kamerlingh Onnes set an example that other laboratories later emulated[6].

[6] For further information on HKO and his achievements see Dirk van Delft, *Freezing Physics. Heike Kamerlingh Onnes and the Quest for Cold*, Edita, Royal Dutch Academy of Sciences and Arts (Amsterdam, 2008)