Superconductivity and Low Temperature Physics II
Superconductivity,
Superfluidity, Condensates, Quantum Liquids
General Remarks on the Courses to the Field
Superconductivity and Low Temperature Physics

1. Superconductivity and Low Temperature Physics I + II
   ➔ Part I (WS 2022/2023): Foundations of Superconductivity
   ➔ Part II (SS 2023): Quantum Liquids, BECs, Quantum Interference Effects,
                        Foundations of Low Temperature Physics and Techniques

2. Applied Superconductivity I + II
   ➔ WS 2022/23 and SS 2023, 2 hrs lecture + 2 hrs exercises
   ➔ Josephson-Effect, Superconducting Electronics, Qubits, Quantum Circuits, …

3. Seminars (SS 2023, WMI seminar room)
   ➔ Advances in Solid State Physics (TUE 10:15-11:30)
   ➔ Superconducting Quantum Circuits (TUE 14:30-16:00)

Further information:  https://www.wmi.badw.de/teaching
   ➔ announcement of lectures
   ➔ downloads of lecture notes, handouts…
   ➔ seminar topics
<table>
<thead>
<tr>
<th>year</th>
<th>name</th>
<th>discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1913</td>
<td>Heike Kamerlingh Onnes</td>
<td>&quot;For his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium&quot;</td>
</tr>
<tr>
<td>1972</td>
<td>John Bardeen, Leon Neil Cooper and Robert Schrieffer</td>
<td>&quot;for their jointly developed theory of superconductivity, usually called the BCS-theory&quot;</td>
</tr>
<tr>
<td>1973</td>
<td>Brian David Josephson</td>
<td>&quot;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&quot;</td>
</tr>
<tr>
<td>1978</td>
<td>Pjotr Kapiza</td>
<td>&quot;for his basic inventions and discoveries in the area of low-temperature physics&quot;</td>
</tr>
<tr>
<td>1985</td>
<td>Klaus von Klitzing</td>
<td>&quot;for the discovery of the quantized Hall effect&quot;</td>
</tr>
<tr>
<td>1987</td>
<td>Johannes Georg Bednorz und Karl Alex Müller</td>
<td>&quot;for their important break-through in the discovery of superconductivity in ceramic materials&quot;</td>
</tr>
<tr>
<td>1996</td>
<td>David M. Lee, Douglas D. Osheroff und Robert C. Richardson</td>
<td>&quot;for their discovery of superfluidity in helium-3&quot;</td>
</tr>
<tr>
<td>2001</td>
<td>Eric A. Cornell, Wolfgang Ketterle und Carl E. Wieman</td>
<td>&quot;for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates&quot;</td>
</tr>
<tr>
<td>2003</td>
<td>Alexei Abrikosov, Vitali Ginsburg und Anthony James Leggett</td>
<td>&quot;for pioneering contributions to the theory of superconductors and superfluids&quot;</td>
</tr>
<tr>
<td>2016</td>
<td>David J. Thouless, F. Duncan M. Haldane, J. Michael Kosterlitz</td>
<td>&quot;for theoretical discoveries of topological phase transitions and topological phases of matter&quot;</td>
</tr>
</tbody>
</table>
Contents of Lecture

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 ($^4$He and $^3$He)
- 2. Quantum Interference Effects in Mesoscopic Conductors
- 3. Low Temperature Techniques
  (generation and measurement of low temperatures)
## Contents Part I: Quantum Liquids

### 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 $^4\text{He}$ and $^3\text{He}$
- I.1.7 Characteristic Properties of $^4\text{He}$ and $^3\text{He}$
- I.1.8 Specific Heat of $^4\text{He}$ and $^3\text{He}$

### I.2 $^4\text{He}$ 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 $^4\text{He}$

### I.3 Superfluid $^4\text{He}$
- I.3.1 Two-Fluid Model
- I.3.2 Experimental Observations
- I.3.3 Two-Fluid Hydrodynamics
- I.3.4 Excitation Spectrum of $^4\text{He}$

### I.4 Vortices
- I.4.1 Quantization of Circulation
- I.4.2 Experimental Study of Vortices

### I.5 $^3\text{He}$
- I.5.1 normal fluid $^3\text{He}$
- I.5.2 solid $^3\text{He}$ and Pomeranchuk effect
- I.5.3 superfluid $^3\text{He}$

### I.6 $^3\text{He} / ^4\text{He}$ mixtures
Contents Part II: Quantum Transport in Nanostructures

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 ElectronTransport 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
Literature

- 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

- P.V.E. McClintock, D.J. Meredith, J.K. Wigmore
  *Matter at Low Temperatures*, Blackie 1984

- J. Wilks, D.S. Betts
  *Introduction to Liquid Helium*, Oxford 1987

- A. Kent
  *Experimental Low Temperature Physics*, MacMillan, New York

- 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
  *Tieftemperaturtechnologie*, VDI-Verlag, Düsseldorf 1981

- Yoseph Imry

- Supriyoto Datta

- Thomas Heindel

- Thomas Ihn
  *Semiconductor Nanostructures*, Oxford University Press (2010)
Literature

**Rudolf Gross, Achim Marx**

Title: Festkörperphysik, 4th revised and extended edition  
Publisher: Walter de Gruyter GmbH, Berlin/Boston  
Published: January 2023  
Language: German

9783110782349 (hardcover), ISBN 9783110782394 (eBook)
Introduction
**Temperature Scale**

- Center of hottest stars
- Center of the sun, nuclear energies

- Electronic energies, chemical bonding
- Surface of sun, highest boiling temperatures
- Organic life

- Liquid air
- Liquid $^4$He
- Universe

- Superfluid $^3$He

- Lowest temperatures of condensed matter

*Lowest temperature in nuclear spin system achieved by adiabatic demagnetization of Rhodium nuclei: $\approx 100$ pK*

---

**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 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

paramagnetic refrigeration

nuclear demagnetization
# Generation of Low Temperatures

<table>
<thead>
<tr>
<th>Substance</th>
<th>$T_b$ [K]</th>
<th>$T_m$ [K]</th>
<th>$T_{tr}$ [K]</th>
<th>$P_{tr}$ [bar]</th>
<th>$T_c$ [K]</th>
<th>$P_c$ [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>373.15</td>
<td>273.15</td>
<td>273.16</td>
<td>0.06</td>
<td>647.3</td>
<td>220</td>
</tr>
<tr>
<td>Xe</td>
<td>165.1</td>
<td>161.3</td>
<td>161.4</td>
<td>0.82</td>
<td>289.8</td>
<td>58.9</td>
</tr>
<tr>
<td>Kr</td>
<td>119.9</td>
<td>115.8</td>
<td>114.9</td>
<td>0.73</td>
<td>209.4</td>
<td>54.9</td>
</tr>
<tr>
<td>O$_2$</td>
<td>90.2</td>
<td>54.4</td>
<td>54.36</td>
<td>0.016</td>
<td>154.3</td>
<td>50.4</td>
</tr>
<tr>
<td>Ar</td>
<td>87.3</td>
<td>83.8</td>
<td>83.81</td>
<td>0.67</td>
<td>150.9</td>
<td>48.7</td>
</tr>
<tr>
<td>N$_2$</td>
<td>77.4</td>
<td>63.3</td>
<td>63.15</td>
<td>0.12</td>
<td>126.0</td>
<td>33.9</td>
</tr>
<tr>
<td>Ne</td>
<td>27.1</td>
<td>24.5</td>
<td>24.56</td>
<td>0.43</td>
<td>44.5</td>
<td>27.2</td>
</tr>
<tr>
<td>D$_2$</td>
<td>23.7</td>
<td>18.7</td>
<td>18.72</td>
<td>0.17</td>
<td>38.3</td>
<td>16.6</td>
</tr>
<tr>
<td>H$_2$</td>
<td>20.3</td>
<td>14.0</td>
<td>13.80</td>
<td>0.07</td>
<td>33.3</td>
<td>13.0</td>
</tr>
<tr>
<td>$^4$He</td>
<td>4.21</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5.20</td>
<td>2.28</td>
</tr>
<tr>
<td>$^3$He</td>
<td>3.19</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3.32</td>
<td>1.16</td>
</tr>
</tbody>
</table>

![T-P phase diagram](image_url)

- **solid**
- **liquid**
- **gaseous**

1 at

$T_m$, $P_m$, $T_b$, $P_b$, $T_{tr}$, $P_{tr}$, $T_c$, $P_c$
Generation of Low Temperatures

• nuclear demagnetization

experimental setup according to Tauno Knuuttila (2000)

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

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

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 Gegenstrom-verfahren“ liquefaction of oxygen (-182°C = 90 K)

Carl Paul Gottfried von Linde
* 11. Juni 1842 in Berndorf, Oberfranken
† 16. November 1934 in Munich
Low Temperature Technology

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 \(^3\)He/\(^4\)He dilution refrigerators, generation of temperatures down to 2 mK
Discovery of Superconductivity (1911)

Helium liquefaction: 1908
Discovery of superconductivity: 1911

Nobel Price in Physics 1913

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

choice of name:

infinite electrical conductivity \(\Rightarrow\) superconductivity
Discovery of Superconductivity (1911)

Kammerlingh Onnes and van der Waals

Kammerlingh Onnes and Technician Flim
Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner
(1882 – 1974)

perfect diamagnetism

Robert Ochsenfeld
(1901 – 1993)

W. Meißner, R. Ochsenfeld,
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit,
Naturwissenschaften 21, 787 (1933).
Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner (1882 – 1974)

superconductors perfectly expel magnetic field

\[ B_{\text{in}} = (1 + \chi) B_{\text{ext}} = 0 \]

\[ \chi = \text{magnetic susceptibility} \]

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
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

Oxford Instruments Triton family

market share of dry dilution fridges: > 95 %
Low Temperature Physics at WMI

dry dilution fridge designed and fabricated at WMI
Low Temperature Physics at WMI

- BlueFors XLD Dilution Fridge (2020)
Low Temperature Physics at WMI

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

- **Helium liquefier at WMI:** Linde TCF 20

- **Supply of LHe to both Munich Universities**

- **Liquefaction power:** > 150 000 l/year

- **Market price:** about 2 Mio. €
Competence Center for SC Quantum Technology

#we do technology
Quantum Technology Projects @ WMI

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

Demonstrator-QC  ~ 10 Qubits
NISQ-QC  ~ 100 Qubits
FT-QC  ~ 10^6 Qubits
Have Fun !!