MVCMP-1 Low Temperature Physics

Modul MVCMP-1 consists of two parts:

Tutorials	Thu 14:15 - 16:00, INF 227, SR 02.403
Fri   14:15 - 16:00, INF 227, SR 03.404

Coordinator/Tutor: Andreas Fleischmann
Kirchhoff Institute for Physik (KIP)
room: 0.309, phone 06221/549880
email: andreas.fleischmann@kip.uni-heidelberg.de

Lecture:	Mon and Wed 11:15 – 13:00, HS2 KIP

Christian Enss
Kirchhoff Institute for Physik (KIP)
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Office hour: mondays 14:00 – 15:00, in addition by appointment

Web: https://uebungen.physik.uni-heidelberg.de/vorlesung/20241/1875

Tutorials

Start: 2nd week, i.e. 25./26.04.2024

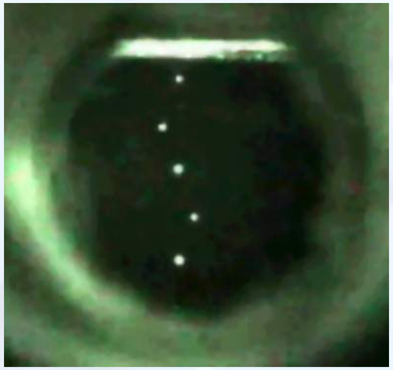
Exercise sheets: Published each Tuesday on homepage of lecture

The active participation in the tutorials will be realized by presenting solutions every week. The willingness to present a solution has to be indicated at the beginning of the tutorial by signing up on a list of all participants. To be permitted to the final exam you need to sign up for at least 60 % of all possible problems.

In addition, you may hand in written solutions, but they will not be included in the grading. However, they will be corrected and returned.

Exam: Takes place as written exam at the end of term – date will be announced later

Content

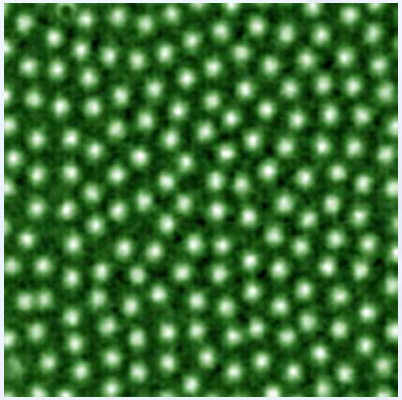


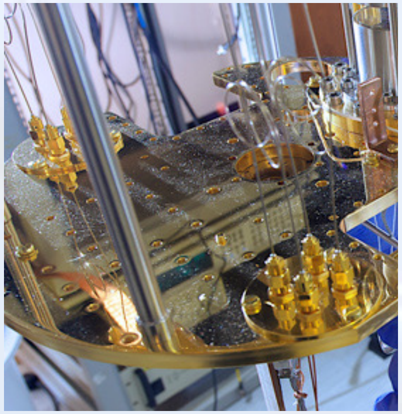
1. Quantum Fluids

Superfluid ^4He
Normalfluid ^3He
Superfluid ^3He
$^3He/^4He$ Mixtures

2. Solids at Low Temperatures

Phonons
Conduction Electrons
Magnetic Moments
Atomic Tunneling Systems
Superconductivity



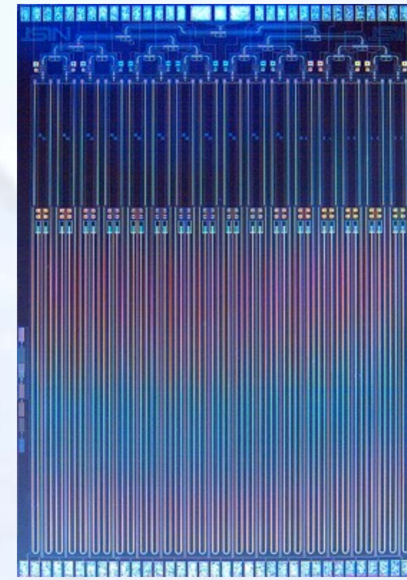


3. Refrigeration und Thermometry

Gas Liquefaction
Bath Cryostats
Dilution Refrigerator
Adiabatic Demagnetization
Primary and Secondary thermometers

Why Low Temperatures?

- selective freezing of degrees of freedom
- systems with small energies
- low noise measurements
- different time scales
- new phenomena and new technologies



Superfluidity

Superconductivity

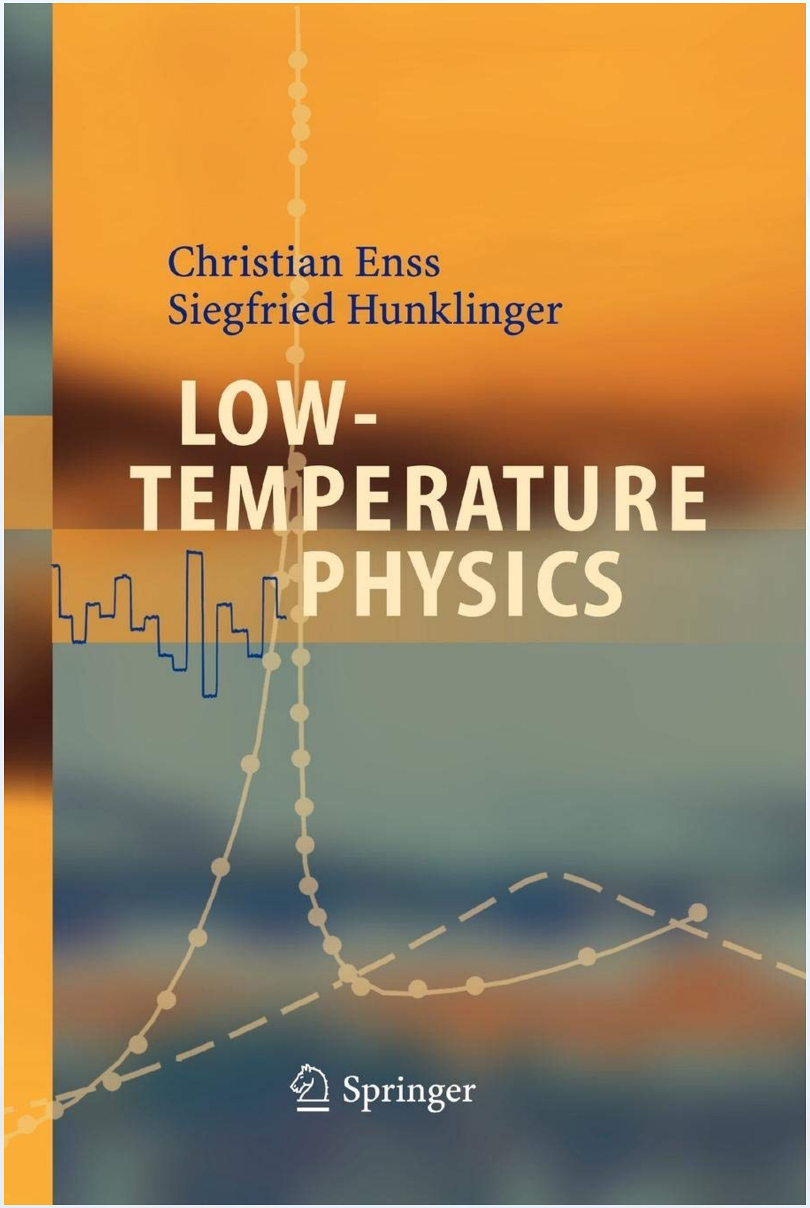
Tunneling of atoms in solids

Quantum Metrology

Quantum Computing

Cryogenic Particle Detectors

Literature


Christian Enss
Siegfried Hunklinger
LOW-TEMPERATURE PHYSICS
Springer

Literature for Specific Topics

Quantum Fluids

C. Barenghi, N.G. Parker, A Primer on Quantum Fluids, Springer 2016
J. Wilks, D.S. Betts, Introduction to Liquid Helium, Oxford 1987
S.J. Putterman, Superfluid Hydrodynamics, North-Holland 1974
F. London, Superfluids II, Wiley 1954
D.R. Tilley and J. Tilley, Superfluidity and Superconductivity, Adam Hilger 1990
D. Vollhardt, P. Wölfle, The Superfluid Phases of 3He, Talyor&Francis 1990
K.R. Atkins, Liquid Helium, Cambridge University Press, 1959
K.H. Bennemann, J. B. Ketterson (eds.), The Physics of Liquid and Solid Helium
Band I und II, John Wiley & Sons New York 1976, 1979
W.E. Keller, Helium-3 und Helium-4, Plenum Press New York 1969

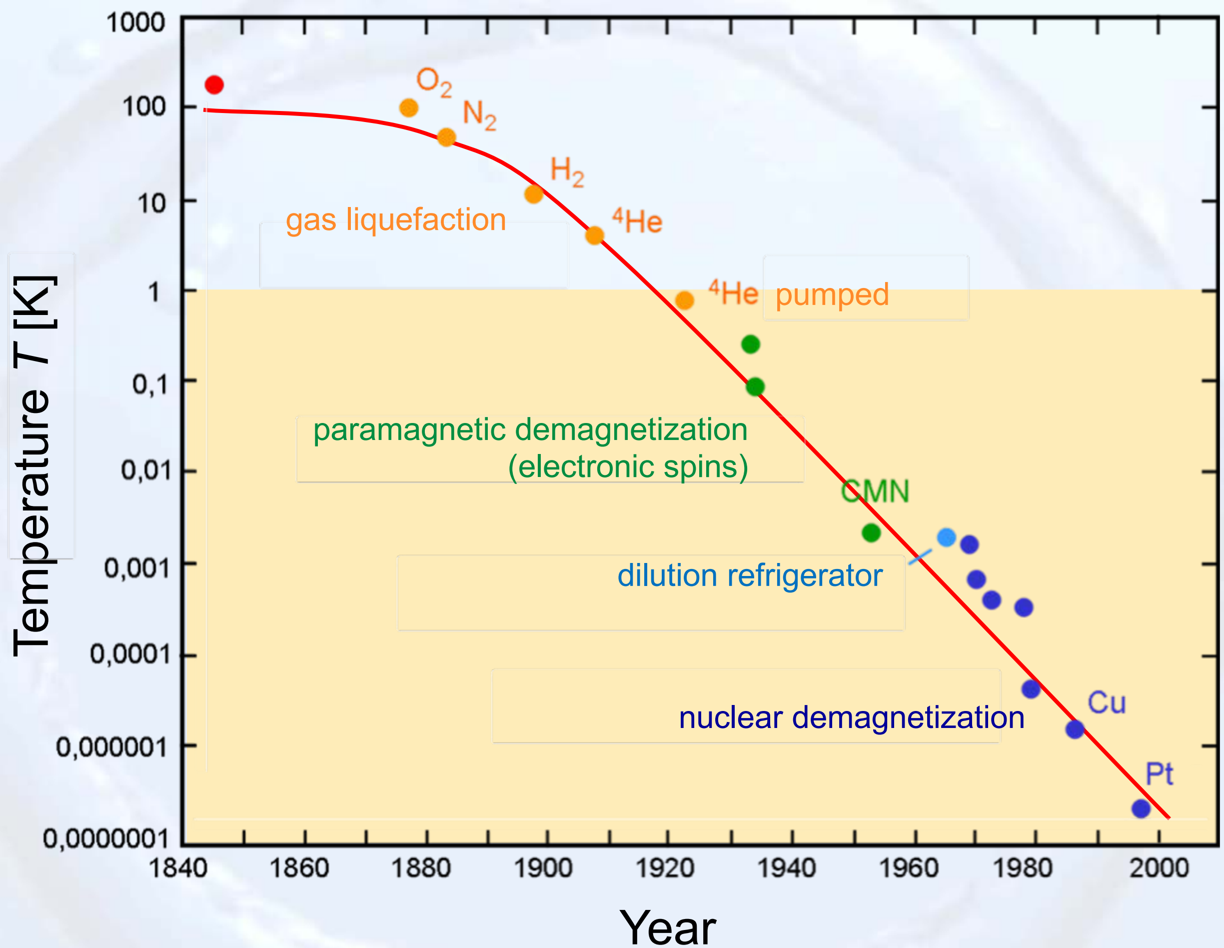
Solids

S. Hunklinger, C. Enss, Solid State Physics, de Gruyter 2022
R.G. Sharma, Superconductivity, Springer 2022
W. Buckel, R. Kleiner Supraleitung, Wiley VCH 2012
J.R. Waldram, Superconductivity of Metals and Cuprates, Institute of Physics 1996
A. Würger, From Coherent Tunneling to Relaxation, Springer 1996
W.A. Philips (ed.), Amorphous Solids, Springer 1981
P.V.E. McClintock, D.J. Meredith, J.K. Wigmore, Matter at Low Temperatures, Blackie 1984
E.S.R. Gopal, Specific Heats at Low Temperatures, Plenum 1966
H.M. Rosenberg, Low Temperature Solid State Physics, Clarendon Press 1963
J. M. Ziman, Prinzipien der Festkörpertheorie, Harri Deutsch-Verlag, 1972

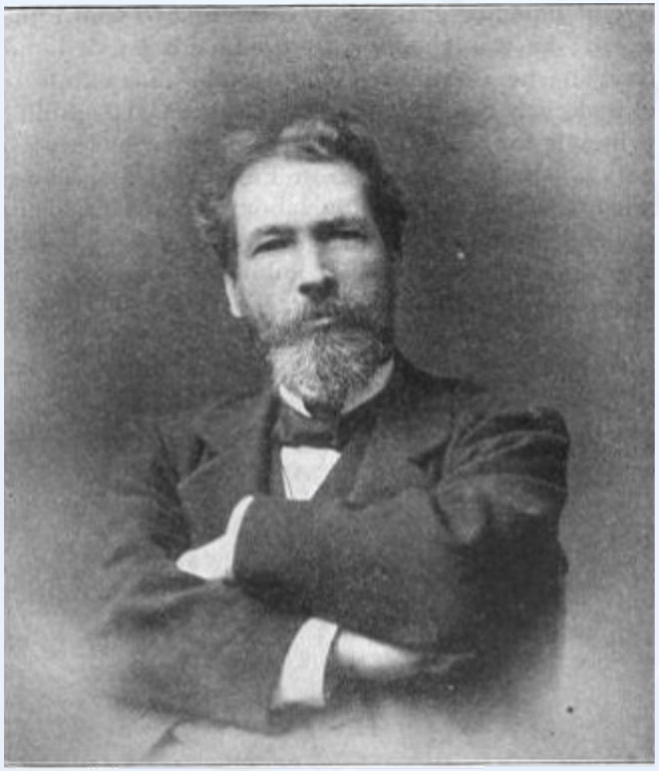
Production of Low Temperatures

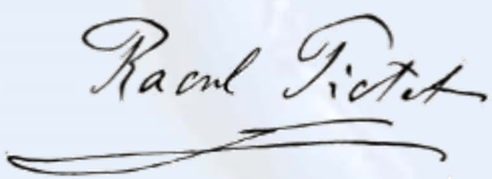
F. Pobell, Matter and Methods at low temperatures, Springer 2007
Handbuch der Physik, Band XIV, Kältephysik I+II, Springer 1956
D.S. Betts, An Introduction to Millikelvin Technology, Cambridge\nl University Press 1989
D.S. Betts, Refrigeration and Thermometry Below One Kelvin, Sussex University Press 1986
O.V. Lounasmaa, Experimental Principles and Methods Below 1 K, Academic Press 1974
A. Kent, Experimental Low-Temperature Physics, American Institute of Physics 1993

Historical Development of Low Temperature Production



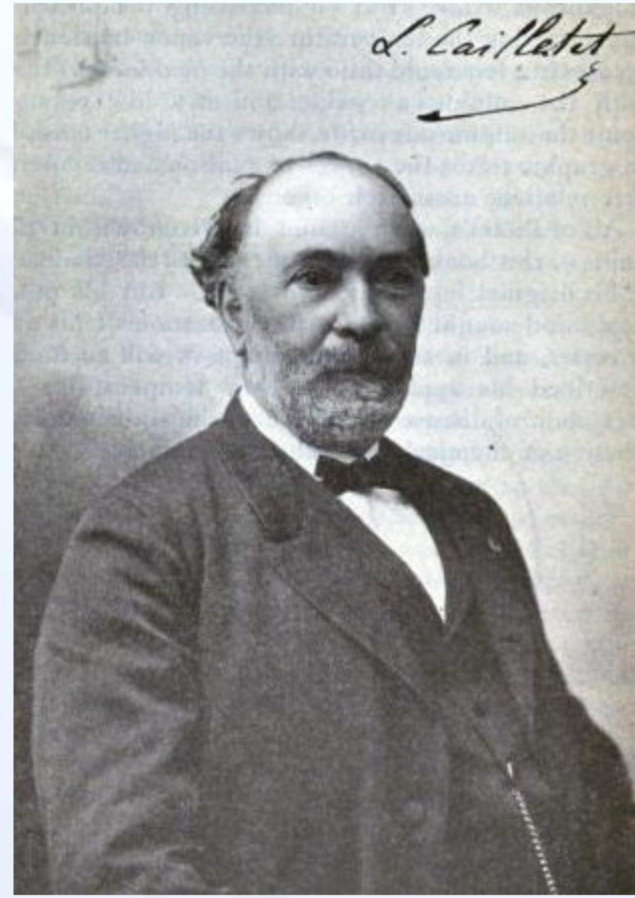
Gas Liquefaction: 1877 Production of O_2 Fog





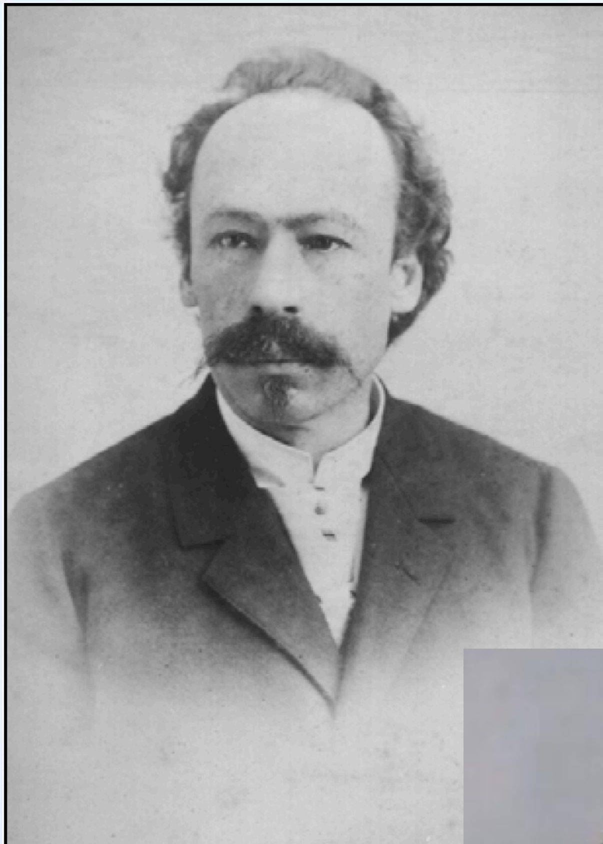
Raoul-Pierre Pictet
Genova

Apparatus of Cailletet



Louis P. Cailletet
Paris

Liquefaction of O_2, N_2 in 1883 and H_2 Fog Production in 1884



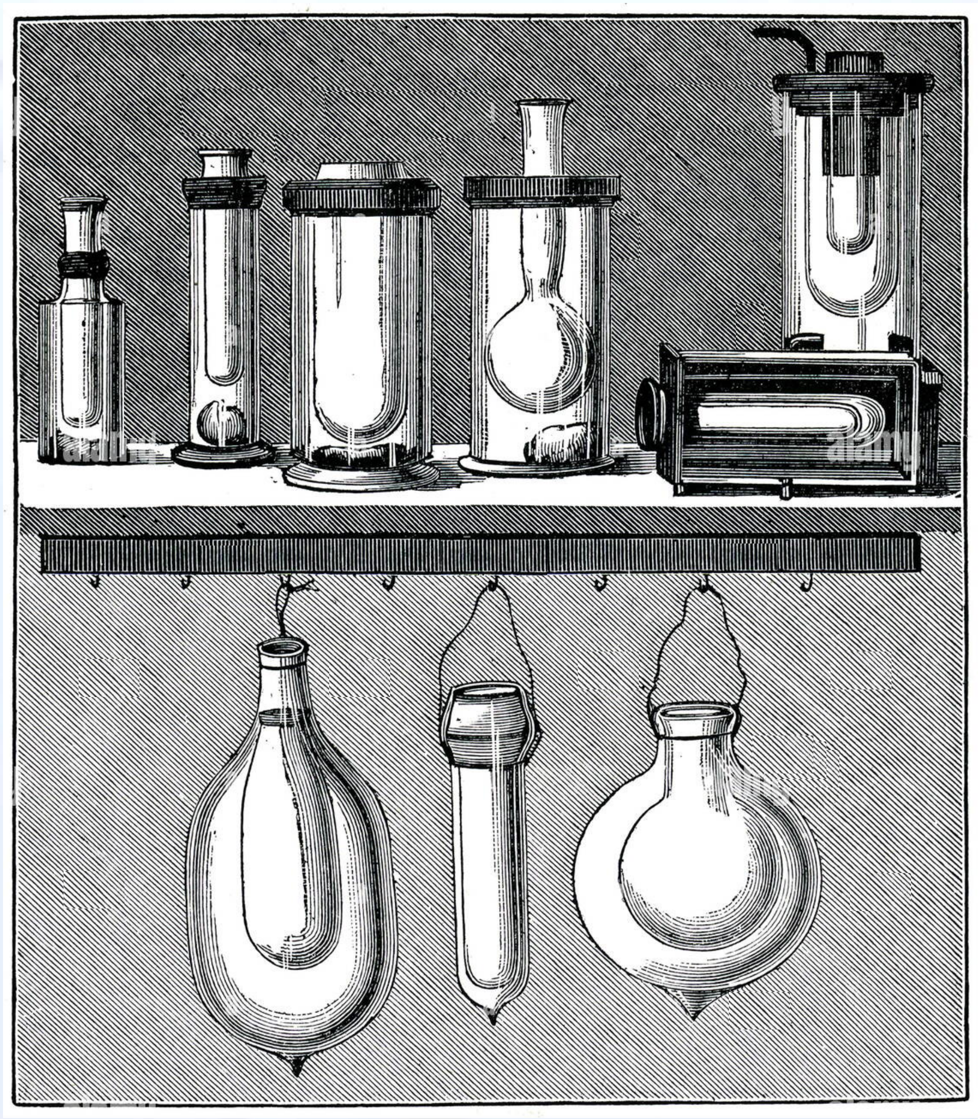
Karol Stanislaw Olszewski

Krakow

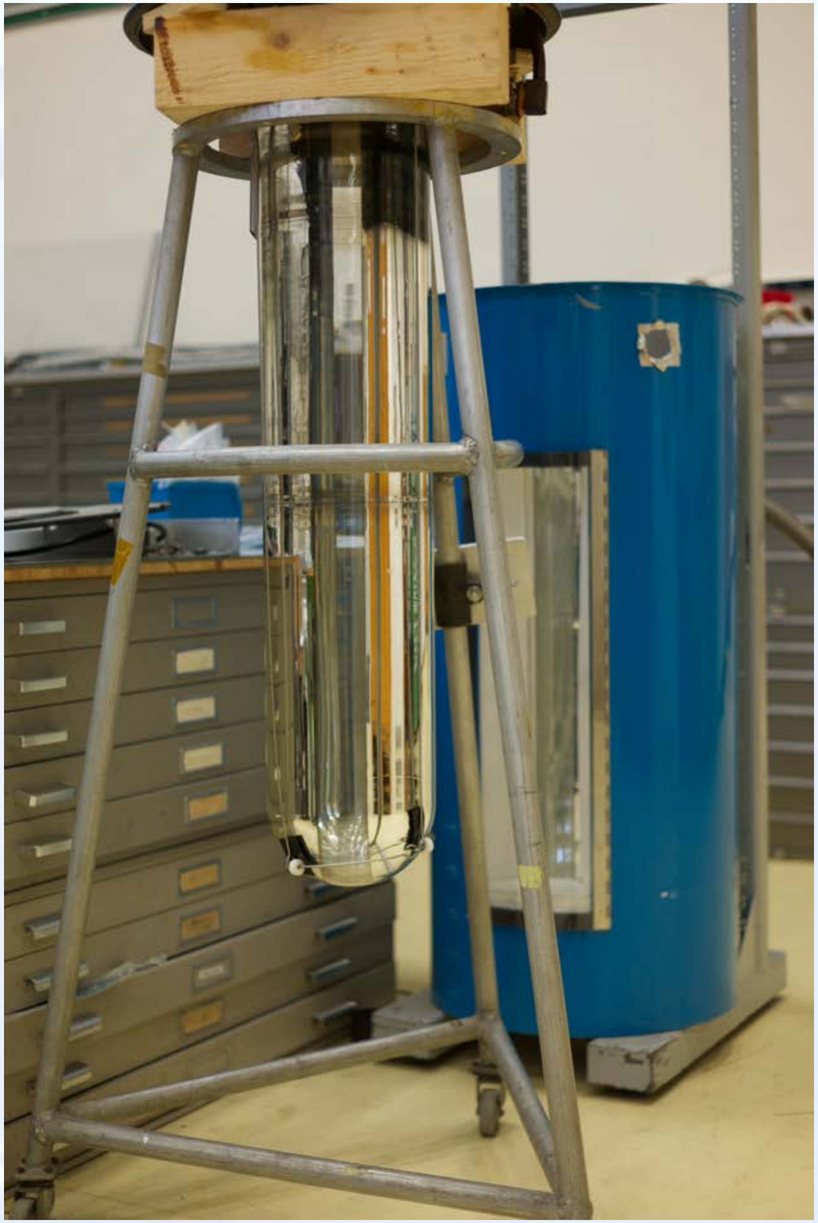
Zygmunt Florenty von Wróblewski

Krakow

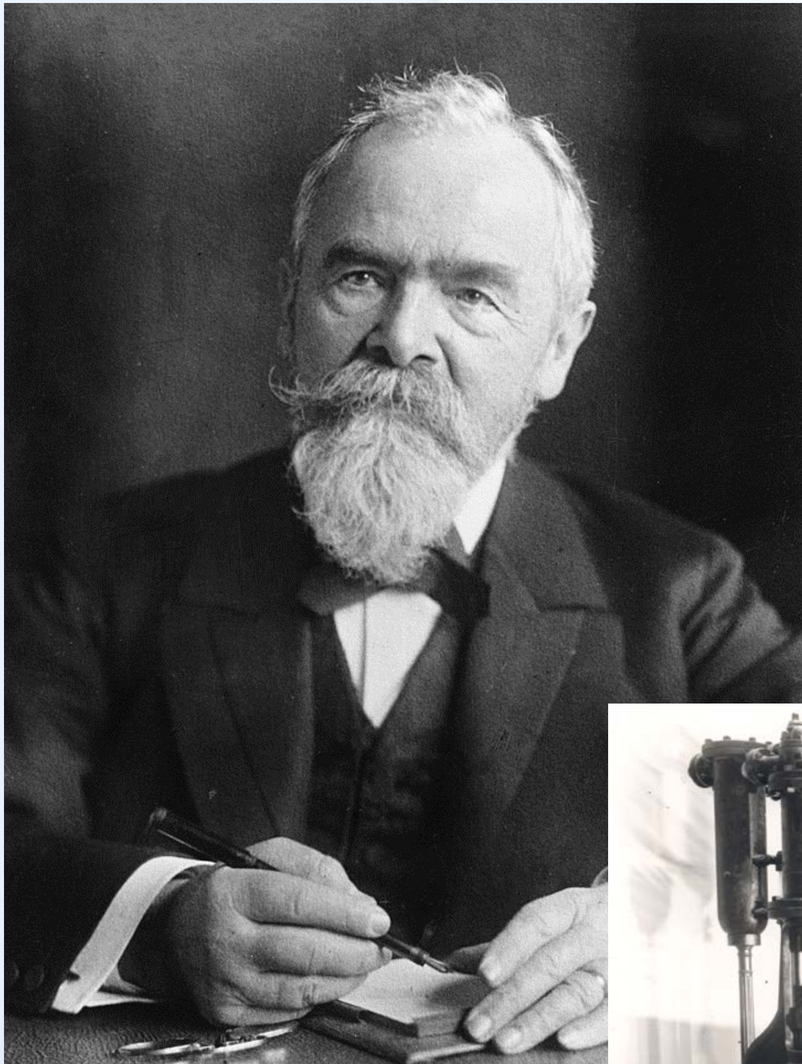
Development of Dewar Vessels in 1890

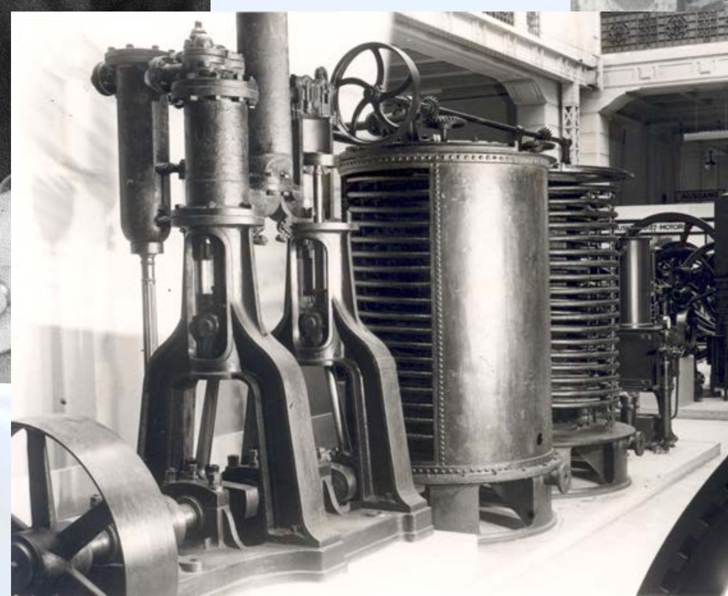


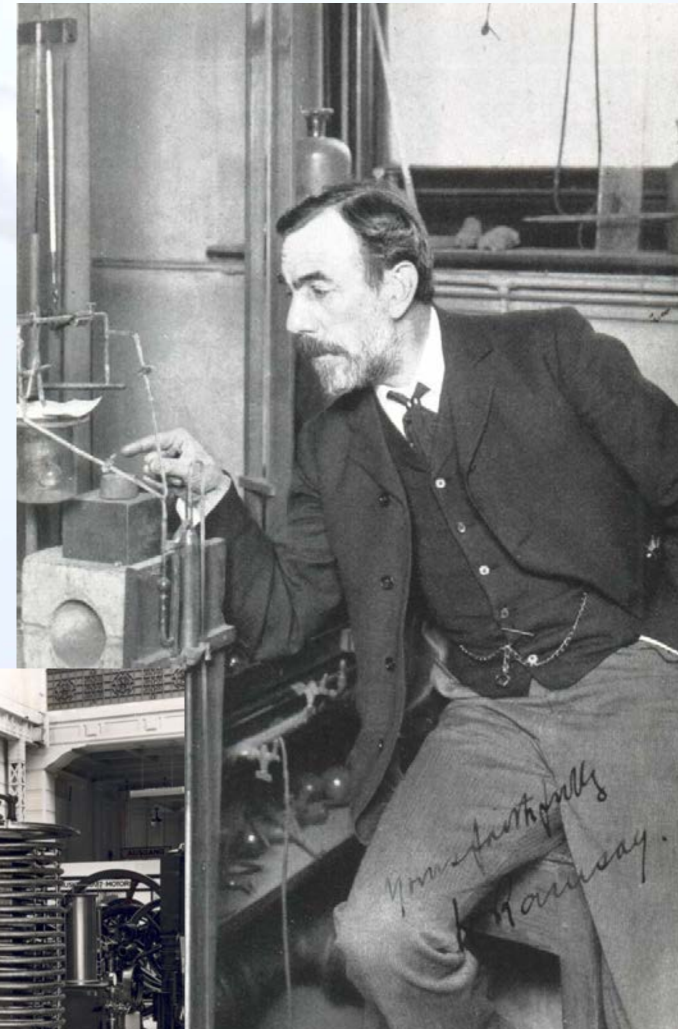
Development of Dewar Vessels in 1890



Liquefaction of Air in 1895



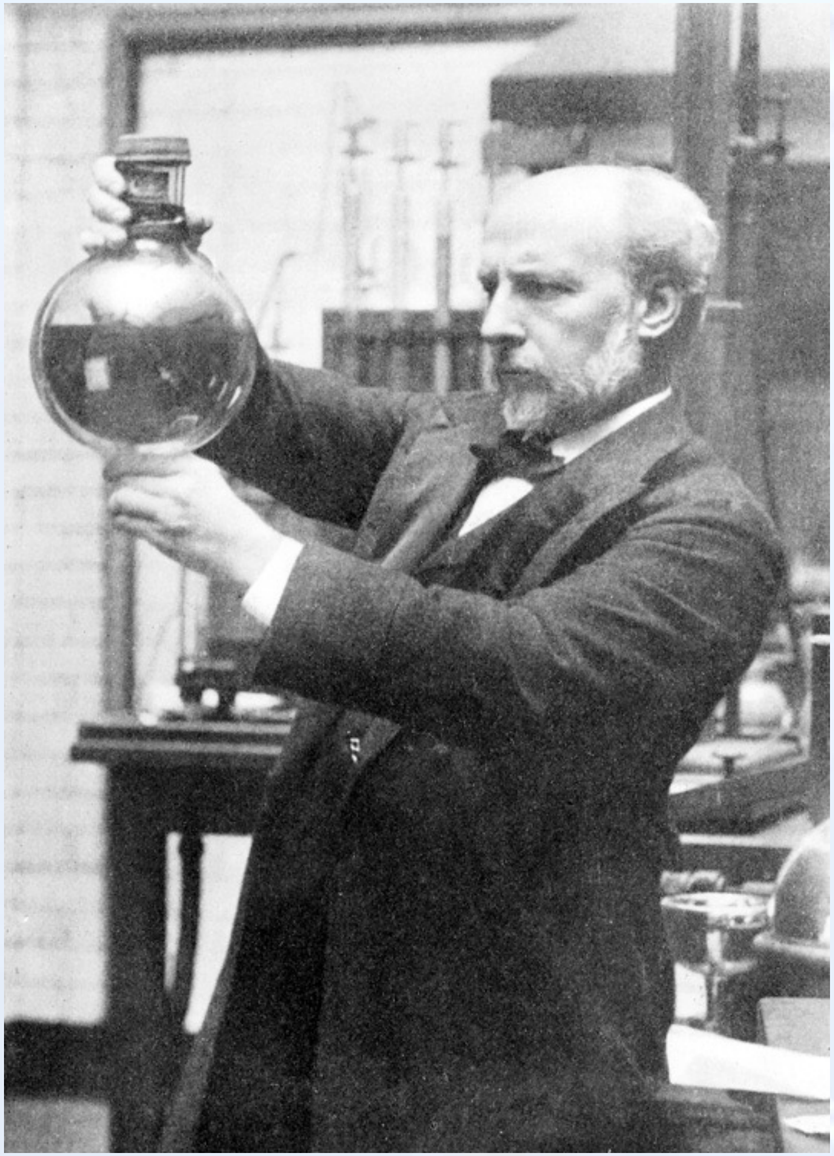




Carl v. Linde
Munich

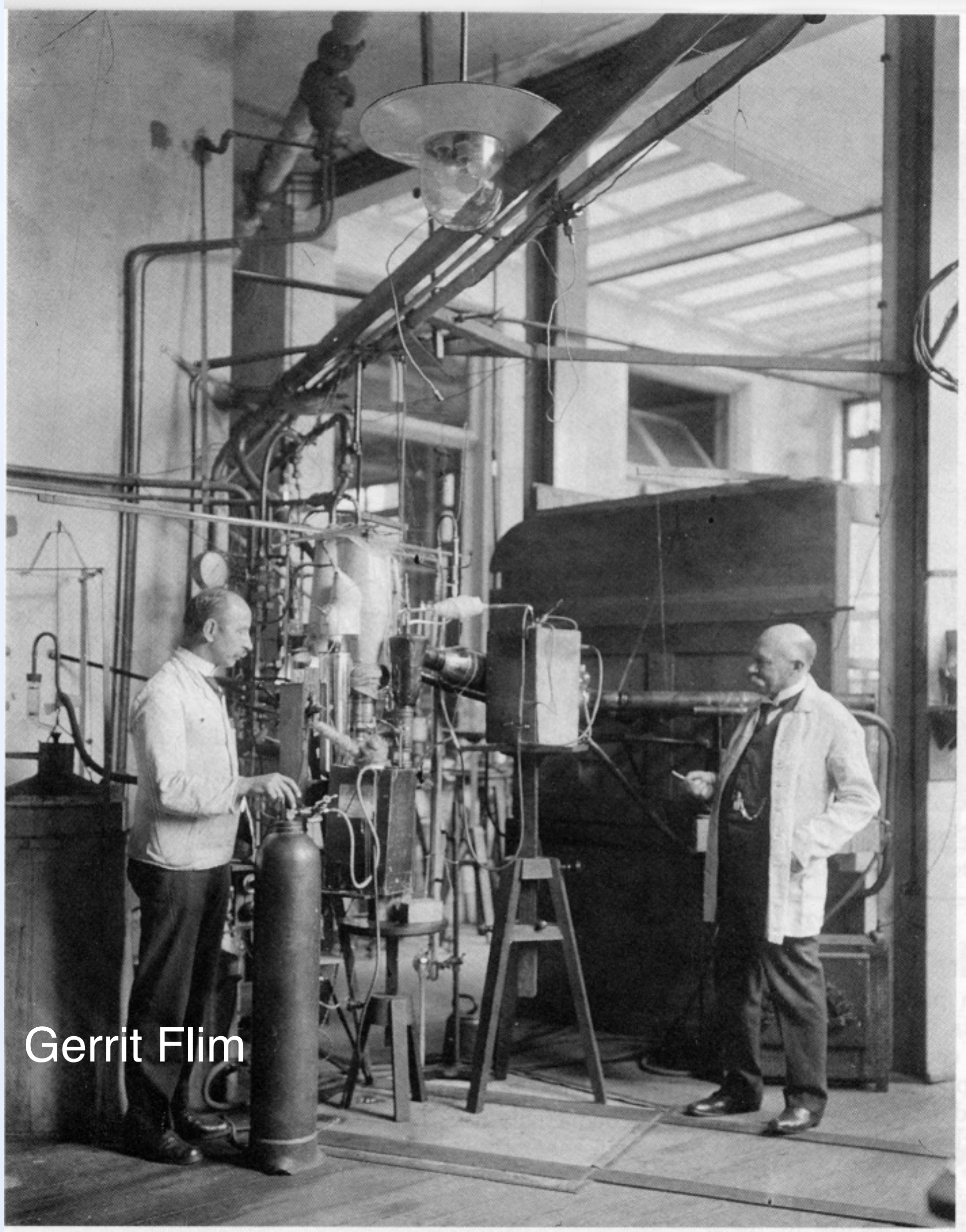
William Hampson
London

Liquefaction of H_2 in 1890



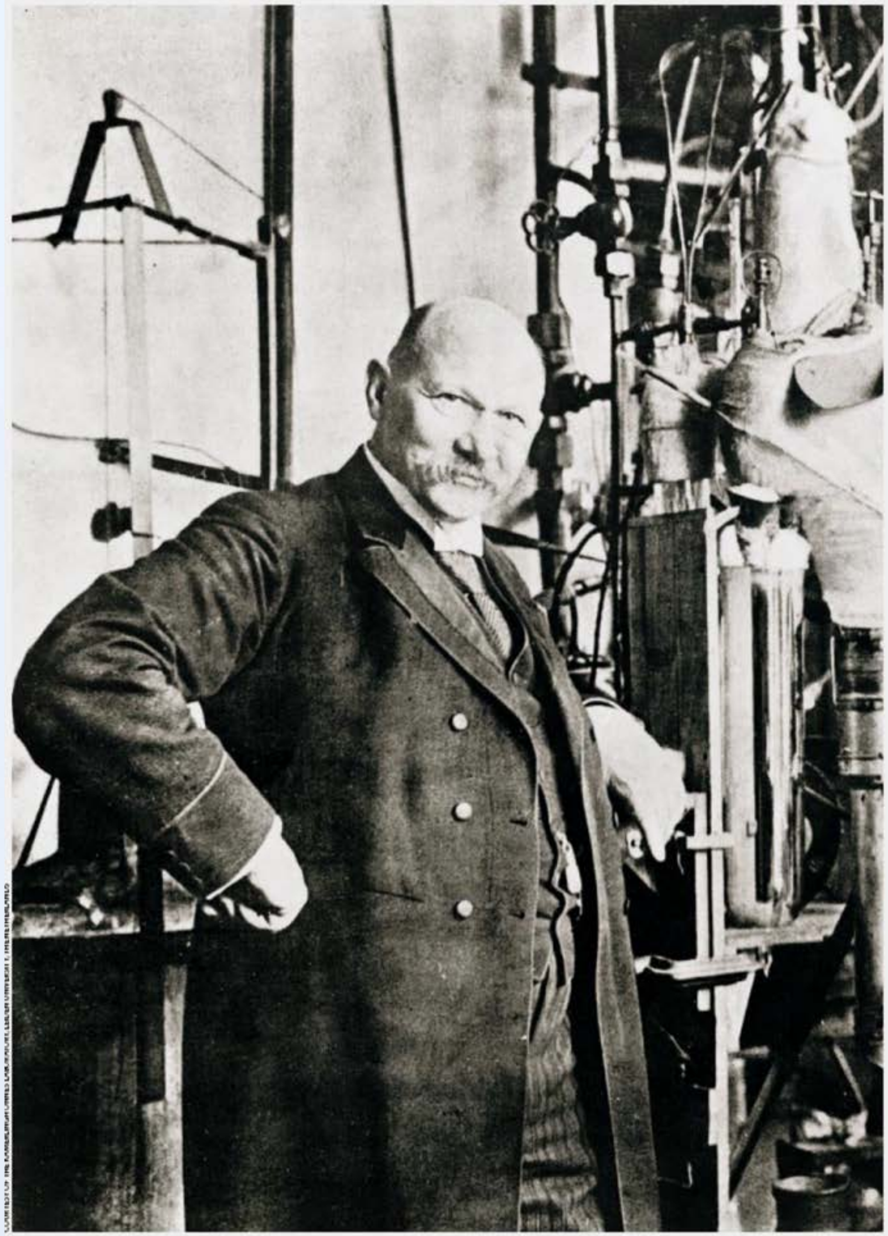
London 1916

Liquefaction of He in 1908

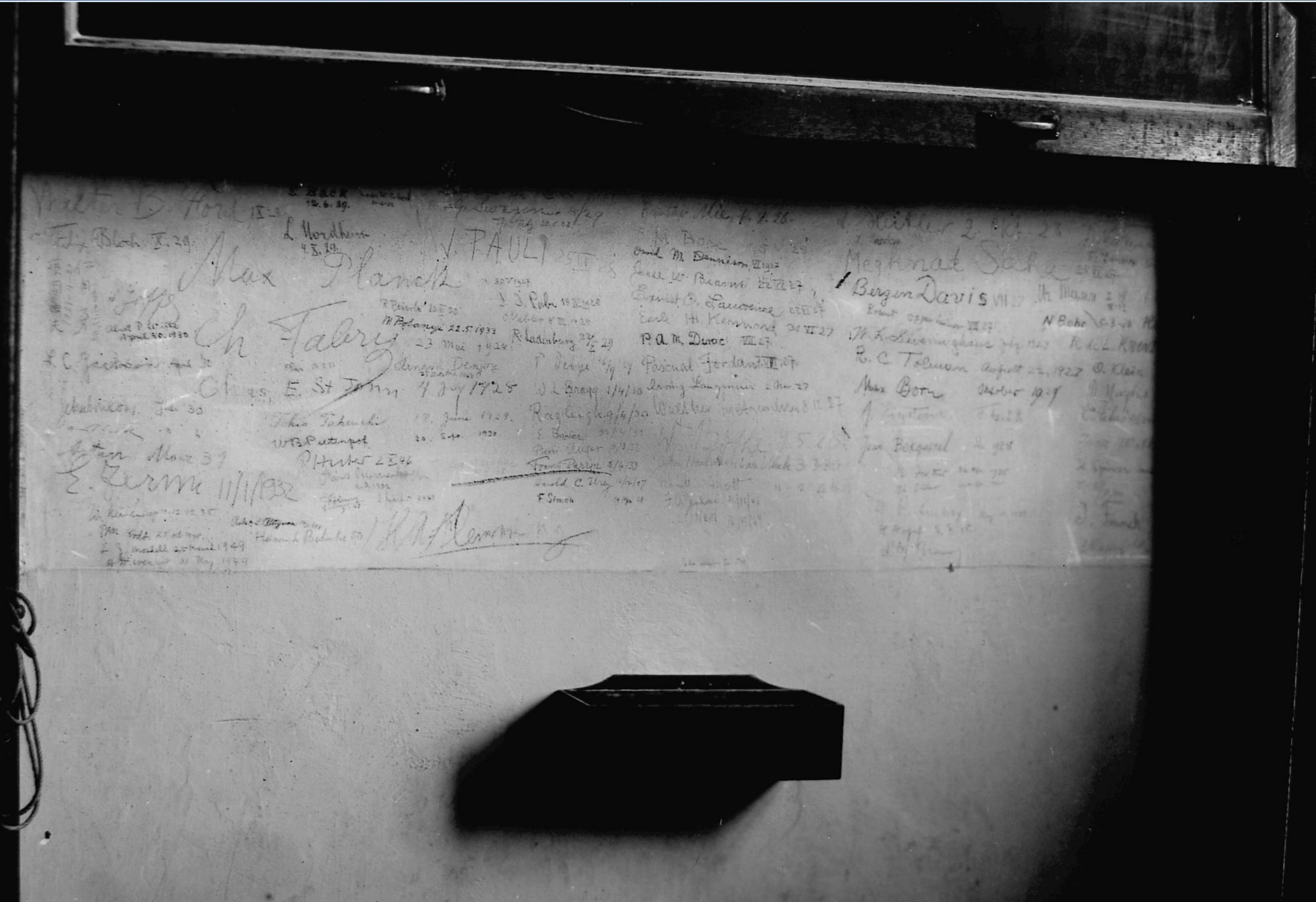


Heike Kamerlingh Onnes
Leiden

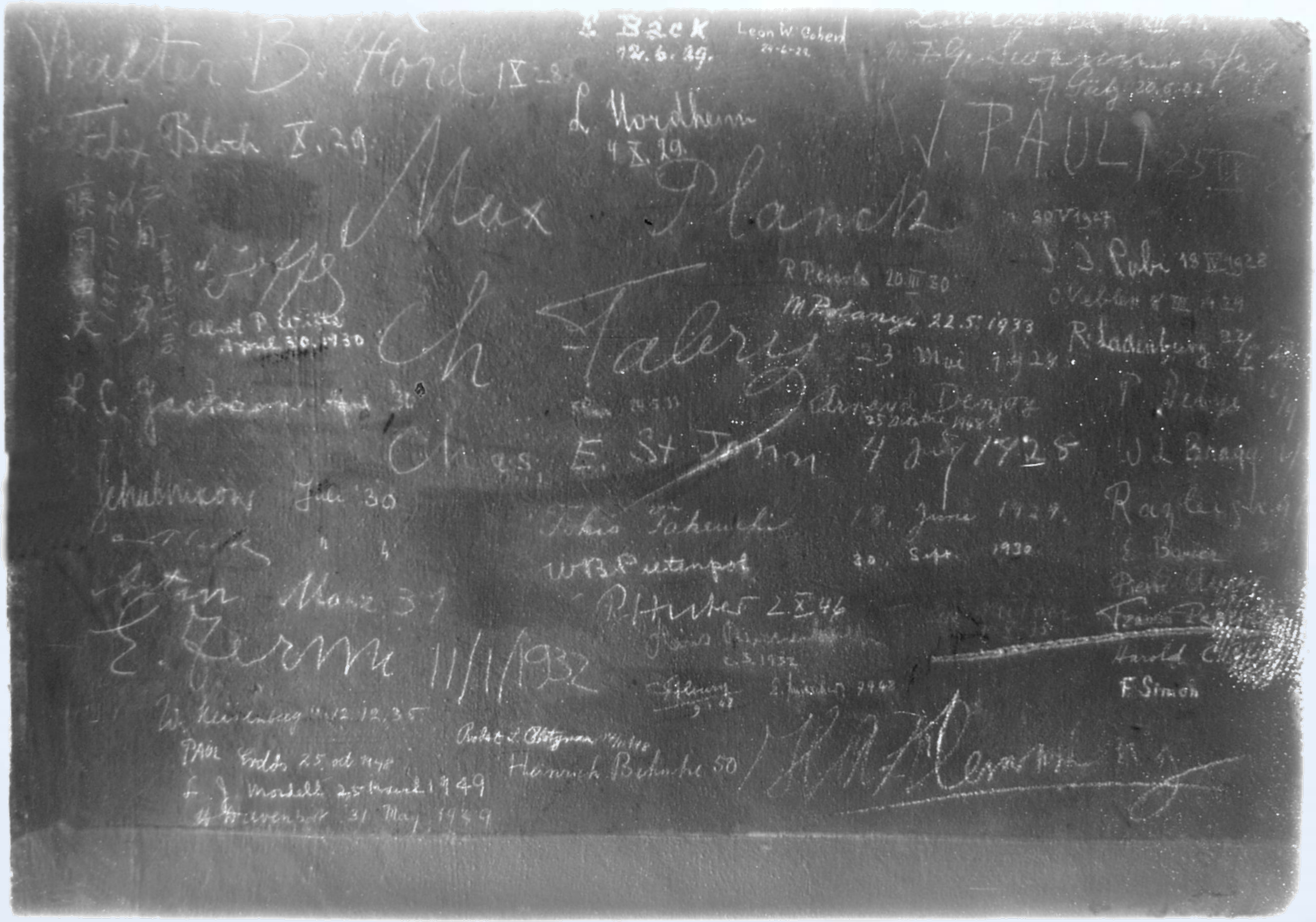
Liquefaction of He in 1908



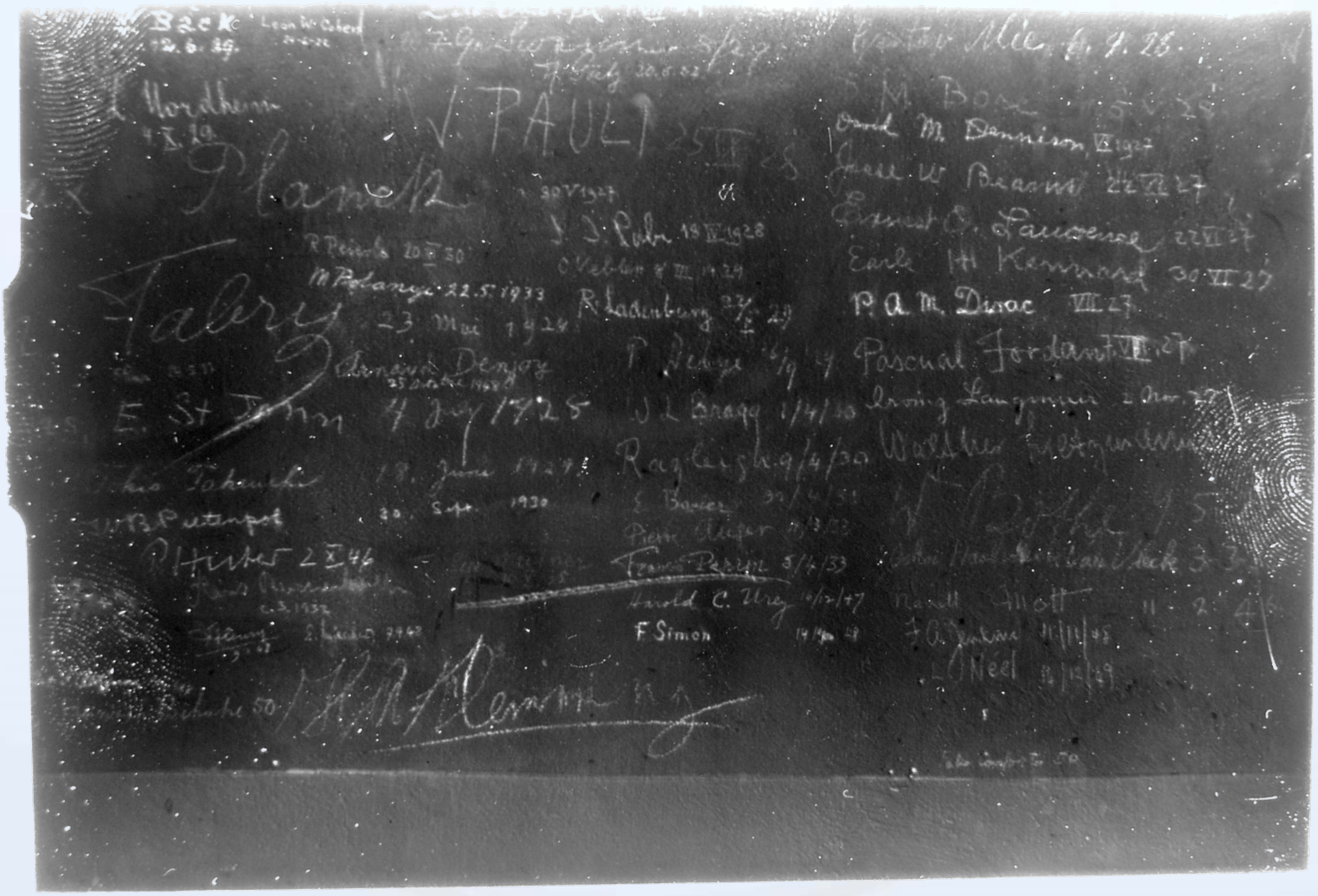
Leiden becomes Center of Low Temperature Physics



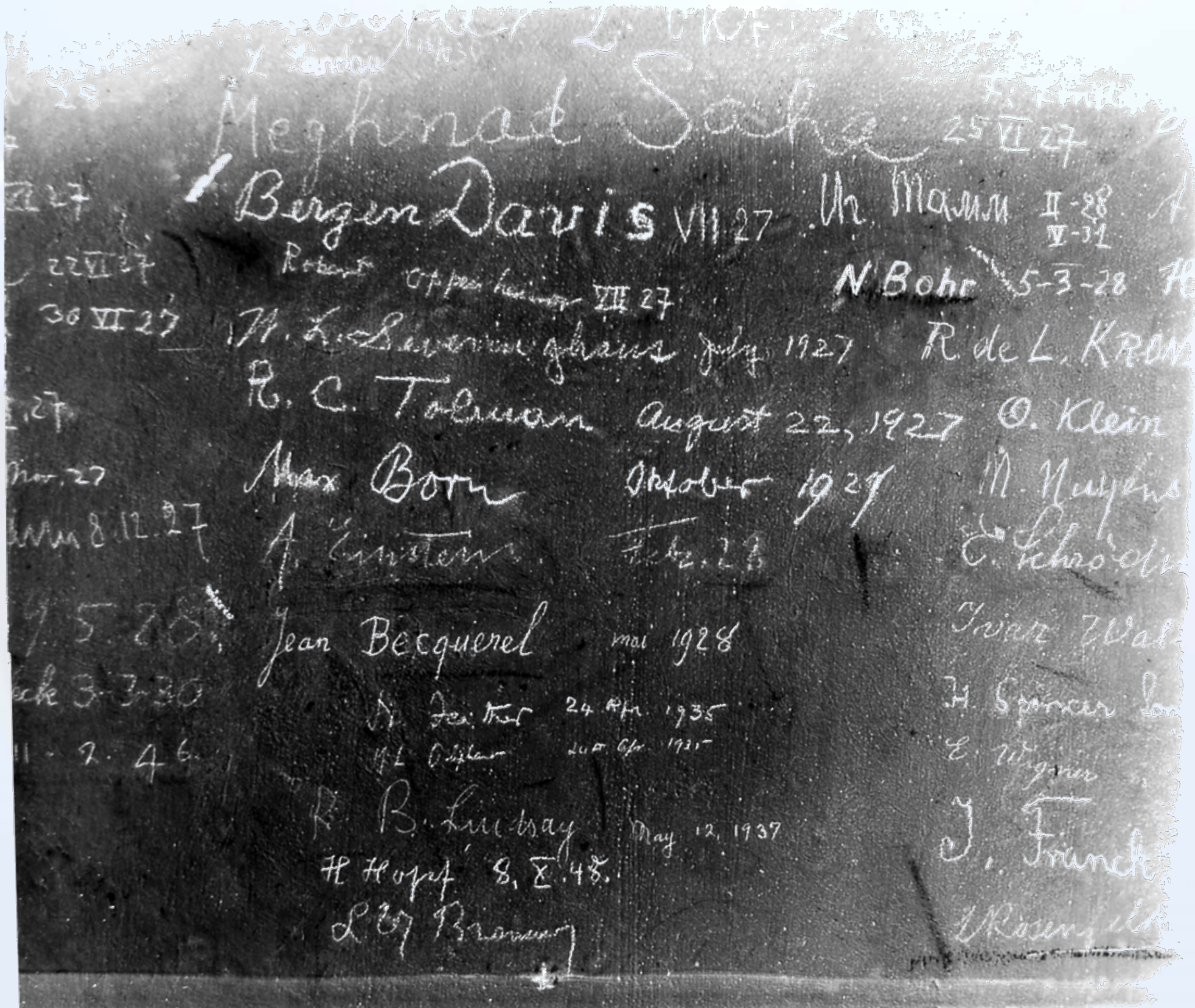
Leiden becomes Center of Low Temperature Physics



Leiden becomes Center of Low Temperature Physics



Leiden becomes Center of Low Temperature Physics



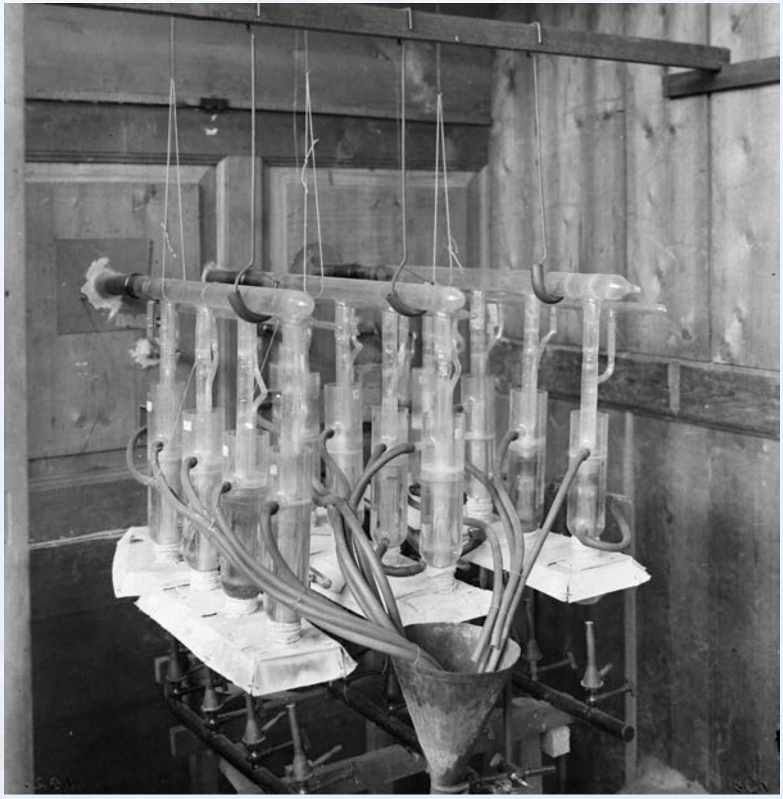
Milestones: Production of Temperatures below 1 K

1922 ^{4}He pumping, Kamerlingh Onnes (Leiden) → 0.82 K

1933 adiabatic demagnetisation paramagnetic salts,
de Haas (Leiden), Giauque (Berkeley) → 0.25 K

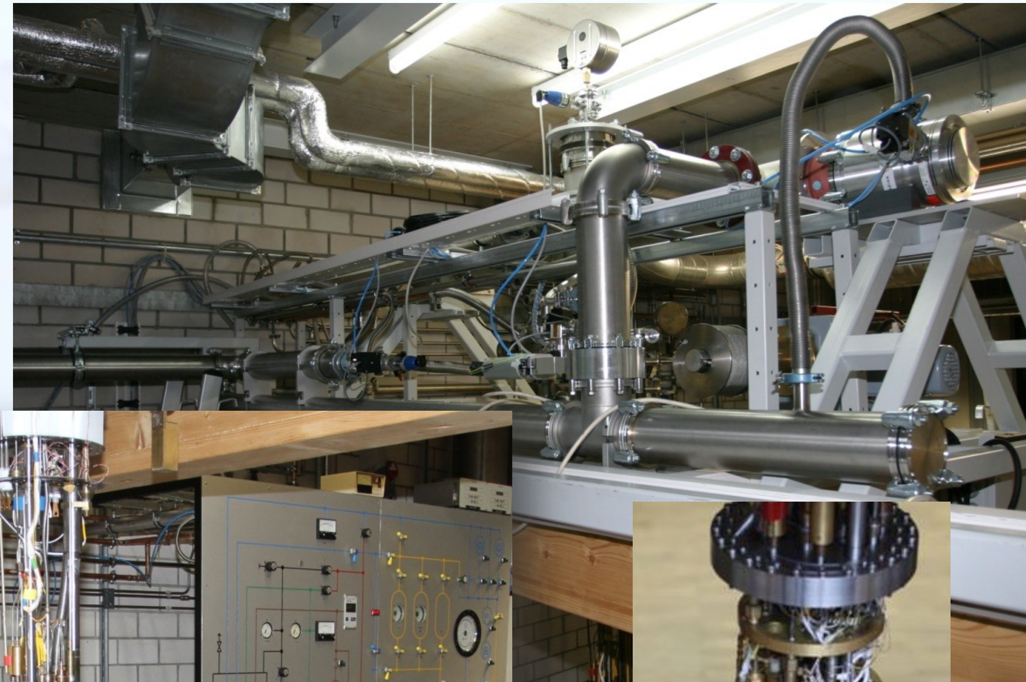
1965 dilution refrigeration, Das, DeBruyn, Taconis (Leiden) → 0.22 K

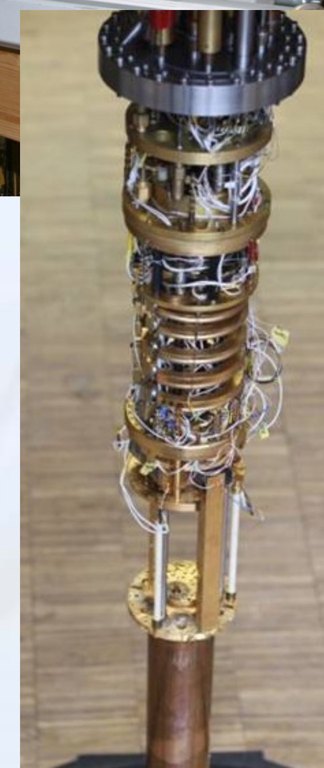
1996 adiabatic demagnetisation of nuclei
Pobell & coworkers (Bayreuth) → 1.5 µK



Battery of mercury diffusion pumps
used 1921 to obtain 0.82 K in Leiden

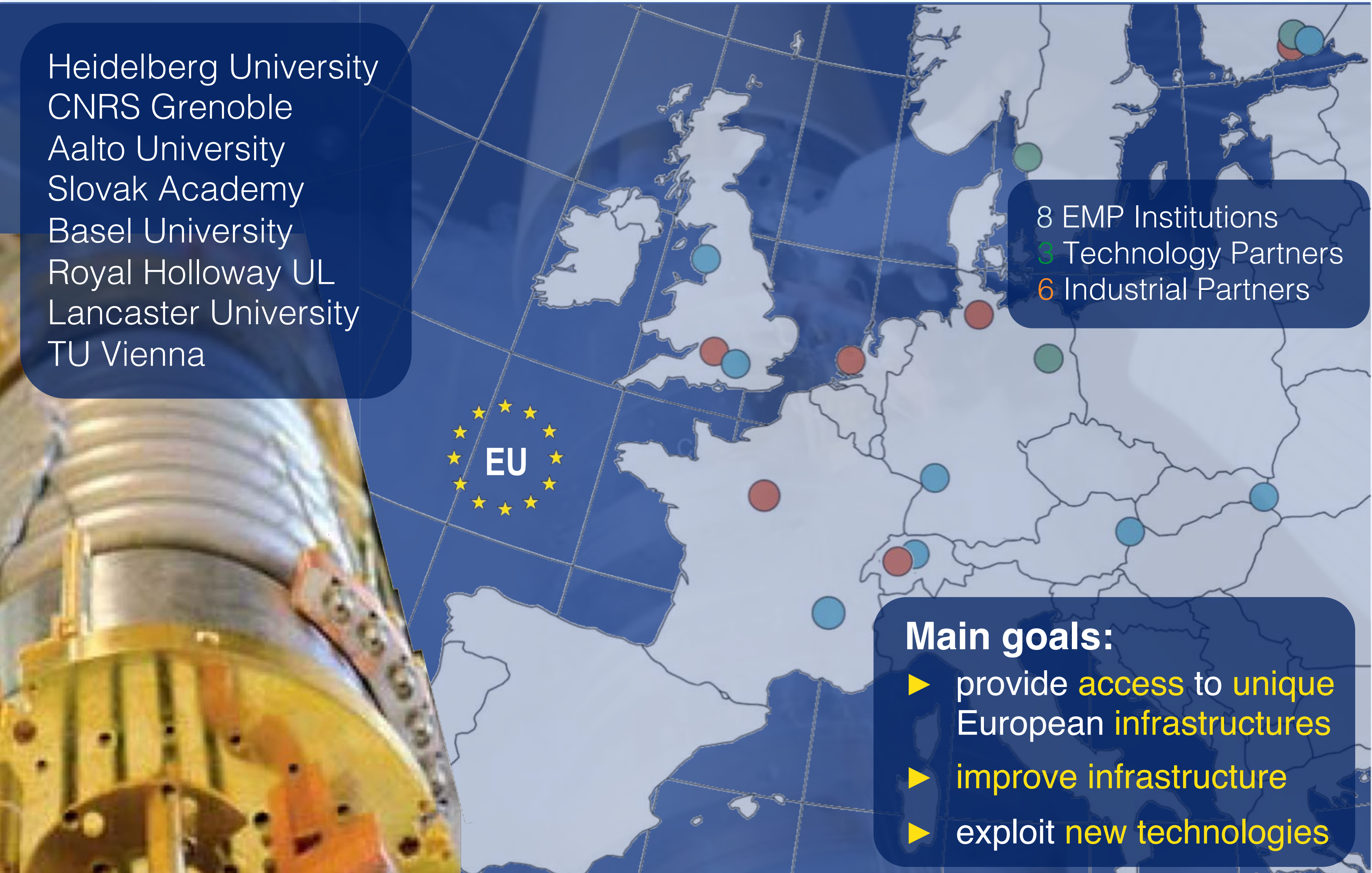
HeiKE – Heidelberg Nuclear Demagnetisation Fridge





European Microkelvin Platform

Heidelberg University
CNRS Grenoble
Aalto University
Slovak Academy
Basel University
Royal Holloway UL
Lancaster University
TU Vienna



8 EMP Institutions
3 Technology Partners
6 Industrial Partners

Main goals:

- provide access to unique European infrastructures
- improve infrastructure
- exploit new technologies

Quantum Fluids

Def: fluids for which quantum effects are important

⬆

Not a clear definition, because all matter consist of atoms and hence quantum effects are important

However, for light elements (H_2), He → spectacular macroscopic effects

Chapter 1 Helium – General Properties

1.1 Basic Facts

- discovery in corona of the sun during eclipse1868 in India by J. Janssen

- confirmed independently in regular daylight by J. Janssen and N. Lockyer
- name coined by N. Lockyer from the Greek word for sun helios (Ἥλιος)
- discovery on earth 1895 in Norwegian rock by W. Ramsay

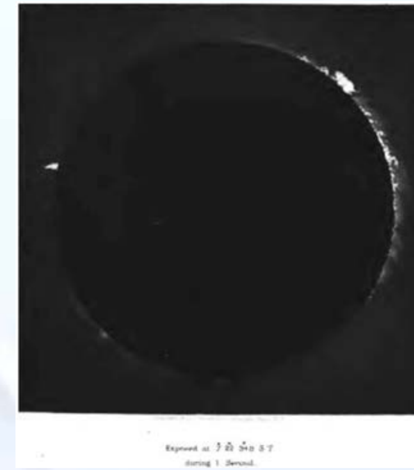
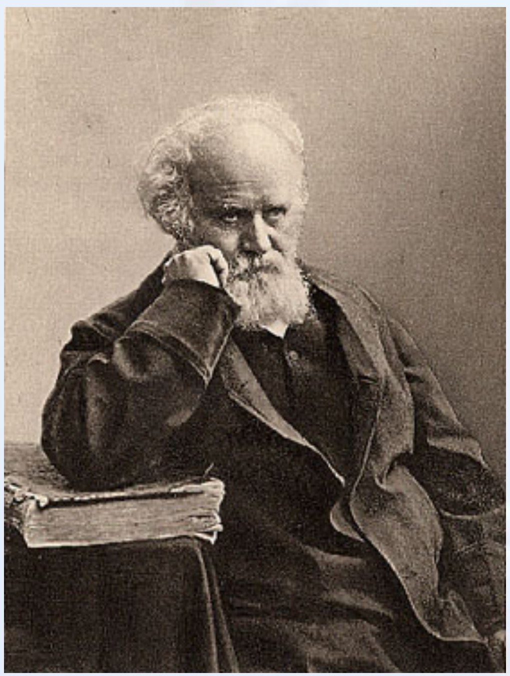
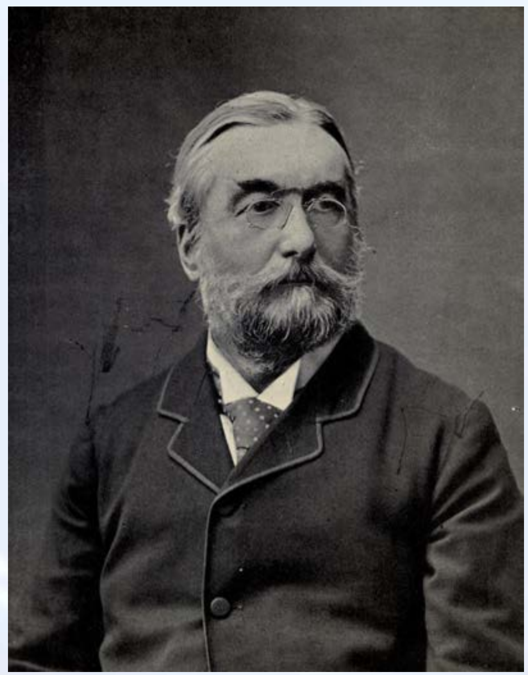


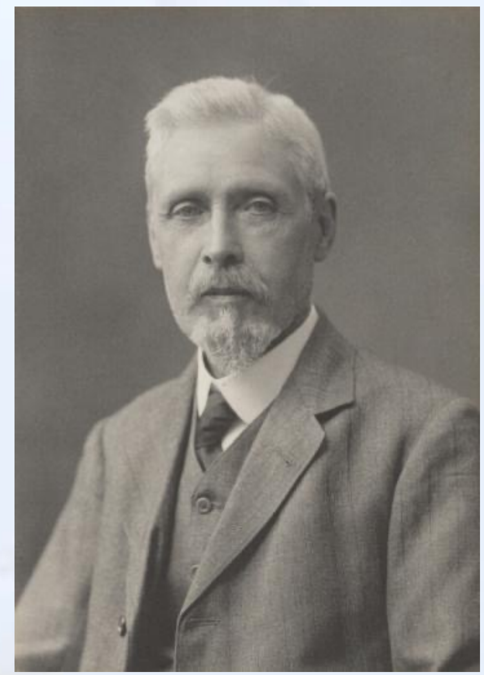
photo of eclipse1868



Pierre Jules César Janssen



Joseph Norman Lockyer



Sir William Ramsay

Terrestial Occurance of Helium

^{4}He

- air (5.2 ppm)
- gas wells (a few percent) USA, Russia, Qatar, Algeria

^{3}He

- Natural abundance ~ 0.14 ppm
- nuclear reactions, reactors, H-bomb

$$^6\mathrm{Li} + \mathrm{n} \longrightarrow {}^3\mathrm{H} + {}^4\mathrm{He}$$

12.5 a $\quad {}^3\mathrm{H} \longrightarrow {}^3\mathrm{He} + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$

^{6}He → not stable: $\tau_{1/2} = 0.85$ s (I = 3/2)

^{8}He → not stable: $\tau_{1/2} = 0.10$ s (I = 3/2)

Atomic and Nuclear Properties of Helium

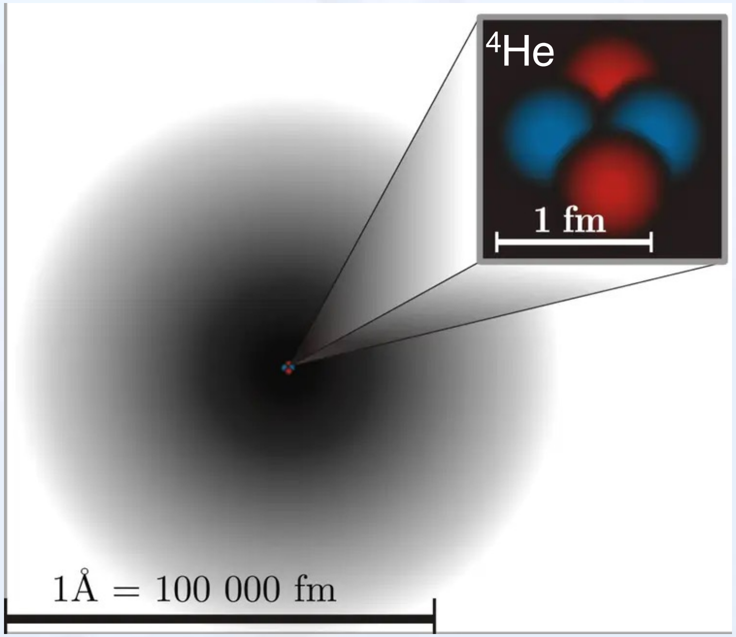
atom:

- closed shell → simple spherical structure / shape
- smallest atom
- $\varepsilon \sim 1$, $n \sim 1$, colorless

nuclear spin:

^{3}He $I = ½$ Fermions

^{4}He $I = 0$ Bosons



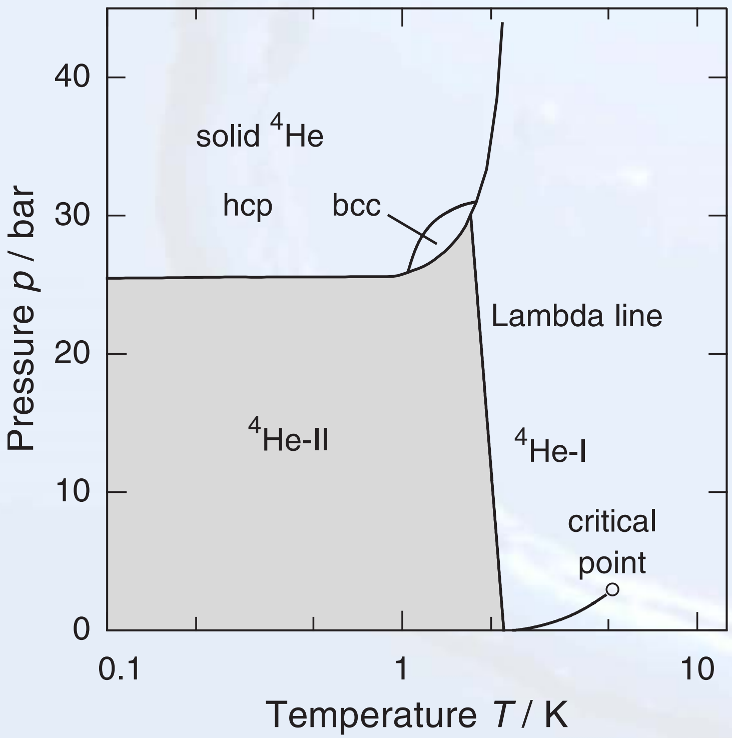
1.2 Phase Diagrams

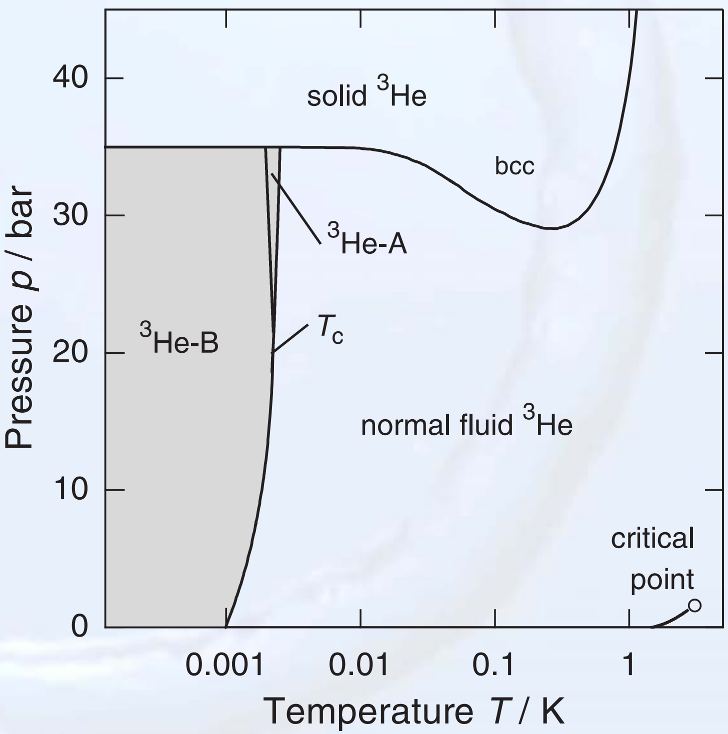
Does helium fit the usual solid-liquid-gas scheme?

➡ no, it remains liquid even for $T \to 0$ K

Reason: small binding forces and large zero-point energy → more later

Solidification under pressure (> 25 bar for ^{4}He, > 33 bar for ^{3}He)





1.2 Phase Diagrams

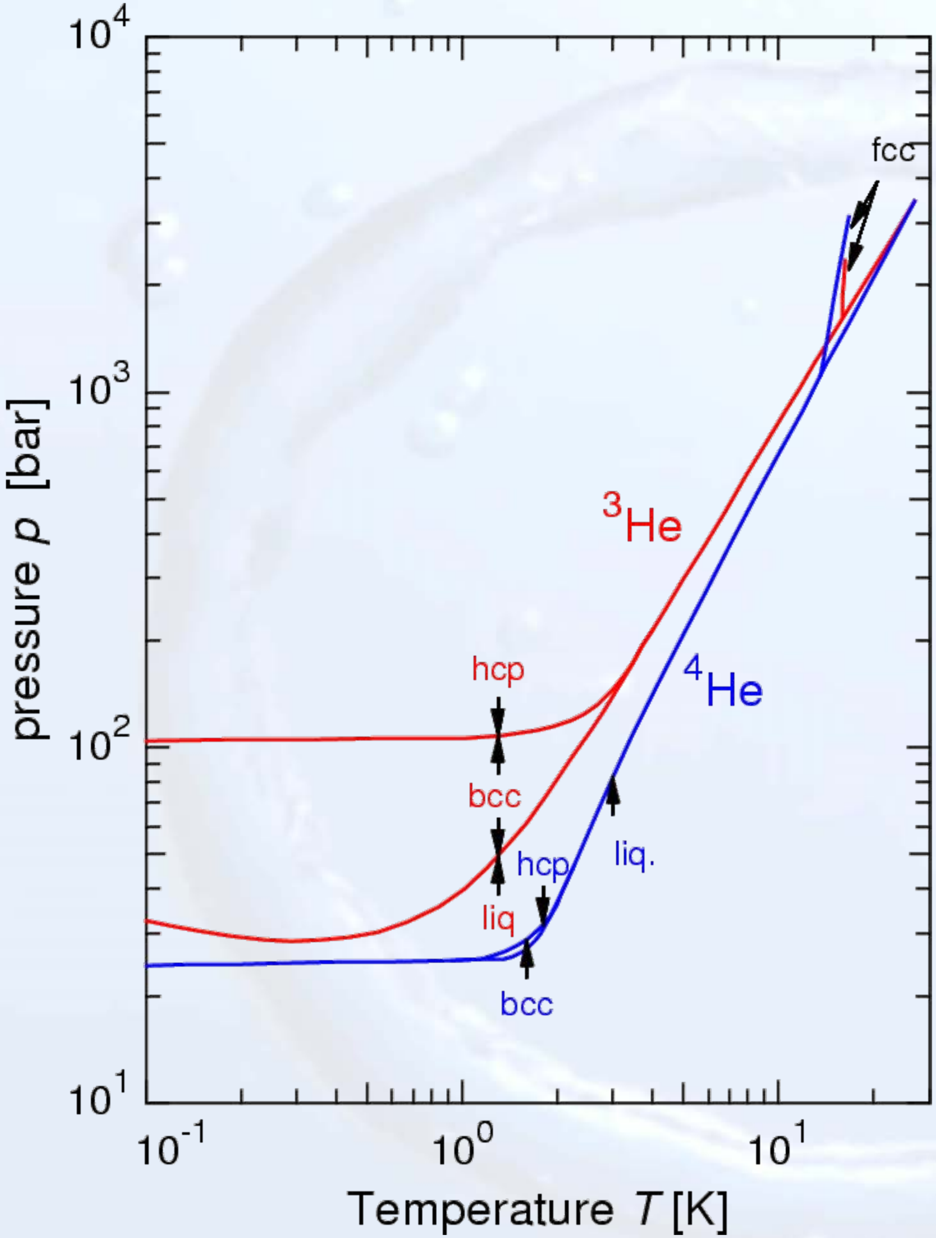
^{4}He has two liquid phases → He-I, normalfluid; He-II, superfluid

^{3}He has four liquid phases → ^{3}He-N, normalfluid; ^{3}He-A, ^{3}He-A$_1$, ^{3}He-B, superfluid

some numbers:

	^{3}He	^{4}He
boiling temperature at normal pressure T_b (K)	3.19	4.21
critical temperature T_c (K)	3.32	5.19
critical pressure p_c (bar)	1.16	2.29
density for $T \to 0$ ϱ_0 ($\mathrm{g\,cm^{-3}}$)	0.076	0.145
density at boiling point ϱ_b ($\mathrm{g\,cm^{-3}}$)	0.055	0.125

1.2 Phase Diagrams



^{3}**He** and ^{4}**He** both have three solid phases: hcp, bcc, fcc

1.2 Phase Diagrams

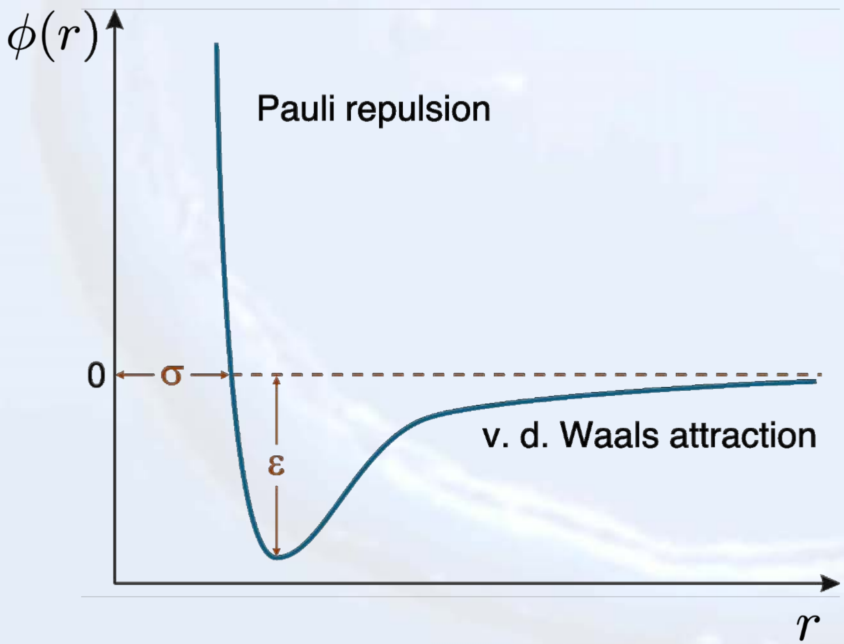
Why does helium remain liquid under normal pressure?

binding energy ⟷ zero-point energy

Binding between two He atoms: v. d. Waals interaction

→ Lennard Jones Potential: $$\phi(r) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$

↑ repulsion ↑ attraction



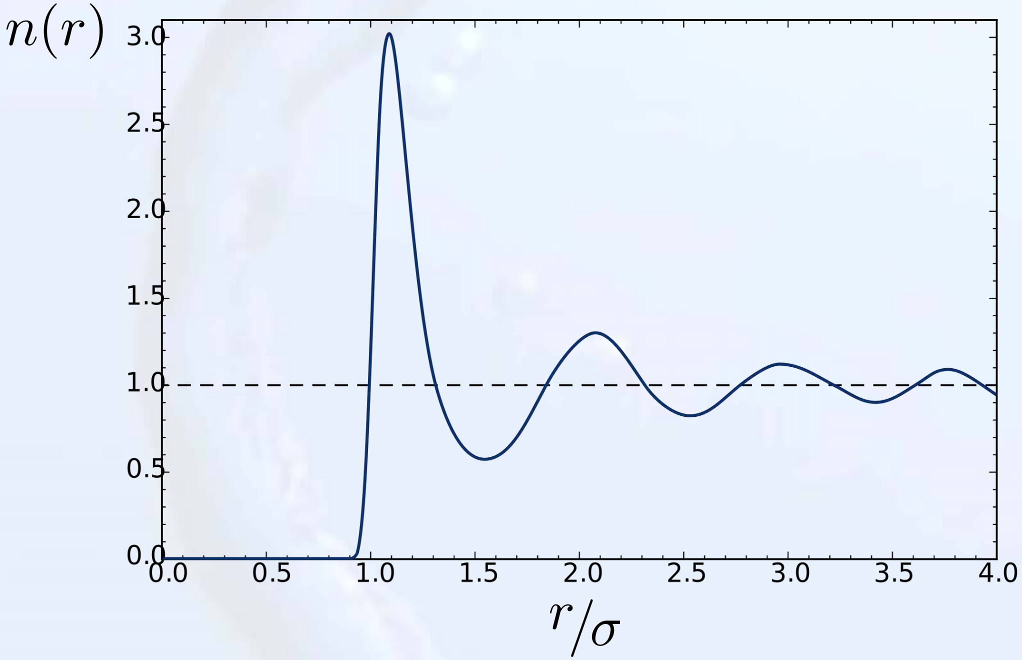
For both He isotopes:

$$\sigma = 2.56\,\text{Å}$$
$$\varepsilon/k_\mathrm{B} = 10.2\,\mathrm{K}$$

1.2 Phase Diagrams

total potential energy for liquid He:

$$\rightarrow \quad E_{\mathrm{pot}} = \frac{1}{2}\int_0^\infty \phi(r)\, 4\pi r^2 n(r)\, \mathrm{d}r$$



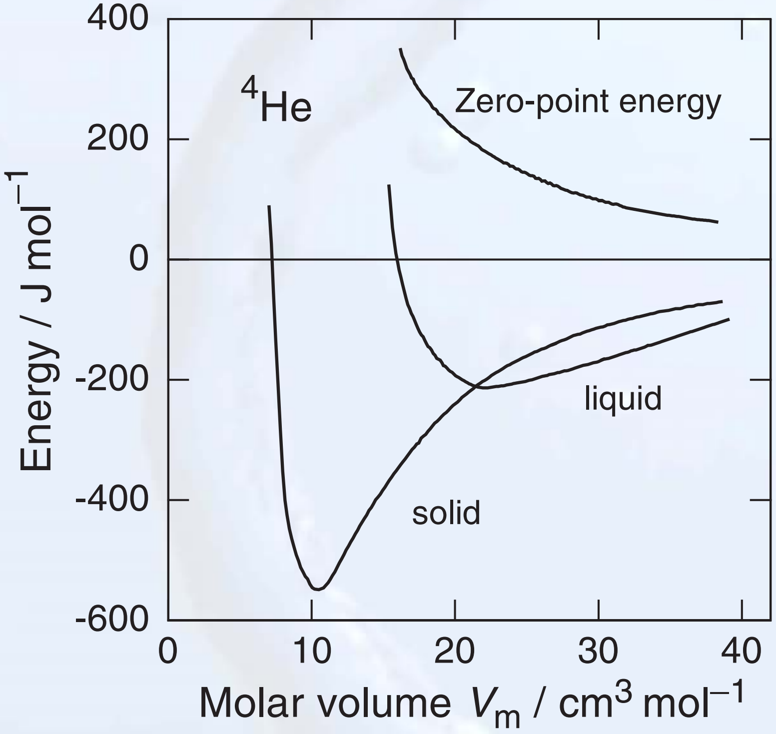
radial density function can be determined by neutron or X-ray scattering

zero-point energy in a simple approximation:
(assumption: 3-d box potential)

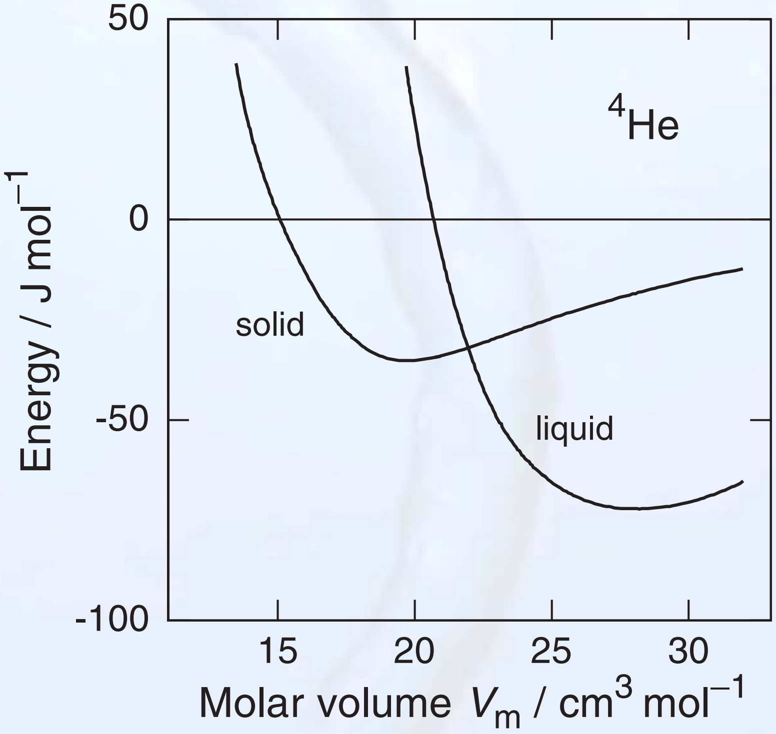
$$E_0 = \frac{3\hbar^2\pi^2}{2mV^{2/3}} \propto \frac{1}{m}$$

1.2 Phase Diagrams

Potential energy for solid and liquid He and zero-point energy



Total binding energy for solid and liquid He



liquid phase is energetically more favorable