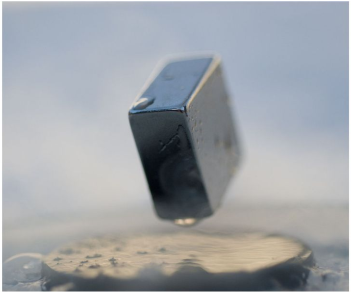
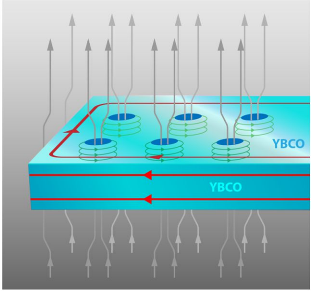
Introduction

Alexander Tsirlin

Division of Quantum Magnetism and Superconductivity

Felix Bloch Institute for Solid-State Physics





UNIVERSITÄT
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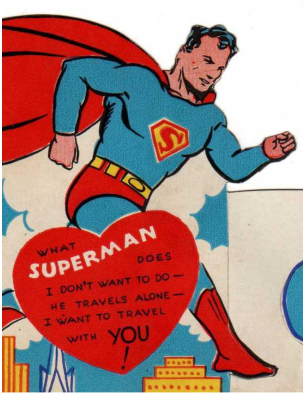
Superconductivity I, SS 24



superman

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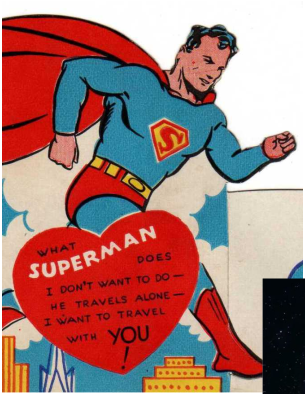
Image credit: MTV International (CC-BY-SA), fair use

supernova



superman

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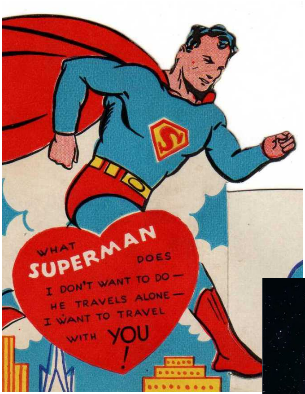

superman

supernova

supernatural

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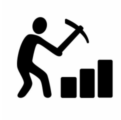
Concepts / Theory

Concepts / Theory



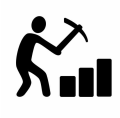
Experiment

Concepts / Theory

Experiment

Technology / Material

Concepts / Theory



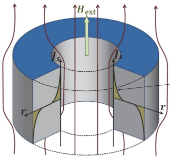
Experiment

Technology / Material

Personality

1. Basic phenomenology

- Meissner effect
- penetration depth / *London theory*
- flux quantization



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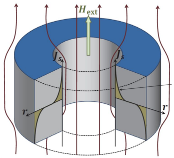
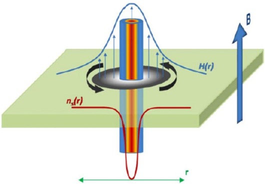


2. Advanced phenomenology

- *Ginzburg-Landau theory*
- vortices, type-II superconductors
- Josephson junctions / qubits



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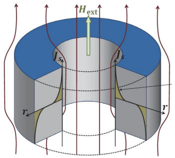

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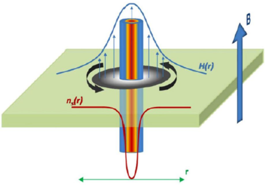
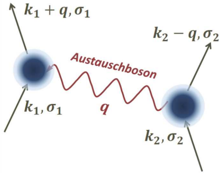


3. Microscopic theory

- *BCS theory* (Bardeen-Cooper-Schrieffer)
- Cooper pairs, superconducting gap
- conventional vs. unconventional



Where and when?

Th 15:15, kleiner Hörsaal
+ exercise classes

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Th 15:15, kleiner Hörsaal
+ exercise classes

Information:

https://research.uni-leipzig.de/sum/sc1.html

- *lecture slides*
- *lecture notes* (alpha-version)
- *supplemental material & reading suggestions*
- details about exercise classes

Organizational

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Information:

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- *lecture slides*
- *lecture notes* (alpha-version)
- *supplemental material & reading suggestions*
- details about exercise classes

Contact: ask your questions after the lecture
or via e-mail, alexander.tsirlin@uni-leipzig.de

- 4 problem sheets
  will be available on the web page
- solutions are due 2-3 weeks later
- merge everything into a single PDF-file
- submit via Moodle

Exercise classes

Th 17:00, kleiner Hörsaal
$\longrightarrow$ 11.04, 25.04, 2.05, 16.05, 6.06, 20.06
solving the four problem sheets,
and additional practical sessions (see web page)

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and additional practical sessions (see web page)

50% points for the solutions
is a pre-requisite for taking the exam

- Oral exam (30 minutes)
- Appointments: ~8.07, ~18.07, and 31.07-2.08 (main slot)
  (last lecture will be on 27.06)
- List of questions will be available

- Pre-requisites:
  - know and understand the main concepts
  - able to explain solutions to the exercises
  - know practical aspects:
    - how to measure this or that parameter?
    - what is important for applications?

- **V. Schmidt. The physics of superconductors**
  systematic and mathematically simple, yet rigorous;
  may be difficult to find

- Buckel, Kleiner. Superconductivity: fundamentals and applications
  both English and German versions

- Tinkham. Introduction to superconductivity
  phenomenological and microscopic aspects strongly intermixed

- solid-state physics textbooks
  have extensive chapters on superconductivity
  for example, over 100 pages in Gross, Marx. Festkörperphysik

- beware of textbooks that are geared toward theorists
- don't overlook **supplemental material** (see the web page)

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Expulsion of magnetic field

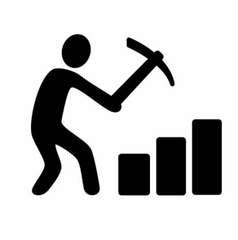
ideal conductor + ideal diamagnet

cryogenic techniques

mercury

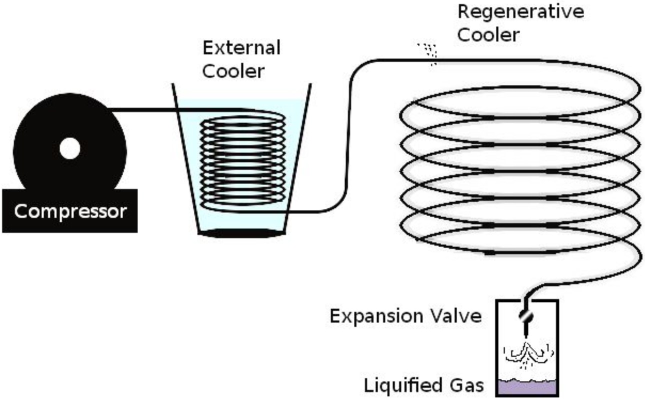
Heike Kamerlingh Onnes

Lecture 1: April 4, 2024



Experiment

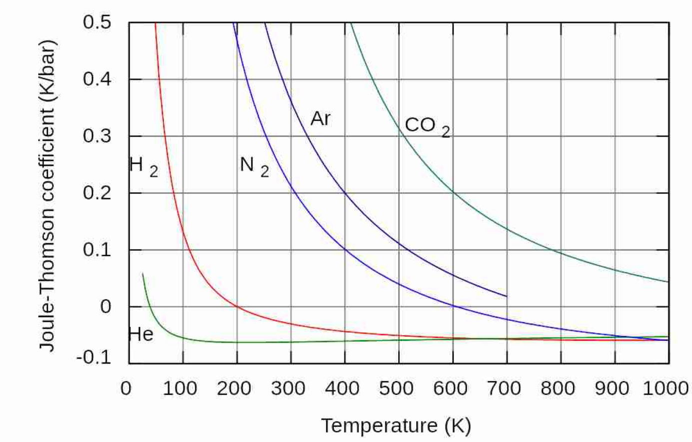
cryogenic techniques



Cooling by expansion

Efficiency depends on the Joule-Thomson coefficient, $\left(\frac{\partial T}{\partial p}\right)_H$

Image credit: Riventree (CC-zero) and Hankwang (CC-BY-SA)



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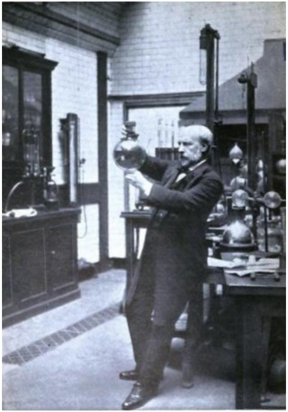


James Dewar
1842–1923

developed vacuum flask
for cryogenic liquids (1892)

first obtained liquid hydrogen (1898)

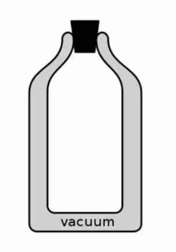
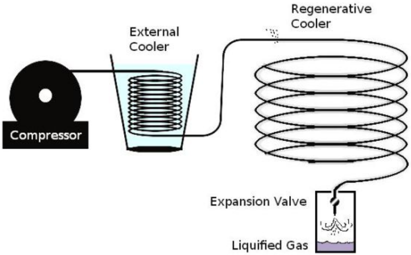
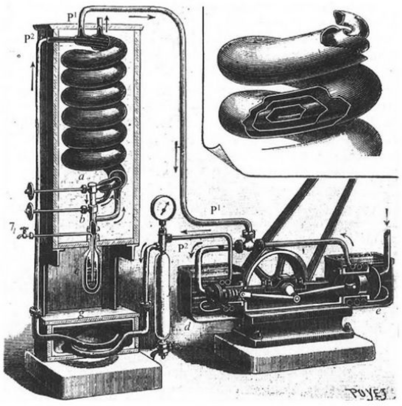


Image credit: Vicarious, Denae Bedard, LepoRello, Jeffrey M. Vinocur (CC-BY-SA)





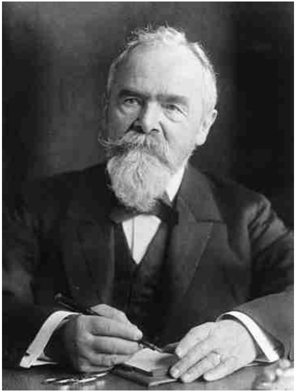
independently patented by

William Hampson (UK)
Carl von Linde (Germany)

Closed-cycle process for liquefaction of gases

Cold gas is used to cool new portions of the compressed gas

Image credit: Riventree (CC-zero) and Cryogenic Engineering: 50 years of progress (Springer, 2007)



Carl von Linde
1832–1934

engineer of refrigeration systems

from 1879: *Gesellschaft für Linde's Eismaschinen Aktiengesellschaft* (nowadays, Linde group)

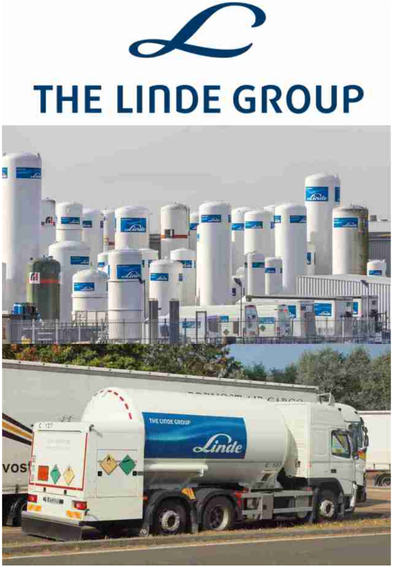
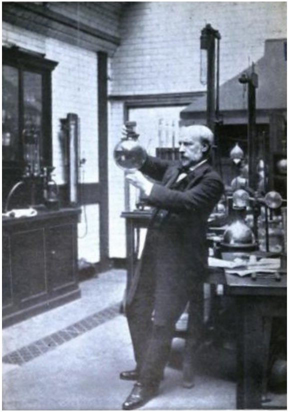


Image credit: Raimond Spekking and François GOGLINS (CC-BY-SA)



James Dewar
1842–1923

Dewar flask,
first large-scale production
of liquid oxygen (1891),
first liquefaction of hydrogen (1898)

Heike Kamerlingh Onnes
1853–1926

1913 Nobel prize in physics "for his investigations on the properties of matter at low temperatures which led, *inter alia*, to the production of liquid helium"

- **"Standard" ^{4}He cryostat:**
  $T \geq 1.5 - 4.2\,\mathrm{K}$

- **^{3}He cryostat:**
  $T \geq 350 - 400\,\mathrm{mK}$

- **Dilution refrigerator**
  (^{3}He–^{4}He mixture): $T \geq 20\,\mathrm{mK}$

- **Micro-Kelvin temperatures:**
  adiabatic demagnetization, nuclear spins

Image credit: Quantum Design and EPJ Quantum Technol. 6, 2 (2019)

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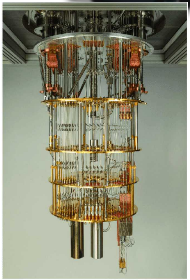

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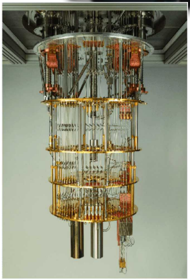

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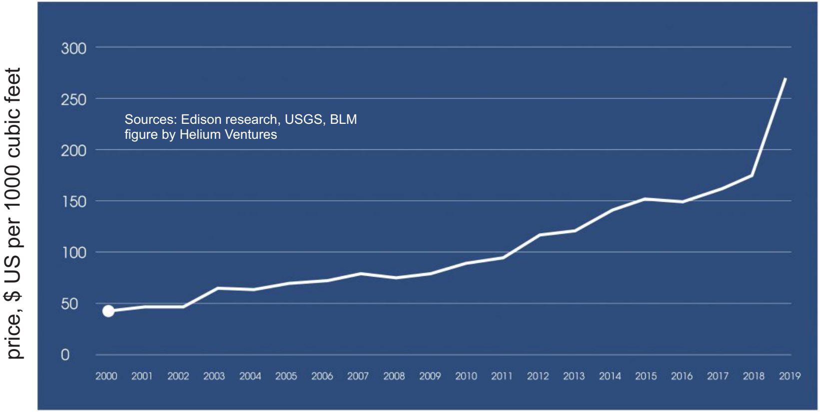
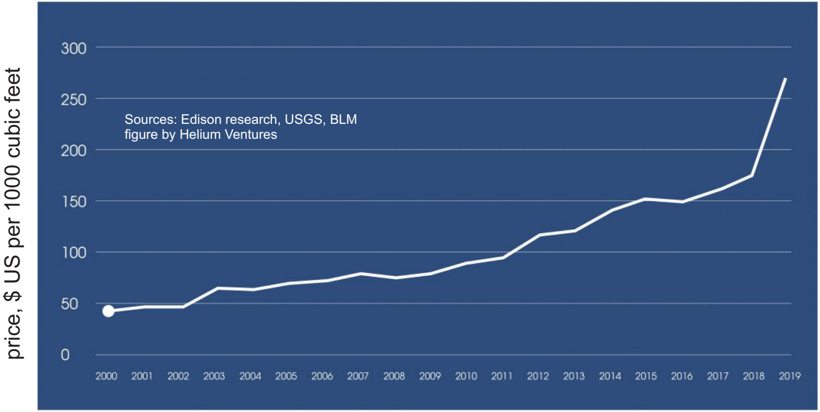


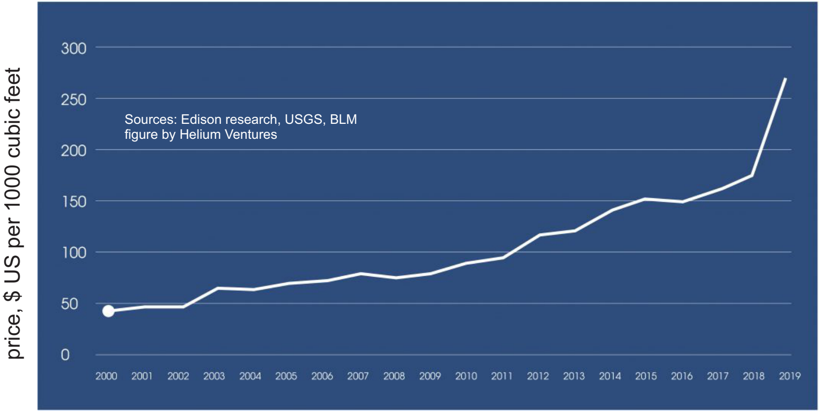
Our price in Leipzig (liquid helium)

- 2021: 16.90 EUR per liter



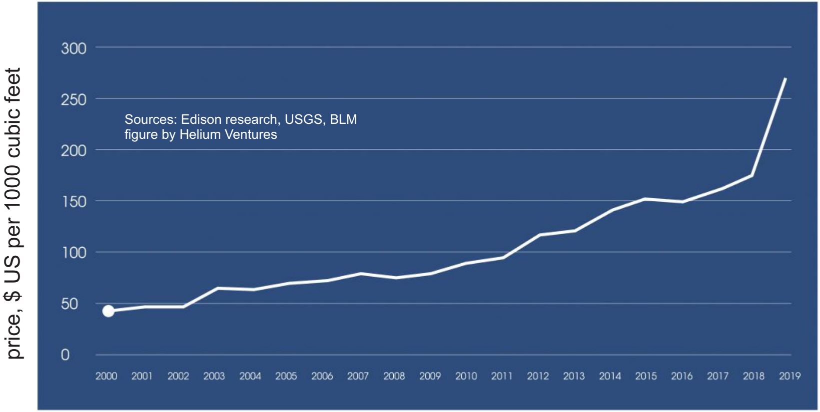
Our price in Leipzig (liquid helium)

- 2021: 16.90 EUR per liter
- 2022: 27.15 EUR per liter



Our price in Leipzig (liquid helium)

- 2021: 16.90 EUR per liter
- 2022: 27.15 EUR per liter
- 2023: 43.20 EUR per liter



Our price in Leipzig (liquid helium)

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- 2023: 43.20 EUR per liter

Typical consumption:

20–100 liters per week per cryostat

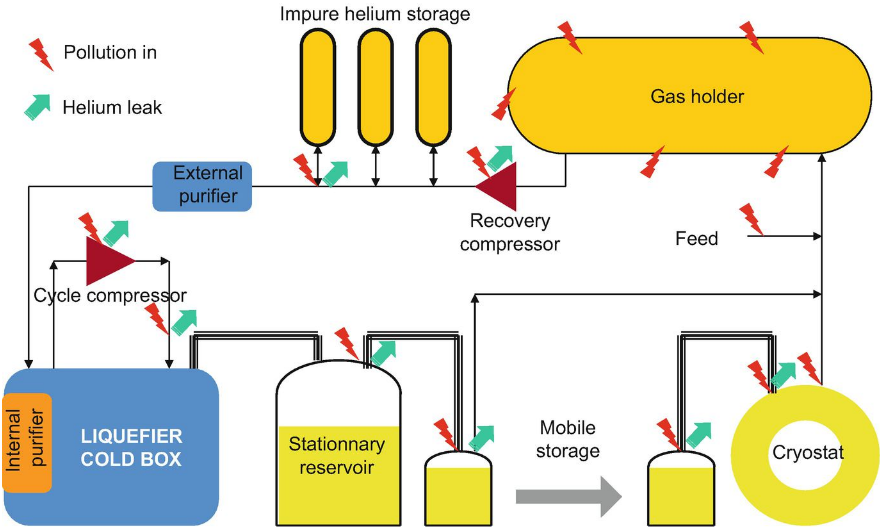


Image credit: G.G. Baguer, Cryogenic helium refrigeration for middle and large powers (Springer, 2020)

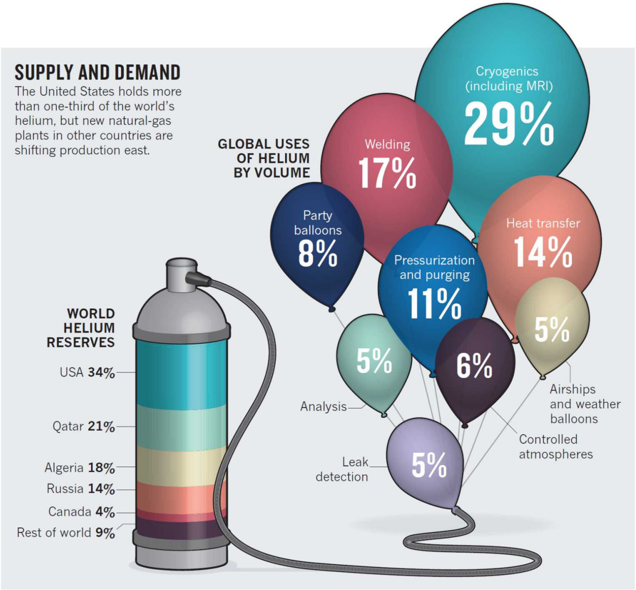
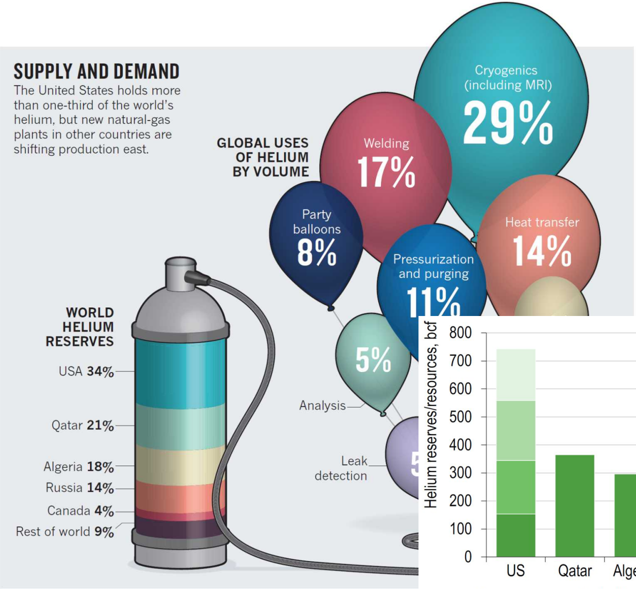
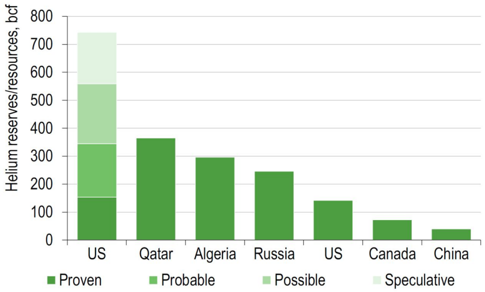


Image credit: Nature 485, 574 (2012) and Edison International





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Personality

Heike Kamerlingh Onnes

- 1870–1878: physics studies at Groningen and Heidelberg
- 1879: PhD on "New proofs for the axial rotation of the Earth"
- 1879–1882: lecturer at Delft
- from 1882: professor at Leiden, properties of gases
- 1904: founded the dedicated cryogenics lab
- 1908: liquefaction of helium

Heike Kamerlingh Onnes
1853–1926

Liquefaction of helium

Monazite sand
the source of helium

At first the great difficulty was how to obtain sufficient quantities of this gas. Fortunately the Office of Commercial Intelligence at Amsterdam under the direction of my brother, Mr. O. KAMERLINGH ONNES, to whom I here express my thanks, succeeded in finding in the monazite sand the most suitable commercial article as material for the preparation, and in affording me an opportunity to procure large quantities on favourable terms. The monazite sand being inexpensive, the preparation of pure helium in large quantities became chiefly a matter of perseverance and care.[2]

[2]) [Even the quantity of 200 liters (and 160 liters of reserve) of the extreme purity required, though requiring a great deal of labour, was not out of reach].

Image source: KNAW Proceedings 11, 168 (1908)

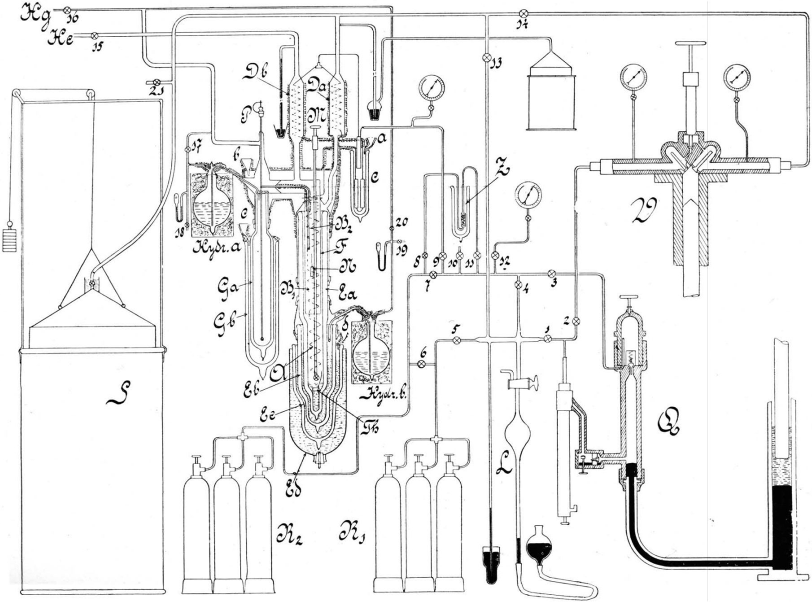

Image source: KNAW Proceedings 11, 168 (1908)

Liquefaction of helium

The liquefiers constructed by H. Kamerlingh Onnes:

1906	hydrogen liquefier	production 4 liters liquid/hour
1908	first helium liquefier	production 0.28 liter liquid/hour
1912	improved version	production 0.5 liter liquid /hour
1919	second helium liquefier	production 1.7 liter liquid/hour
1923	first transfer of liquid helium into a separate cryostat	

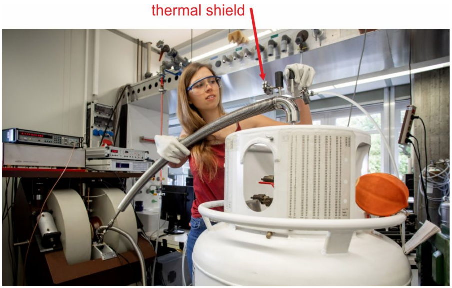

Image source: IEEE Trans. Magn. 23, 355 (1987) and PI1, Uni Stuttgart

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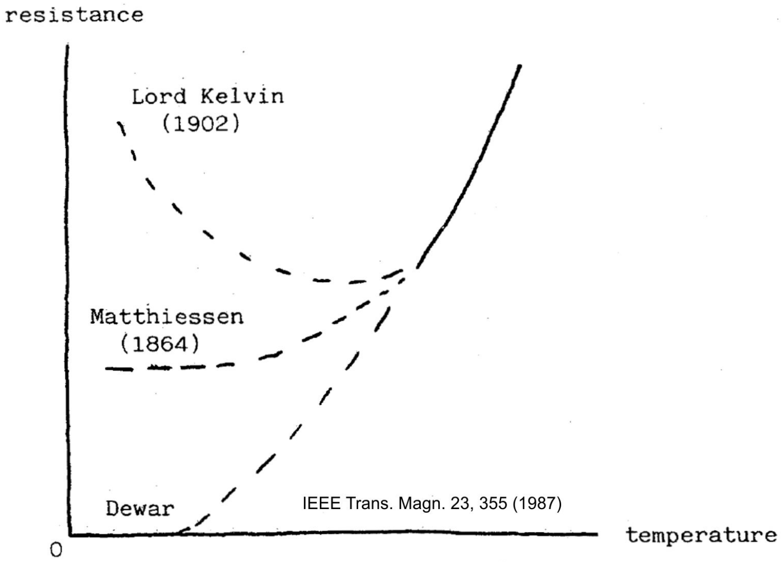
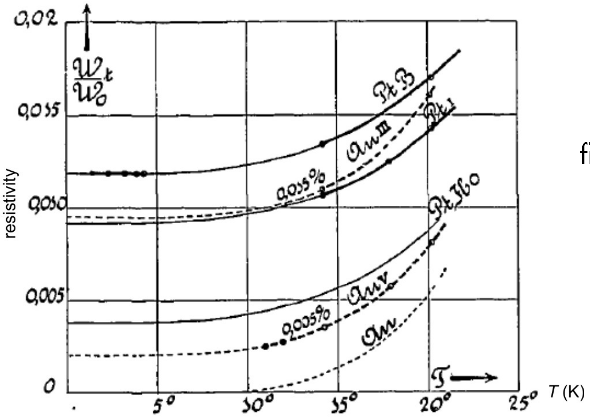
- 1879–1882: lecturer at Delft
- from 1882: professor at Leiden, properties of gases
- 1904: founded the dedicated cryogenics lab
- 1908: liquefaction of helium
- 1911: conductivity of metals, superconductivity
- 1913: Nobel prize in physics
- 1923: first liquid helium transfer
- until 1930's: Leiden remains the only low-T research center in the world

Heike Kamerlingh Onnes
1853–1926

Material / Technology

mercury


resistance
Lord Kelvin
(1902)
Matthiessen
(1864)
Dewar
IEEE Trans. Magn. 23, 355 (1987)
temperature
0

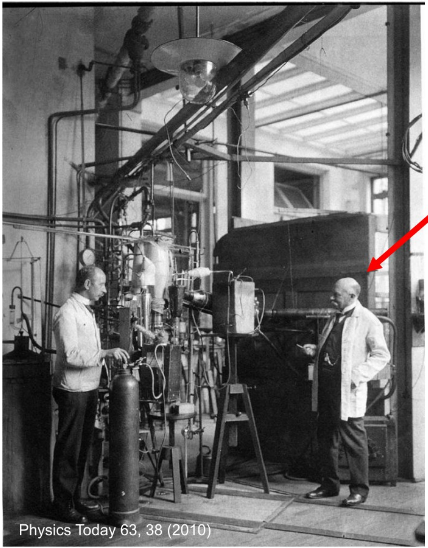


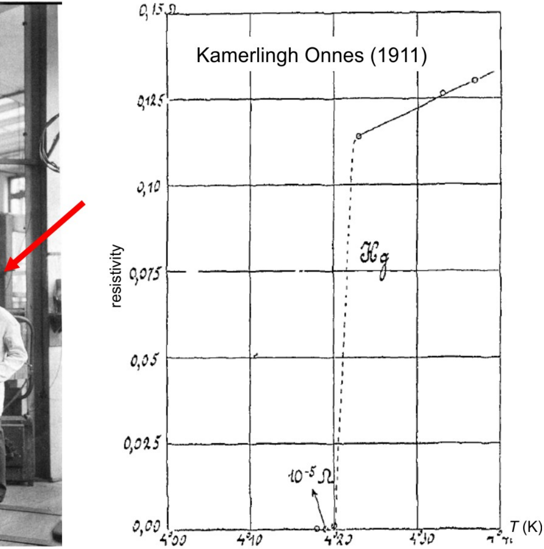
Kamerlingh Onnes

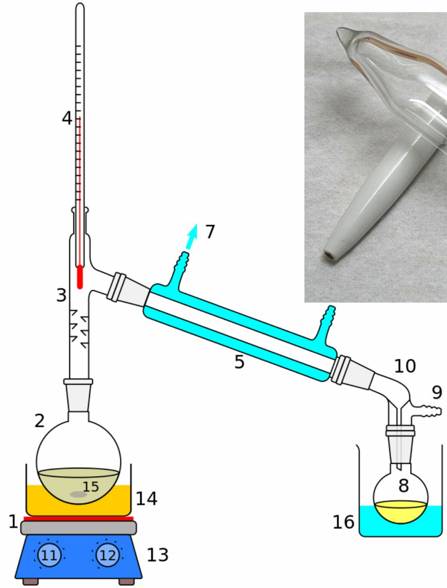
first ever measurements down to 10 K

Resistivity in the $T \to 0$ limit depends on the sample purity

Residual resistivity ratio: $\mathrm{RRR} = \rho_{300\,\mathrm{K}}/\rho_{0\,\mathrm{K}}$, gauges sample quality


Physics Today 63, 38 (2010)





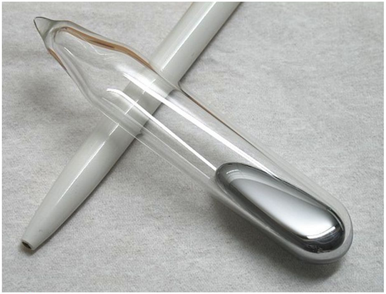


Image credit: Quantockgoblin (PD) and W. Oelen (CC-BY-SA)