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Meißner
Institut

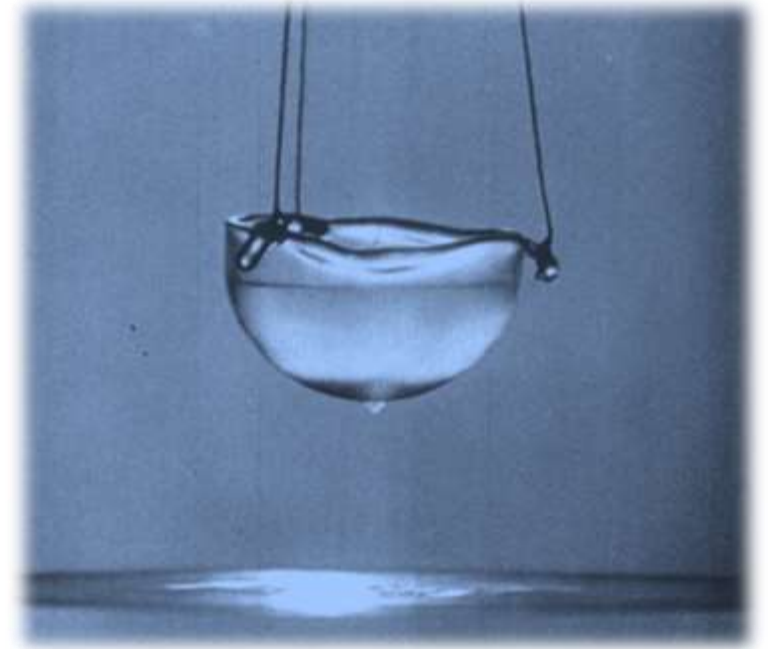
BAaW

BAYERISCHE
AKADEMIE
DER
WISSENSCHAFTEN

Technische
Universität
München

TUM

Superconductivity and Low Temperature Physics II



**Lecture Notes
Summer Semester 2024**

**R. Gross
© Walther-Meißner-Institut**



***Superconductivity,
Superfluidity, Condensates, Quantum Liquids***

1. Superconductivity and Low-Temperature Physics I + II

- Part I (WS 2023/2024): Foundations of Superconductivity
- Part II (SS 2024): Quantum Liquids, BECs, Quantum Interference Effects, Foundations of Low Temperature Physics and Techniques

This lecture

2. Applied Superconductivity I + II

-  → WS 2023/24 and SS 2024, 2 hrs lecture + 2 hrs exercises
- Josephson-Effect, Superconducting Electronics, Qubits, Quantum Circuits,

3. Seminars (SS 2024, WMI seminar room)

- Advances in Solid State Physics (TUE 10:15-11:45)
- Superconducting Quantum Circuits (TUE 12:15-13:45)

Topics available

Further information: <https://www.wmi.badw.de/teaching>

- announcement of lectures
- downloads of lecture notes, handouts...
- seminar topics

Nobel Prizes in Physics related to LT Physics

year	name	discovery
1913	Heike Kamerlingh Onnes	"For his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium "
1972	John Bardeen , Leon Neil Cooper and Robert Schrieffer	"for their jointly developed theory of superconductivity , usually called the BCS-theory "
1973	Brian David 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 effect "
1978	Pjotr Kapiza	"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	Johannes Georg Bednorz und Karl Alex Müller	"for their important break-through in the discovery of superconductivity in ceramic materials"
1996	David M. Lee , Douglas D. Osheroff und Robert C. Richardson	"for their discovery of superfluidity in helium-3 "
1997	Steven Chu , Claude Cohen-Tannoudji and William D. Phillips	"for development of methods to cool and trap atoms with laser light" See Laser cooling .
1998	Robert B. Laughlin , Horst Ludwig Störmer and Daniel Chee Tsui	"for their discovery of a new form of quantum fluid with fractionally charged excitations". See Quantum Hall effect .
2001	Eric A. Cornell , Wolfgang Ketterle and 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 Abrikosov , Witali Ginsburg and Anthony James Leggett	"for pioneering contributions to the theory of superconductors and superfluids"
2016	David J. Thouless , F. Duncan M. Haldane , J. Michael Kosterlitz	"for theoretical discoveries of topological phase transitions and topological phases of matter"

Superconductivity and Low Temperature Physics I

Introduction

1. **Basic Properties of Superconductors**
2. **Phenomenological Models of Superconductivity :**
 - London equations
 - macroscopic quantum model
 - Ginzburg-Landau theory
3. **Thermodynamics**
4. **Microscopic (BCS) theory**
5. **Flux pinning and critical currents**
6. **High Temperature Superconductivity**
7. **Applications**

Superconductivity and Low Temperature Physics II

1. **Quantum Gases & Liquids: Bose-Einstein condensation, Superfluid Helium (^4He and ^3He)**
2. **Quantum Interference Effects in Mesoscopic Conductors**
3. **Low Temperature Techniques**
(generation and measurement of low temperatures)

I.1 Foundations and General Properties

- I.1.1 Quantum Gases & Liquids
- I.1.2 Helium
- I.1.3 Van der Waals Bonding
- I.1.4 Zero-Point Fluctuations
- I.1.5 Helium under Pressure
- I.1.6 pT-Phase Diagram of ^4He and ^3He
- I.1.7 Characteristic Properties of ^4He and ^3He
- I.1.8 Specific Heat of ^4He and ^3He

I.2 ^4He as an Ideal Bose Gas

- I.2.1 Bose-Einstein Condensation
- I.2.2 Ideal Bose Gas
- I.2.3 Bose Gas with Interactions
- I.2.4 Bose-Einstein Condensation of ^4He

I.3 Superfluid ^4He

- I.3.1 Two-Fluid Model
- I.3.2 Experimental Observations
- I.3.3 Two-Fluid Hydrodynamics
- I.3.4 Excitation Spectrum of ^4He

I.4 Vortices

- I.4.1 Quantization of Circulation
- I.4.2 Experimental Study of Vortices

I.5 ^3He

- I.5.1 normal fluid ^3He
- I.5.2 solid ^3He and Pomeranchuk effect
- I.5.3 superfluid ^3He

I.6 ^3He / ^4He mixtures

II.1 Introduction

- II.1.1 General Remarks
- II.1.2 Mesoscopic Systems
- II.1.3 Characteristic Length Scales
- II.1.4 Characteristic Energy Scales
- II.1.5 Transport Regimes

II.2 Description of Electron Transport by Scattering of Waves

- II.2.1 Electron Waves and Waveguides
- II.2.2 Landauer Formalism
- II.2.3 Multi-terminal Conductors
- II.2.4 Statistics of Charge Transport

II.3 Quantum Interference Effects

- II.3.1 Double Slit Experiment
- II.3.2 Two Barriers – Resonant Tunneling
- II.3.3 Aharonov-Bohm Effect
- II.3.4 Weak Localization
- II.3.5 Universal Conductance Fluctuations

II.4 From Quantum Mechanics to Ohm's Law

II.5 Coulomb Blockade

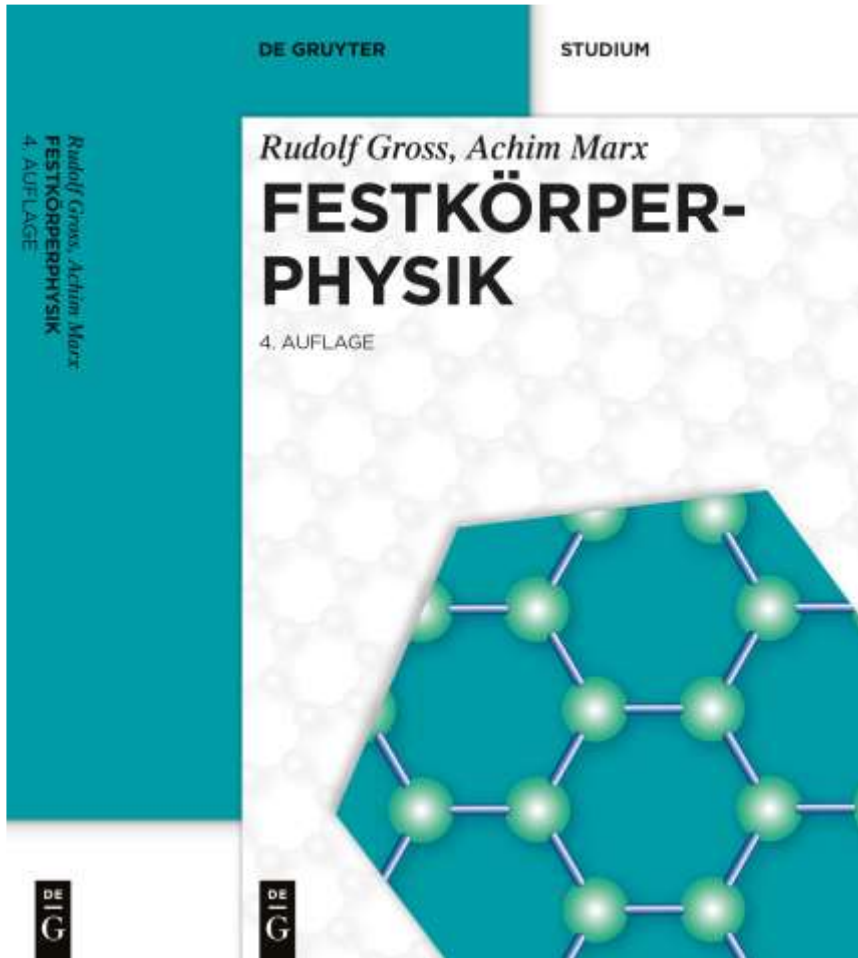
III.1 Generation of Low Temperatures

- III.1.1 Introduction
- III.1.2 Expansion Machine
- III.3 Regenerative Machine
- III.1.4 Joule-Thomson Cooling
- III.1.5 Summary
- III.1.6 Evaporation Cooling
- III.1.7 Dilution Cooling
- III.1.8 Pomeranchuk Cooling
- III.1.9 Adiabatic Demagnetization

III.2 Thermometry

- III.2.1 Introduction
- III.2.2 Primary Thermometers
- III.2.3 Secondary Thermometers

- F. Pobell
Matter and Methods at Low Temperatures, Springer 1996
- D.R. Tilley and J. Tilley
Superfluidity and Superconductivity, Adam Hilger 1990
- C. Enss and S. Hunklinger
Low-Temperature Physics, Springer 2005
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Quantum Liquids - Bose Condensation and Cooper Pairing in Condensed-Matter Systems, Oxford University Press, 2022
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Introduction to Liquid Helium, Oxford 1987
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- G.K. White, P.J. Meeson
Experimental Techniques in Low Temperature Physics, Oxford University Press, 2002
- K.H. Bennemann, J.B. Ketterson
The Physics of Liquid and Solid Helium I and II, Wiley 1978
- H. Frey, R.A. Haefer
Tiefemperaturtechnologie, VDI-Verlag, Düsseldorf 1981
- Yoseph Imry
Introduction to Mesoscopic Physics, Oxford University Press, Oxford (1997)
- Supriyoto Datta
Electronic Transport in Mesoscopic Systems, Cambridge University Press, Cambridge (1995)
- Thomas Heinzel
Mesoscopic Electronic in Solid State Nanostructures, Wiley VCH, Weinheim (2003)
- Thomas Ihn
Semiconductor Nanostructures, Oxford University Press (2010)



Rudolf Gross, Achim Marx

Title: Festkörperphysik, 4th revised and extended edition

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Published: January 2023

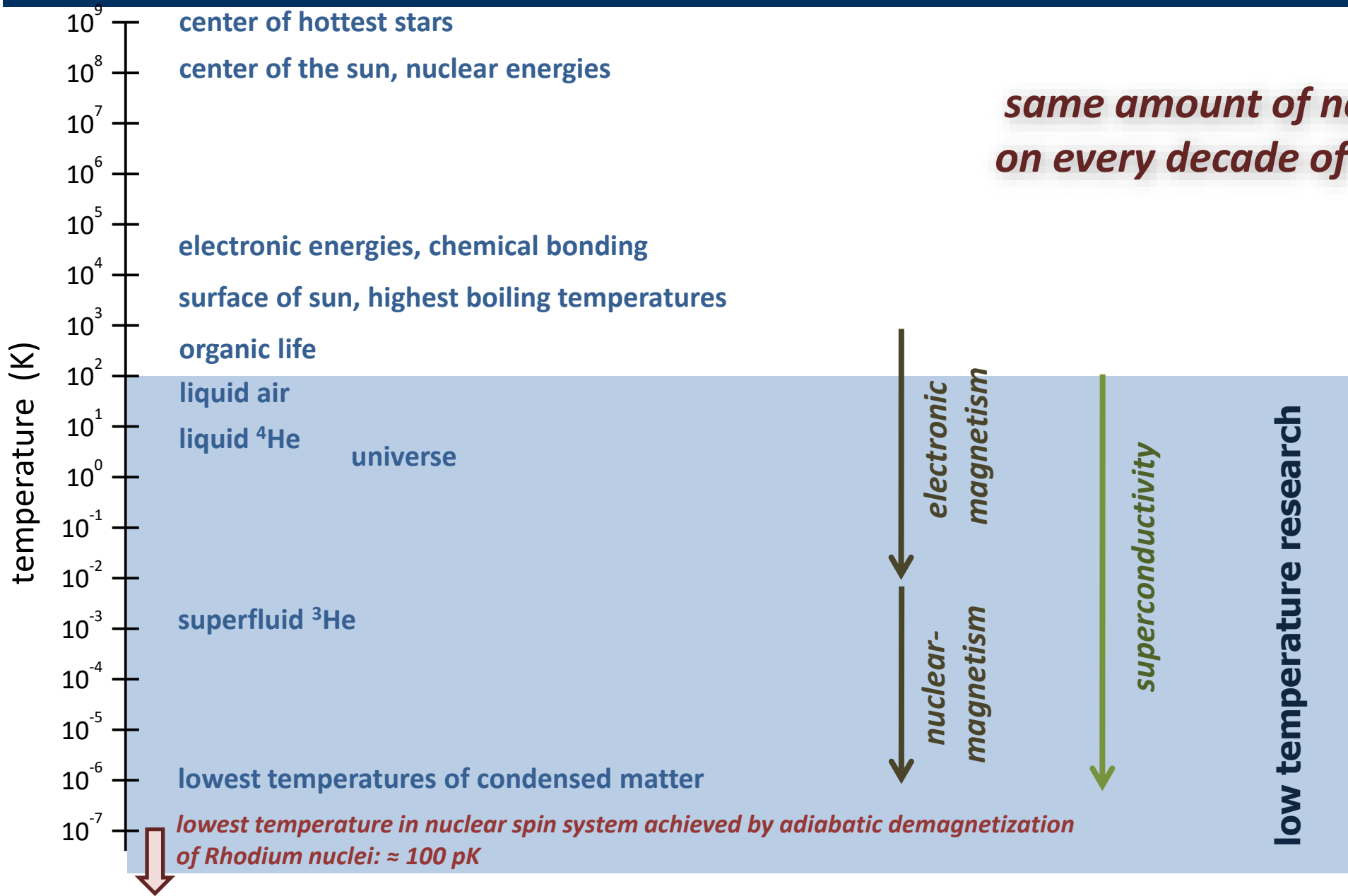
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9783110782349 (hardcover), ISBN 9783110782394 (eBook)

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Introduction

Temperature Scale

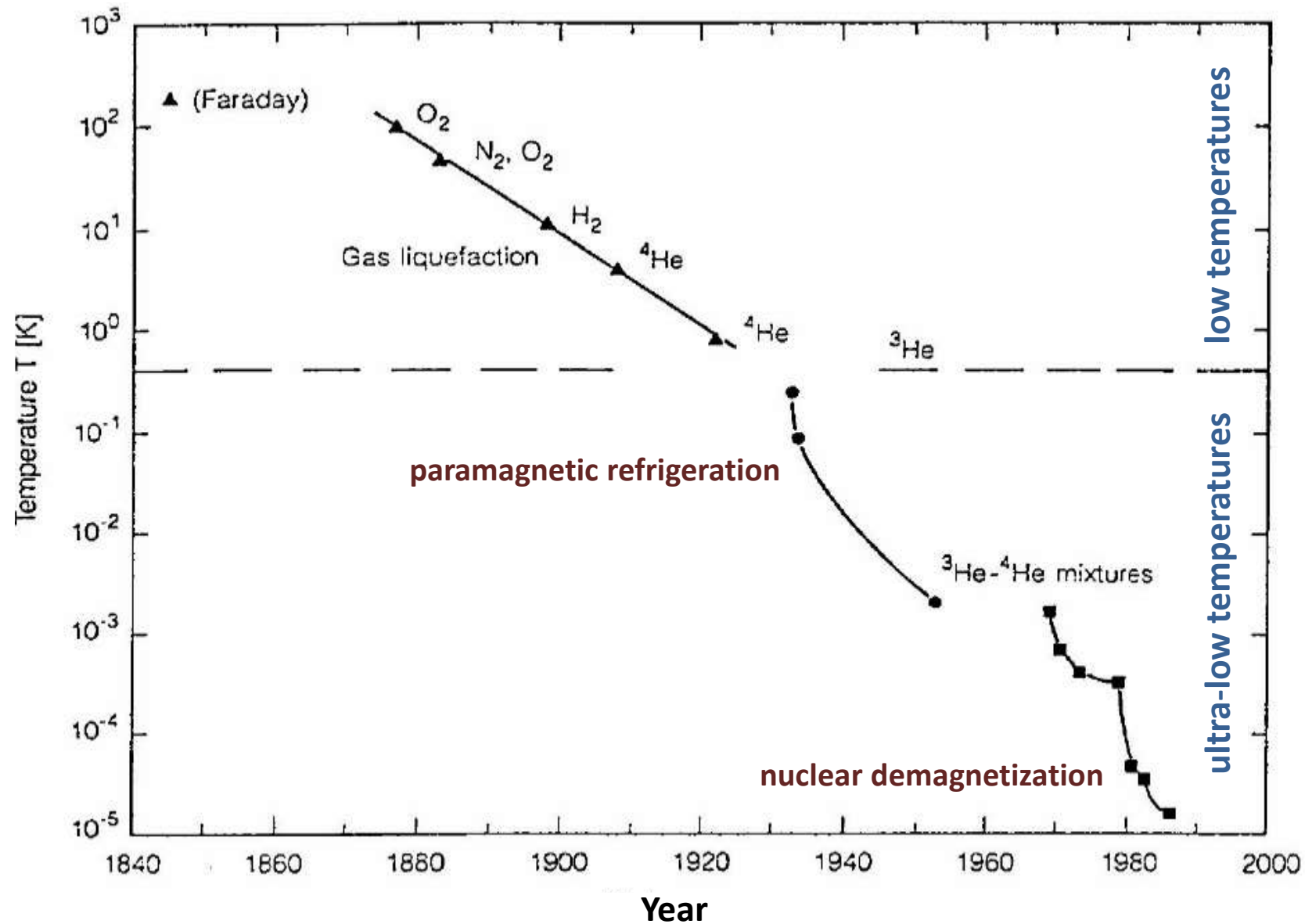


same amount of new physics on every decade of log T scale

Low Temperature Phenomena

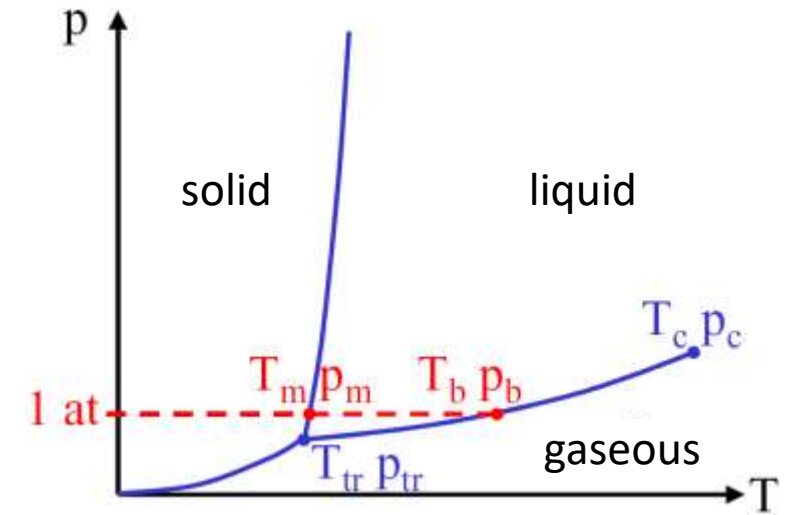
- many direct implications of quantum mechanics only show up at sufficiently low temperatures
e.g. magnetism, superconductivity
- particularly interesting are quantum phenomena manifesting themselves on a macroscopic length scale
→ *macroscopic quantum phenomena*
 - Superconductivity
 - **Superfluidity**
 - **Bose-Einstein Condensation** } this lecture

Generation of Low Temperatures



Generation of Low Temperatures

Substance	T_b [K]	T_m [K]	T_{tr} [K]	P_{tr} [bar]	T_c [K]	P_c [bar]
	@ 1 bar					
H ₂ O	373.15	273.15	273.16	0.06	647.3	220
Xe	165.1	161.3	161.4	0.82	289.8	58.9
Kr	119.9	115.8	114.9	0.73	209.4	54.9
O ₂	90.2	54.4	54.36	0.016	154.3	50.4
Ar	87.3	83.8	83.81	0.67	150.9	48.7
N ₂	77.4	63.3	63.15	0.12	126.0	33.9
Ne	27.1	24.5	24.56	0.43	44.5	27.2
D ₂	23.7	18.7	18.72	0.17	38.3	16.6
H ₂	20.3	14.0	13.80	0.07	33.3	13.0
⁴ He	4.21	--	--	--	5.20	2.28
³ He	3.19	--	--	--	3.32	1.16



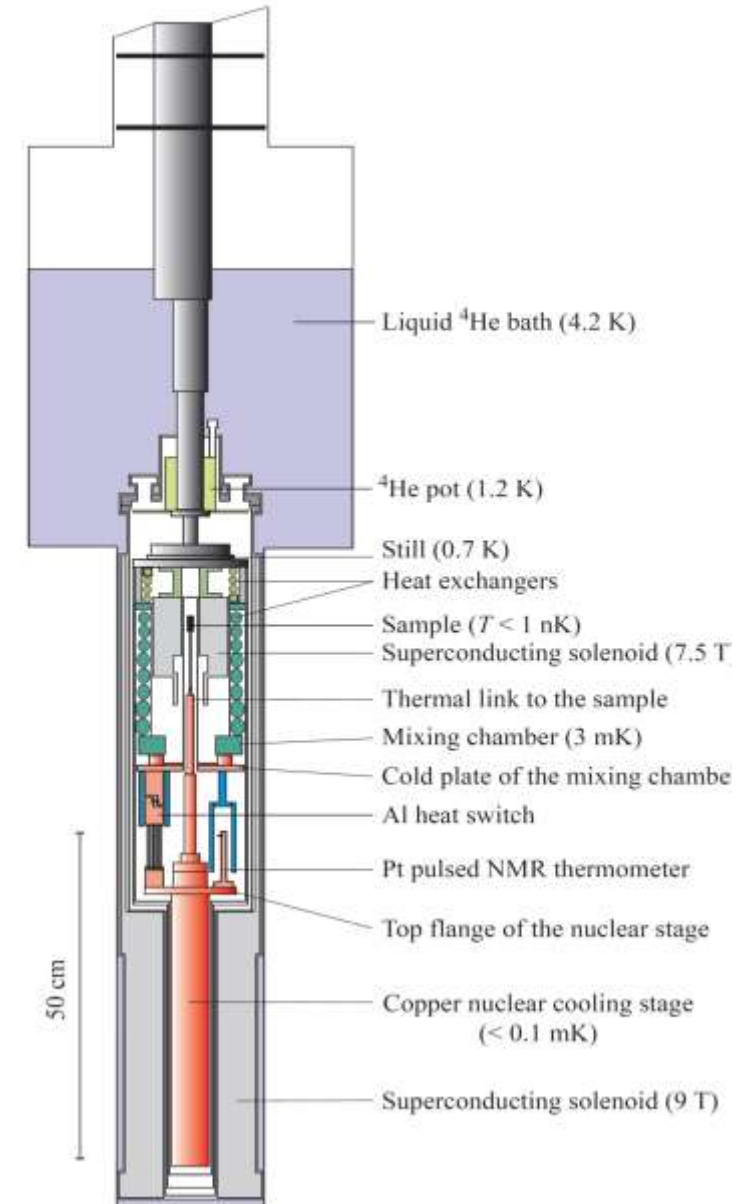
Generation of Low Temperatures

- nuclear demagnetization

experimental setup according to
Tauno Knuutila (2000)

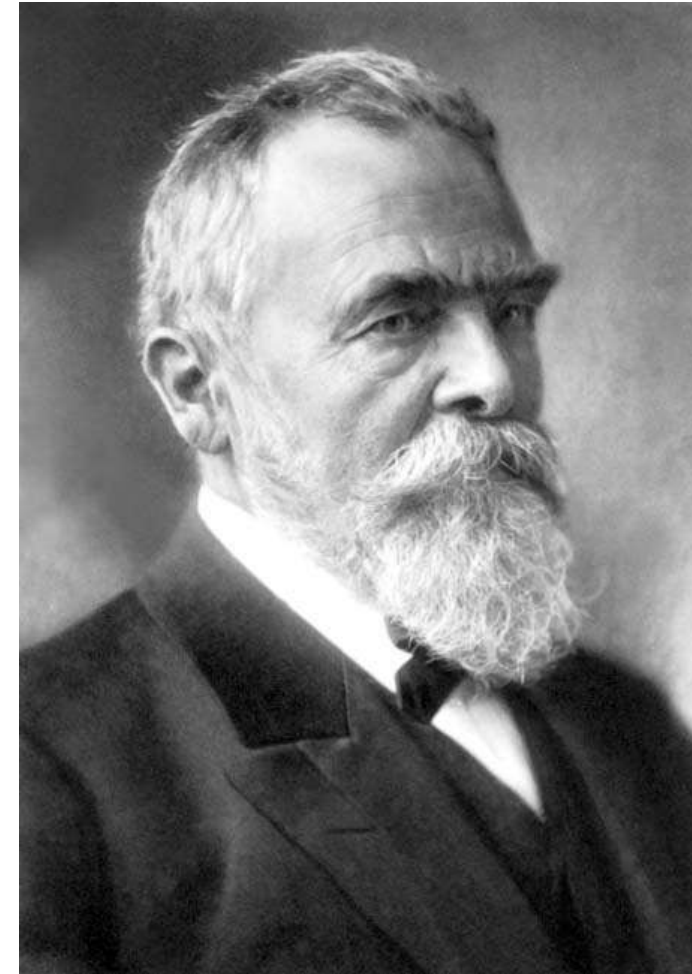
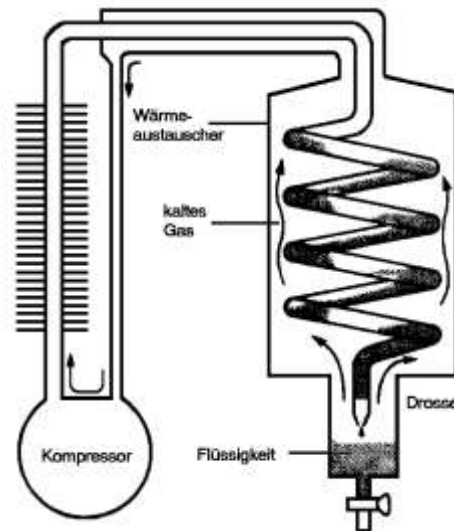
lowest temperature of nuclear spin system:
about **100 pK**
by demagnetization of Rhodium nuclei

PhD Thesis,
Helsinki University of Technology
(Espoo, Finland)



- 1868** offer of chair at the Polytechnische Schule München (now TUM)
- 1873** development of cooling machine allowing the temperature stabilization in beer brewing
- 21. 6. 1879** foundation of „*Gesellschaft für Linde's Eismaschinen AG*“ together with two beer brewers and three other co-founders
- 1892 – 1910** re-establishment of professorship

12.5.1903 patent application:
 „*Lindesches Gegenstromverfahren*“
 liquefaction of oxygen
 ($-182^{\circ}\text{C} = 90\text{ K}$)



Carl Paul Gottfried von Linde

* 11. Juni 1842 in Berndorf, Oberfranken
 † 16. November 1934 in Munich

1930 Linde AG uses the first cooling turbines for the generation of low temperatures

turbines have higher efficiency and therefore are used today in all larger liquefaction machines

e.g. He liquefier at the Walther-Meißner-Institut

1947 first commercial He liquefier (design by engineer Collins, therefore denoted as „Collins“ machine)

Arthur D. Little Inc. (today CTI)

1966 ***Hall*** et al. and ***Neganov*** et al. develop $^3\text{He}/^4\text{He}$ dilution refrigerators, generation of temperatures down to 2 mK

Discovery of Superconductivity (1911)

Heike Kamerlingh Onnes (1853-1926)

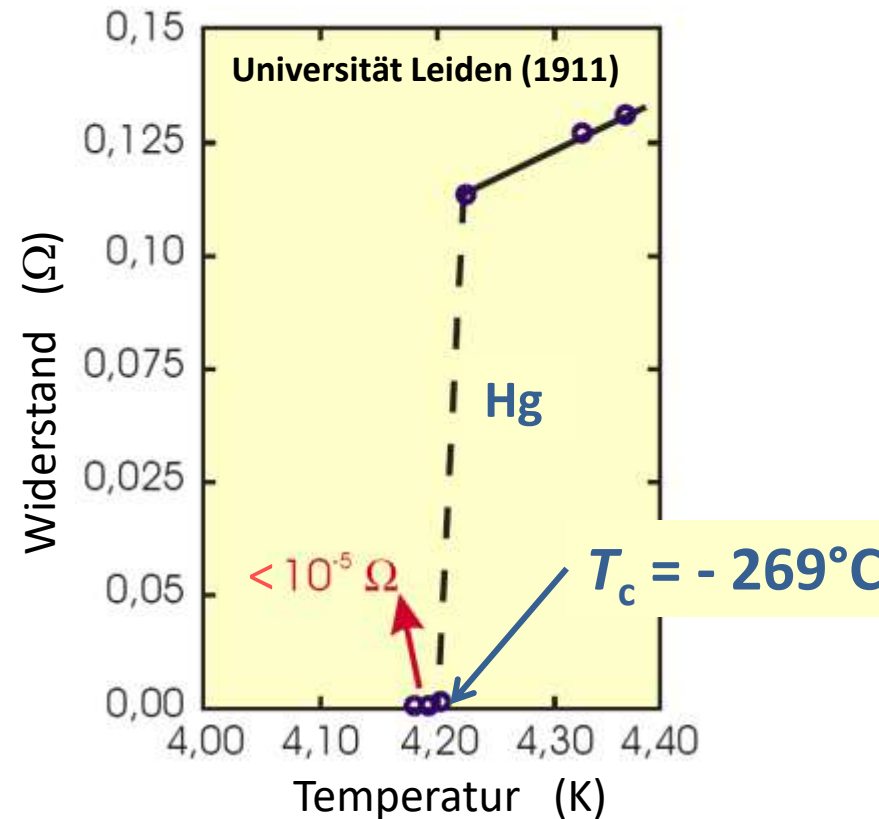


- Helium liquefaction: 1908
- discovery of superconductivity: 1911

Nobel Price in Physics 1913

choice of name:

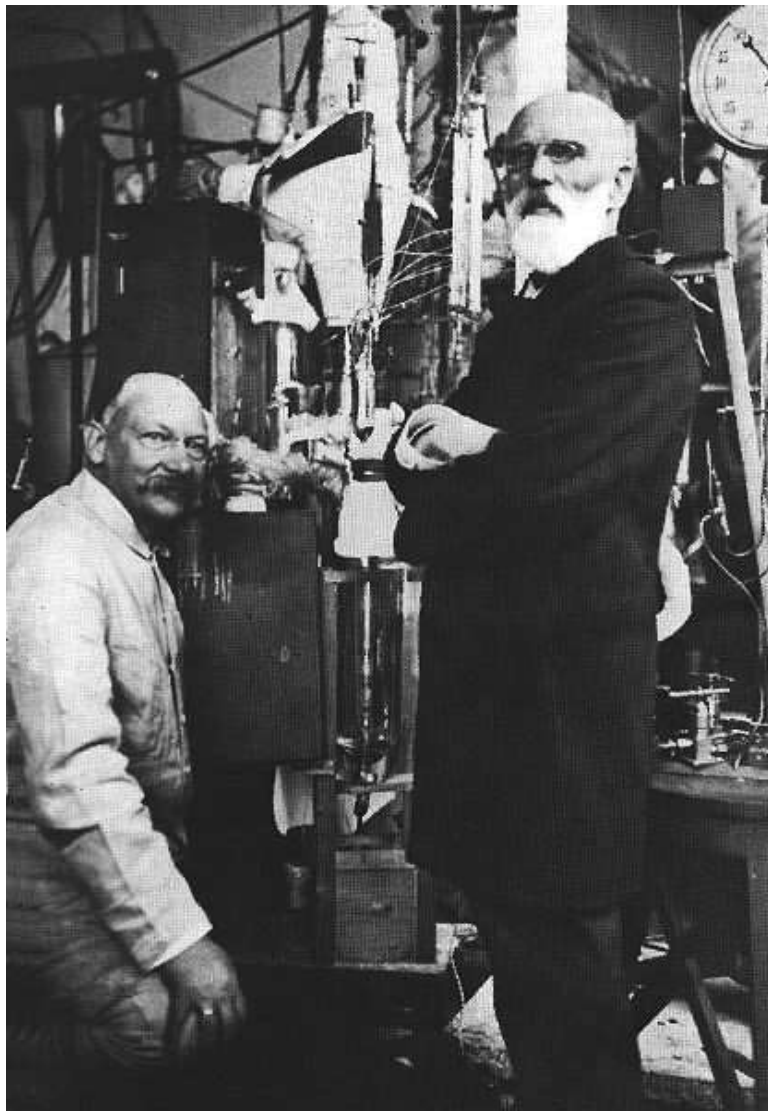
infinite electrical conductivity → **superconductivity**



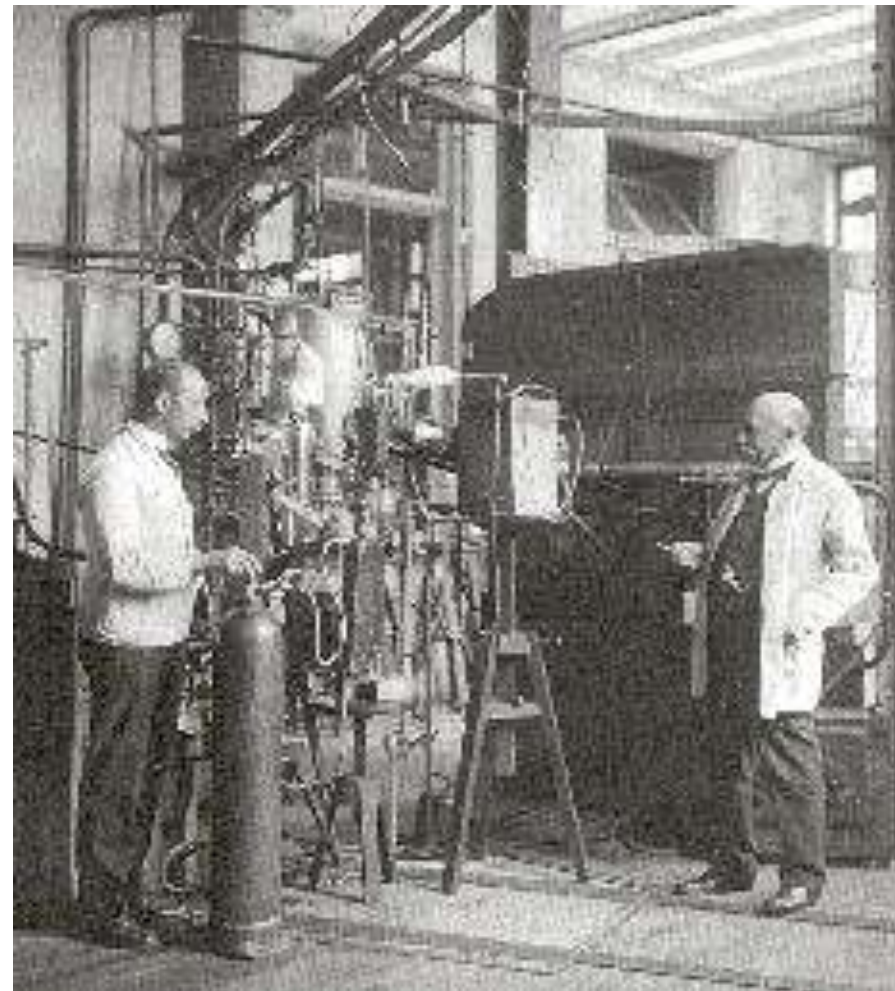
H. K. Onnes, Comm. Leiden 120b (1911)

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

Discovery of Superconductivity (1911)



Kammerlingh Onnes and van der Waals



Kammerlingh Onnes and Technician Flim

Discovery of the Meißner-Ochsenfeld Effect (1933)



Robert Ochsenfeld
(1901 – 1993)



perfect diamagnetism

*W. Meißner, R. Ochsenfeld,
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit,
Naturwissenschaften 21, 787 (1933).*

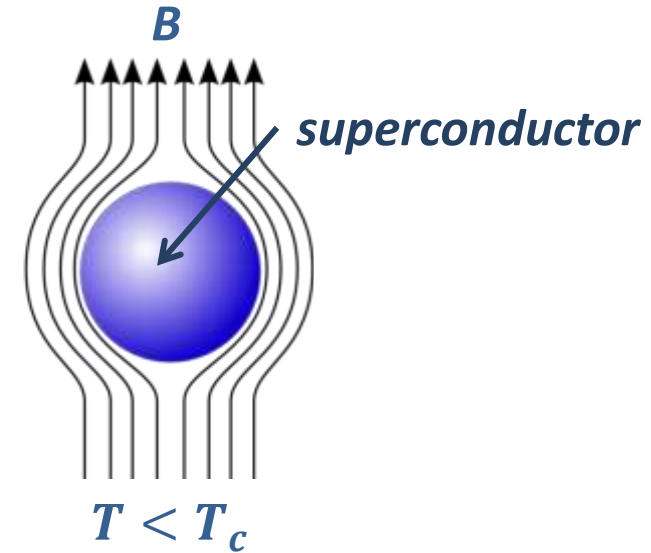
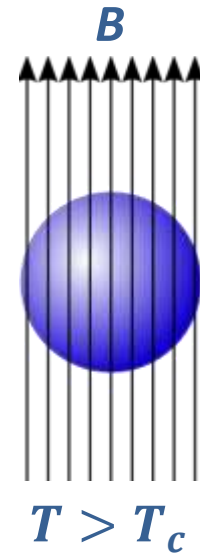


Dr. Walther Meißner
a. Prof. für technische Physik. Präsident 1946-50

Walther Meißner
(1882 – 1974)

Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner (1882 – 1974)



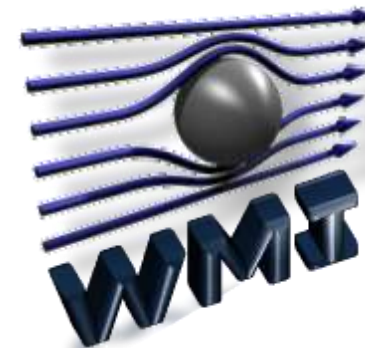
superconductors perfectly expel magnetic field

$$B_{\text{in}} = (1 + \chi) B_{\text{ext}} = 0 \quad \chi = \text{magnetic susceptibility}$$

➔ ideal diamagnetism, $\chi = -1$

choice of name for perfect diamagnetism:

Meißner-Ochsenfeld Effect



Walther Meißner (1882 – 1974)

- 1913 – 1934** building and heading of low temperature laboratory at the Physikalisch-Technischen-Reichsanstalt, **liquefaction of H₂ (20K)**

- 7.3.1925** **first liquefaction of He in Germany** (4.2 K, 200 ml), 3rd system world-wide besides Leiden and Toronto

- 1933** discovery of perfect diamagnetism of superconductors together with Ochsenfeld
 → ***Meißner-Ochsenfeld Effect***

- 1934** offer of chair at the Technische Hochschule München (now TUM)

- 1946 – 1950** president of the Bavarian Academy of Sciences and Humanities

- 1946** foundation of the commission for Low Temperature Research
 → ***Walther-Meißner-Institut***



Walther Meißner

* 16. Dezember 1882 in Berlin

† 15. November 1974 in Munich

Walther Meißner - der Mann, mit dem die Kälte kam

W. Buck, D. Einzel, R. Gross, Physik Journal, Mai 2013

Low Temperature Physics

at

WMI

- **superconductivity and superfluidity**
- **magnetism and spintronics**
- **nanoscale superconducting and spintronic devices**
- **solid-state based quantum systems**
- **superconducting quantum circuits for quantum computing**
- **quantum microwave communication and sensing**
- **.....**

an appetizer

innovative cryoengineering

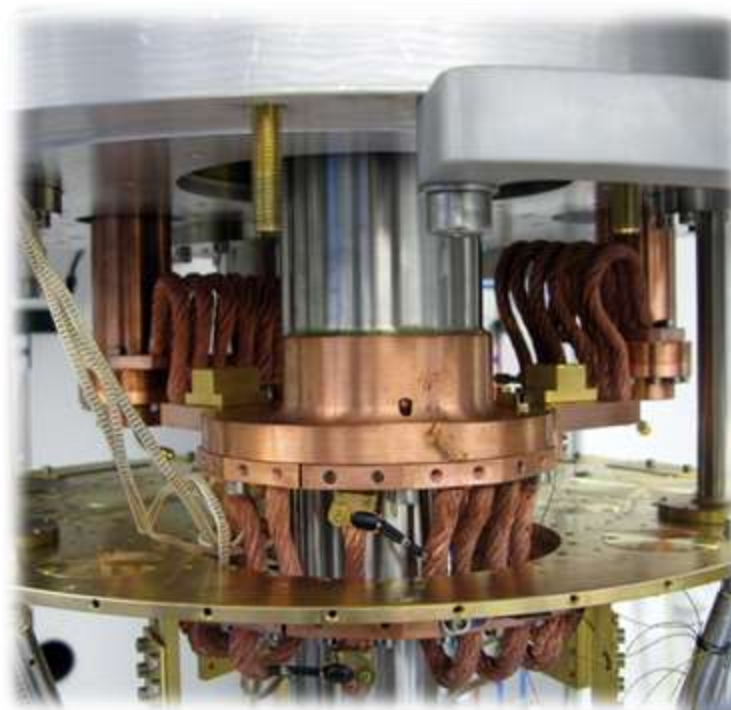
....WMI develops first dry dilution fridge

K. Uhlig, Cryogenics 42, 73 – 77 (2002)

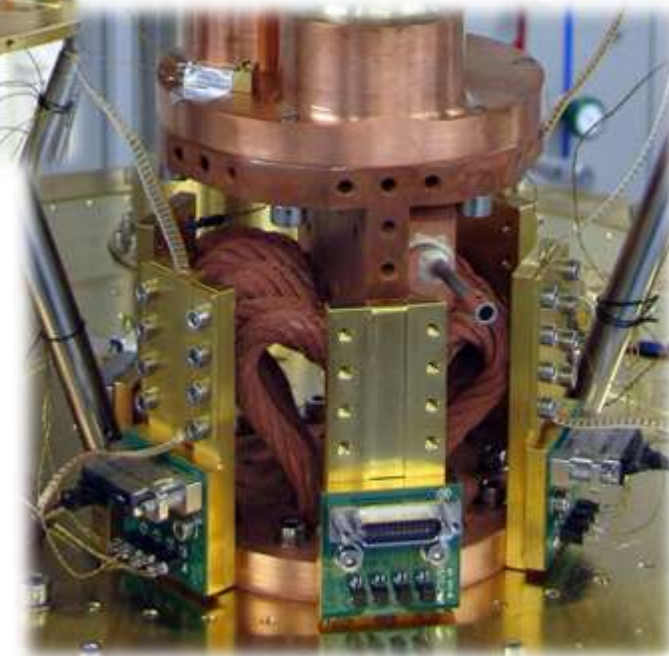


Oxford Instruments Triton family

market share of dry dilution fridges: > 95 %



*dry dilution fridge
designed and fabricated
at WMI*



- BlueFors XLD Dilution Fridge (2020)



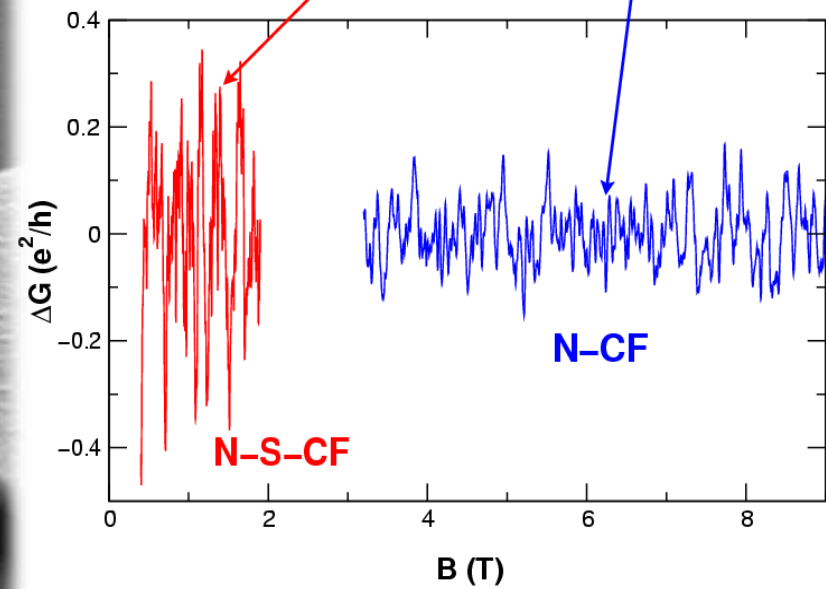
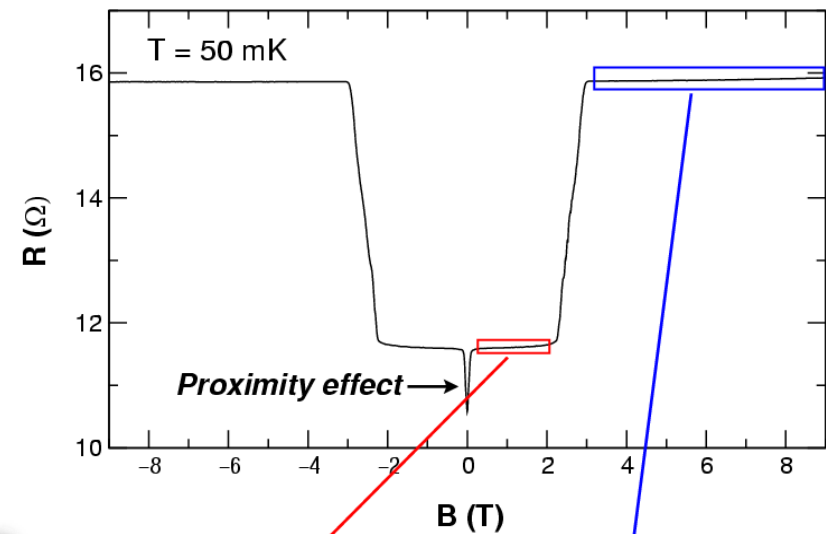
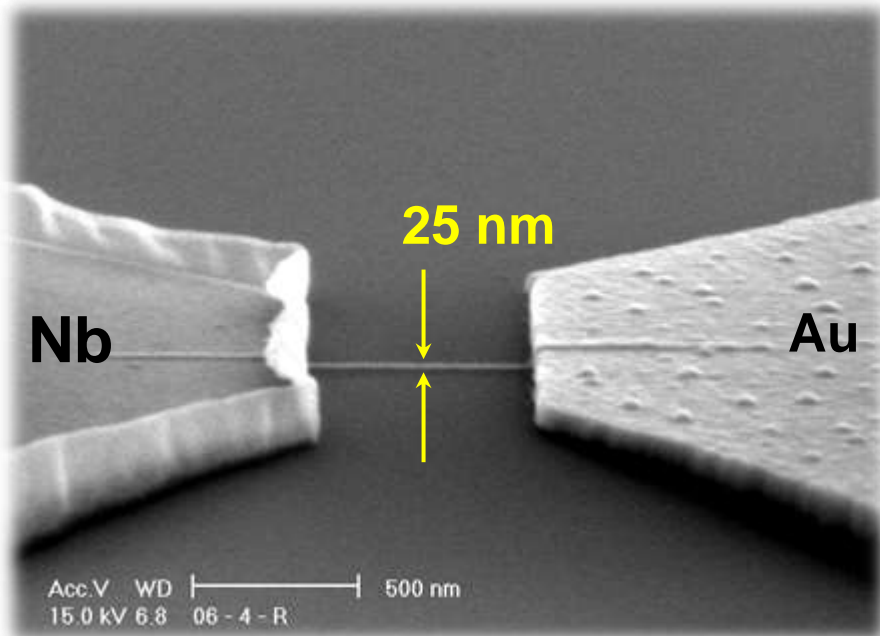
- Oxford Instruments Dilution Fridge (2011)
(with 3D vector magnet)



- **Helium liquefier at WMI:
Linde TCF 20**
- **supply of LHe to both Munich
Universities**
- **liquefaction power:
> 150 000 l/year**
- **market price:
about 4 Mio. €**

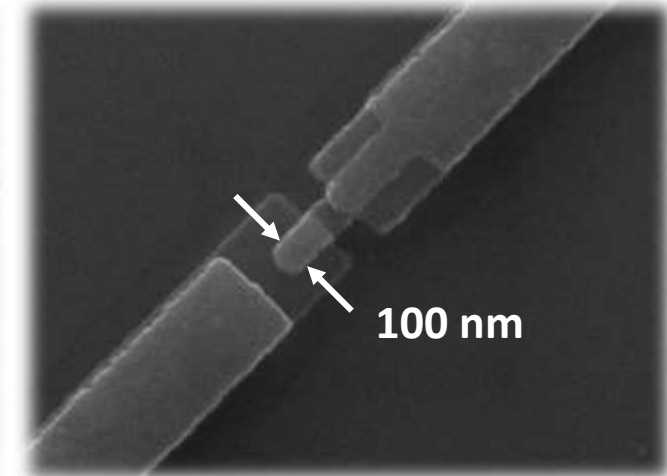
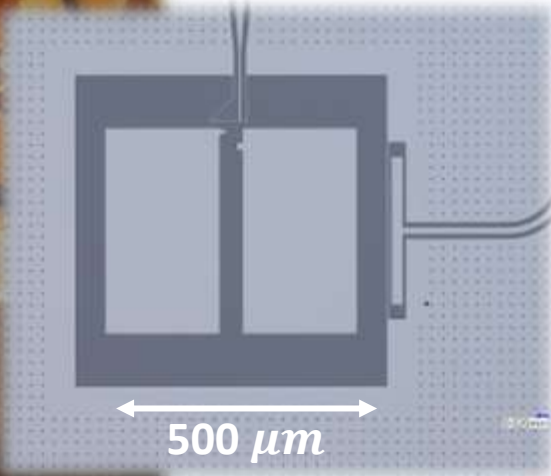
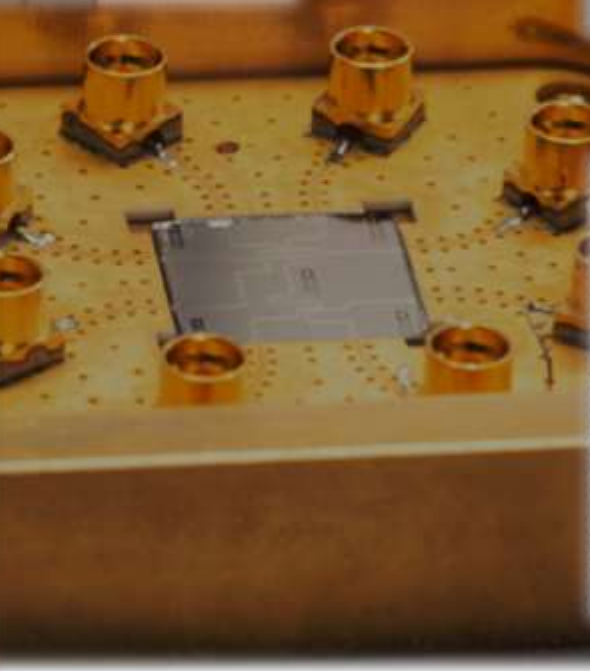
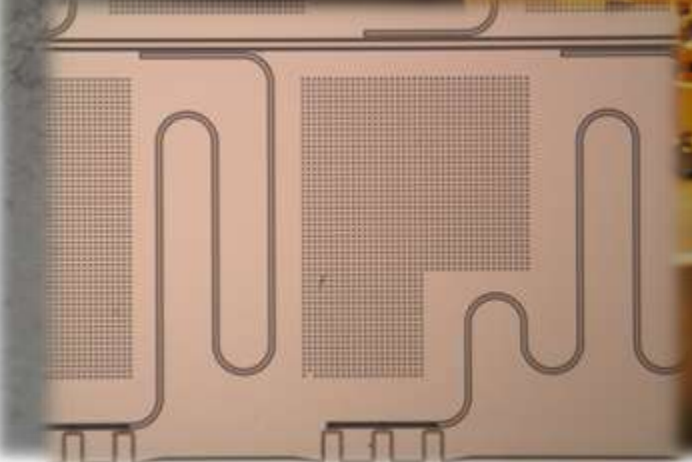
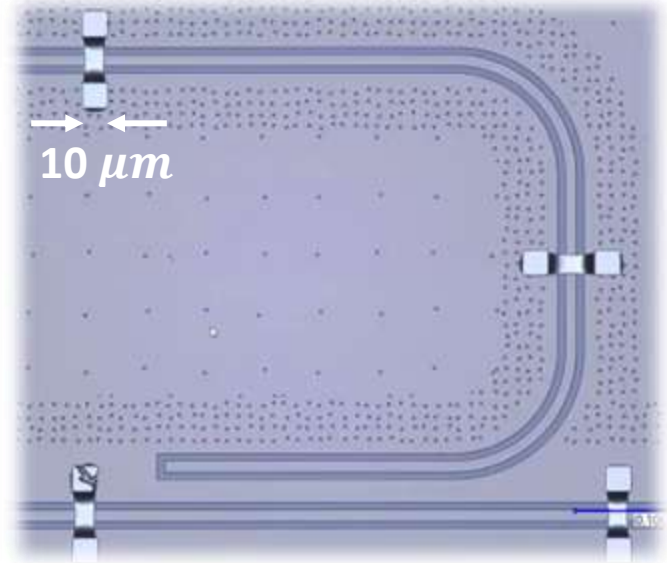


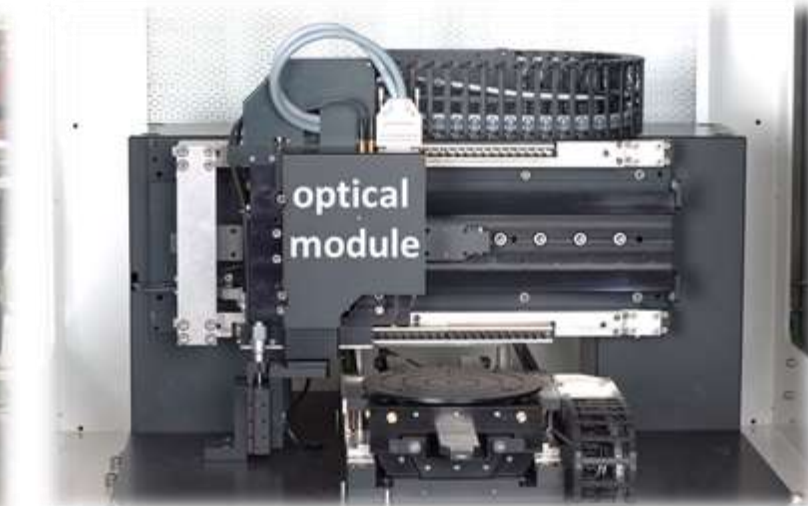
Low Temperature Physics at WMI





#we do technology





Quantum Technology Projects @ WMI



Bayerisches Staatsministerium
für Wissenschaft und Kunst

GeQCoS (BMBF)
MQV-SQQC (StMWK Bayern)
MUNIQC-SC (BMBF)



Bundesministerium
für Bildung
und Forschung

R. Gross © Walther-Meißner-Institut (2004 - 2024)



Bundesministerium
für Bildung
und Forschung



QuaMe

DFG Deutsche
Forschungsgemeinschaft



BUILDING
**QUANTUM
COMPUTERS**

Demonstrator-QC
~ 10 Qubits



NISQ-QC
~ 100 Qubits



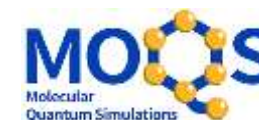
FT-QC
~ 10⁶ Qubits



kiutra



Funded by
the European Union



**Have
Fun !!**