Superconductivity and Low Temperature Physics I

Lecture Notes
Winter Semester 2023/2024

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Chapter 1

Basic Properties of Superconductors
1. Basic Properties of Superconductors

1.1 History of Superconductivity
1.2 Perfect Conductivity
1.3 Perfect Diamagnetism
1.4 Type-I and Type-II Superconductors
1.5 Flux Quantization
1.6 Superconducting Materials
1.7 Transition Temperatures
1.1 History of Superconductivity

Discovery and explanation of the phenomena of superconductivity and superfluidity was honored by many Nobel Prizes

1908  Liquefaction of Helium, 4.2 K (Kamerlingh Onnes)
1911  Discovery of zero resistance (Kamerlingh Onnes)
1933  Discovery of the Meißner-Ochsenfeld effect (Meißner & Ochsenfeld)
1935  London theory (Fritz & Heinz London)
1936  Type-II superconductivity (Shubnikov)
1939  Discovery of superfluid $^4$Helium (Kapitza, Allen, and Misener)
1952  Ginzburg-Landau theory (Ginzburg & Landau)
1957  Abrikosov theory of type-II superconductivity (Abrikosov)
1957  Bardeen-Cooper-Schrieffer (BCS) theory (Bardeen, Cooper & Schrieffer)
1961  Discovery of flux quantization (Doll/Näbauer & Deaver/Fairbank)
1962  Cooper pair tunneling: Josephson effect (Josephson, Giaever)
1966  Development of Superconducting Quantum Interference Devices (Clarke)
1971  Discovery of superfluid $^3$Helium (Lee, Richardson, Osheroff)
1975  Theory of superfluid $^3$Helium (Leggett)
1979  Discovery of heavy fermion superconductors (Steglich)
1981  Discovery of organic superconductors (Bechgaard)
1986  Discovery of high-temperature superconductivity (Bednorz, Müller)
2006  Discovery of superconductivity in iron pnictides (Hosono)

Blue: Nobel Prize winners
Discovery and explanation of the phenomena of superconductivity and superfluidity was honored by many Nobel Prizes.
1.1 Discovery of Superconductivity (1911)

• what was the basic interest?

**temperature dependence of very pure metals for** $T \to 0$ ??

- $R \to 0$
- $R \to \text{const.}$
- $R \to \infty$

*use of Hg, since very pure Hg was available*

**H. K. Onnes**

"... Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state"
1.1 Discovery of Superconductivity (1911)

Heike Kammerlingh Onnes (1853-1926)

• 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 ➔ superconductivity
1.1 Discovery of Superconductivity (1911)

Kammerlingh Onnes and van der Waals

Kammerlingh Onnes and Technician Flim
1.1 Discovery of Superconductivity (1911)

an early picture of the Onnes Laboratory

Kamerlingh Onnes Laboratory, 1924
1.1 Discovery of Superconductivity (1911)

Heike Kamerlingh Onnes (far right) shows his helium liquefactor to three theoretical physicists: Niels Bohr (visiting from Kopenhagen), Hendrik Lorentz, and Paul Ehrenfest (far left).
1.1 Discovery of Superconductivity (1911)

Prof. Heike Kamerlingh Onnes and his wife with some colleagues among them their friend Albert Einstein (**standing behind Mrs. Kamerlingh Onnes**), ca. 1920.
1.1 Discovery of the Meißner-Ochsenfeld Effect (1933)

Robert Ochsenfeld (1901 – 1993)

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

perfect diamagnetism

Walther Meißner (1882 – 1974)
1.1 Discovery of the Meißner-Ochsenfeld Effect (1933)

Superconductors perfectly expel magnetic field

\[ B_{\text{in}} = (1 + \chi) B_{\text{ex}} = 0 \quad (\chi = \text{magnetic susceptibility}) \]

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 Bayerischen Akademie der Wissenschaften

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

Walther Meißner
* 16. Dezember 1882 in Berlin
† 15. November 1974 in Munich
1935 Fritz and Heinz London

first „quantum mechanical“
three of superconductivity
(purely phenomenological)

→ macroscopic wave function

Fritz London
(1900 – 1954)
1936 Lev W. Shubnikov

discovery of the Shubnikov phase in superconductors

→ type-I and type-II superconductivity

Lev Wassiljevitsch Shubnikov
(1901 – 1937)
Discovery of Superfluid $^4$Helium (1939)

Pyotr Leonidovich Kapitza (1894-1984)

Nobel Prize in Physics 1978

„for his basic inventions and discoveries in the area of low-temperature physics"

phenomenon analogous to superconductivity is found in an uncharged system

P.L. Kapitza with his assistant S.I. Filimonov carrying out an experiment with superfluid helium. IPP, Moscow, 1940.

Pyotr Leonidovich Kapitza (1894-1984)
Ginzburg-Landau Theory (1952)

application of Landau’s theory for phase transitions to superconductors using a complex order parameter

Lev Landau

Nobel Prize in Physics 1962
"for his pioneering theories for condensed matter, especially liquid helium"

Vitaly Ginzburg

Nobel Prize in Physics 2003
“for their pioneering contributions to the theory of superconductors and superfluids”

(together with Alexei Abrikosov and Anthony Leggett)
Abrikosov Theory of Type-II Superconductivity (1957)

Abrikosov used the Ginzburg-Landau phenomenology to derive the existence of a “mixed-state”

Alexei Abrikosov

Nobel Prize in Physics 2003

“for their pioneering contributions to the theory of superconductors and superfluids”

(together with Vitaly Ginzburg and Anthony Leggett)
Alexei A. Abrikosov
The Nobel Prize in Physics 2003

Alexei A. Abrikosov  Vitaly L. Ginzburg  Anthony J. Leggett

..... for their pioneering contributions to the theory of superconductors and superfluids.
Lev Landau
Vitaly L. Ginzburg
Microscopic (BCS) Theory (1957)

J. Bardeen  L. N. Cooper  R. Schrieffer

Nobel Prize in Physics 1972
"for their jointly developed theory of superconductivity, usually called the BCS-theory"
John Bardeen

* 23 May 1908, Madison, Wisconsin
† 30 January 1991, Boston
two-times Nobel Price winner
Pioneers of superconductivity honored at BCS@50
From left: Dale J. Van Harlingen, Lev Gor'kov, Charles P. Slichter, Leo Kadanoff, David Pines, Leon Cooper, Marvin Cohen, Michael Tinkham

* 28 February 1930, New York
Nobel Prize in Physics 1972
John Robert Schrieffer

* 31 May 1931, Oak Park, Illinois
Nobel Prize in Physics 1972
Discovery of Flux Quantization (1961)

Robert Doll and Martin Näbauer, WMI

Measuring the flux quantum. Graduate student Bascom Deaver refills his apparatus with liquid nitrogen at Stanford University in 1961, a necessary step in maintaining a superconductor at liquid helium temperature. He and William Fairbank used this setup to show that the magnetic field threading a superconducting loop is always quantized. [Credit: J. Mercado/Stanford News Service]
Prediction of the Josephson Effect (1962)

Brian David Josephson (geb. 1940)

Nobel Prize in Physics 1973

"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 effects"

(together with Leo Esaki and Ivar Giaever)
Discovery of Superfluid $^3$Helium (1971/72)

Nobel Prize in Physics 1996
"for their discovery of superfluidity in helium-3"

$T_c = 2.6 \text{ mK}$

1966 $^3\text{He}/^4\text{He}$ dilution refrigerator: Hall, Neganov
2 mK .... 500 mK
Development of SQUID (1966)

Superconducting Quantum Interference Devices

John Clarke
Theory of Superfluid $^3$Helium (1975)

Anthony J. Leggett

Nobel Prize in Physics 2003

..... for their pioneering contributions to the theory of superconductors and superfluids.

(together with Alexey A. Abrikosov and Vitaly Ginzburg)
Discovery of the High $T_c$ Superconductivity (1986)

J. Georg Bednorz (b. 1950)  K. Alexander Müller (b. 1927)

Nobel Prize in Physics 1987

"for their important break-through in the discovery of superconductivity in ceramic materials"
Discovery of the High $T_c$ Superconductivity (1986)

Karl Alexander Müller  
* 20. April 1927 in Basel

Johannes Georg Bednorz  
* 16. Mai 1950 in Neuenkirchen im Kreis Steinfurt
Summary of Lecture No. 1

• information on contents and structure of the lectures on superconductivity and low temperature physics I & II
  related lectures and seminars

• general introduction into the field of low temperature physics
  important research fields, related Nobel prizes
  information on related research at WMI

• A brief history of superconductivity and low temperature physics
  important discoveries, key researchers, ....
Superconductivity and Low Temperature Physics I

Lecture No. 2

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Chapter 1

1. Basic Properties of Superconductors

1.1 History of Superconductivity
1.2 Perfect Conductivity
1.3 Perfect Diamagnetism
1.4 Type-I and Type-II Superconductors
1.5 Flux Quantization
1.6 Superconducting Materials
1.7 Transition Temperatures
1.2 Perfect Conductivity

- can we measure $R = 0$?

no, only lower threshold can be obtained in experiment

limited resolution of voltage measurement

\[ \Delta R = \Delta V/I \approx 10^{-8} \Omega \]

@ $\Delta V = 10 \text{nV}, I = 1 \text{ A}$

**H. K. Onnes**: resistance drops by about 4 orders of magnitudes (later 14)
1.2 Perfect Conductivity

Improvement of resistance measurement by study of decay of persistent current

\[ B_{\text{ext}} > 0 \]

\[ T > T_c \]

\[ B_{\text{ext}} > 0 \]

\[ T < T_c \]

\[ B_{\text{ext}} = 0 \]

\[ T < T_c \]

Flux trapping: Faraday's law:

\[ - \frac{\partial B}{\partial t} = \nabla \times E \]

\[- \frac{\partial}{\partial t} \int_A B \cdot \hat{n} \, dS = - \frac{\partial}{\partial t} \Phi = \int_A (\nabla \times E) \cdot \hat{n} \, dS = \oint_{\Gamma} E \cdot d\ell = 0 \]

In superconductor (or any perfect conductor): \[ E = 0 \implies \Phi = 0 \text{ or } \dot{B} = 0 \]
1.2 Perfect Conductivity

Improvement of resistance measurement by study of decay of persistent current

- $B_{\text{ext}} > 0$
- $T > T_c$
- $B_{\text{ext}} > 0$
- $T < T_c$
- $B_{\text{ext}} = 0$
- $T < T_c$

→ Measure decay of magnetic moment generated by frozen in persistent current

Loop with inductance $L$ and resistance $R$:

\[ RI + L \frac{dl}{dt} = 0 \Rightarrow I(t) = I_0 \exp \left( -\frac{R}{L} t \right) \]

Example: 10% decay in 1 year observed

@ $L = 1 \text{ nH}$

\[ R < 10^{-17} \Omega \]
1.3 Perfect Diamagnetism

perfect conductor in magnetic field

perfect conductor

increase $B_{\text{ext}}$

decrease $T$

switch off $B_{\text{ext}}$

conductor

decrease $T$

path dependent

final state of the

perfect conductor
1.3 Perfect Diamagnetism

variation of applied magnetic field for a perfect conductor

Faraday’s law:

\[-\frac{\partial B}{\partial t} = \nabla \times E\]

Ohm’s law:

\[J = \sigma E \implies E = \frac{J}{\sigma} = \rho J = 0\]

\[\frac{\partial B}{\partial t} = 0\]

➔ \(B_i = \text{const. inside a perfect conductor}\)

- field variation → screening currents → shielding of temporal variation of flux density
- screening current do not decay → \(B_i = \text{const. forever}\)
- e.g. flux trapping in ring when switching off external field
1.3 Perfect Diamagnetism

Superconductor in magnetic field

- Increase $B_{\text{ext}}$
- Decrease $T$
- Switch off $B_{\text{ext}}$

Path independent final state of the superconductor

Superconducting state is a thermodynamic phase

Meißner-Ochsenfeld-Effect

or

Perfect diamagnetism
1.3 Perfect Diamagnetism

simple experimental technique for determination of $B_i$:

$$V_{\text{ind}} = -\frac{\partial \Phi}{\partial t} \propto -\frac{\partial B_i}{\partial t}$$

$$\Rightarrow \int V_{\text{ind}} \, dt \propto B_i$$
1.3 Perfect Diamagnetism

inner magnetic field $B_i$ and magnetization $M$ of superconductors

**Perfect Diamagnetism**

perfect diamagnetism survives only up to $T$-dependent critical field $B_{\text{cth}}(T)$

- finite energy available for expelling magnetic field
- condensation energy (discussed later)

\[
B_i = \mu_0 (H_{\text{ext}} + M) \quad \chi = -1 \quad M = B_i/\mu_0 - H_{\text{ext}}
\]

\[
\int \mu_0 M \cdot dH_{\text{ext}} = \frac{B_{\text{cth}}^2}{2\mu_0}
\]

work performed for expelling field

\[
M = \frac{B_i}{\mu_0} - H_{\text{ext}}
\]
1.3 Perfect Diamagnetism

**observation:** perfect diamagnetism survives only up to \( T \)-dependent critical field \( B_{\text{cth}}(T) \)

**interpretation:**

superconductor has only finite amount of energy available for expelling field

\[
\frac{B_{\text{cth}}^2(T)}{2\mu_0} = g_n(T) - g_s(T)
\]

condensation energy  free enthalpy difference of \( N \) and \( S \) state

**temperature dependence of \( B_{\text{cth}} \):**

\[
B_{\text{cth}}(T) = B_{\text{cth}}(0) \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]
\]

**empirical relation,**

good approximation to exact result of BCS theory

---

*phase diagram*
1.3 Perfect Diamagnetism

\( B_i = 0 \) independent of path to position \( \mathbb{2} \)

\[ B_i = \mu_0 (H_{ext} + M) = \mu_0 (H_{ext} + \chi H_{ext}) = \mu_0 H_{ext} (1 + \chi) = 0 \]

\( \Rightarrow \) perfect diamagnetism: \( \chi = -1 \)

\( \Rightarrow \) superconducting state is thermodynamic phase
1.3 Perfect Diamagnetism

Meißner effect:

*path-independent complete exclusion of magnetic flux from the interior of a bulk superconductor*

important remaining questions

- How does the magnetic induction $B$ change at the surface? Step-like change?
- How do the screening currents set-off if not according to Faraday’s law?
- Can the magnetic flux penetrate partially to reduce the magnetic energy?
- What happens in a superconductor that is not simply connected (e.g. superconductor with hole such as a cylinder)?
1.3 Perfect Diamagnetism

Levitation of diamagnetic materials

_diamagnetic materials_

\[ \chi < 0 \]

Material becomes "lighter"

\[ B_i = (1 + \chi) \mu_0 H_{ext} \]

\( \chi = \text{magnetic susceptibility} \)

_Faraday balance_

Para- or ferromagnetic materials

\[ \chi > 0 \]

Material becomes "heavier"
1.3 Perfect Diamagnetism

levitation of diamagnetic materials

\[ F_{\text{buoyancy}} = \frac{\chi}{2\mu_0} \mathbf{B} \cdot \nabla \mathbf{B} \]

buoyancy = gravity

\[ \mathbf{F}_{\text{gravity}} = \rho \ g \]

\( \rho \approx 1 \ g/cm^3, \ \chi \approx -1 \cdot 10^{-5} \)

\[ \mathbf{B} \cdot \nabla \mathbf{B} \left[ \frac{T^2}{m} \right] \approx 0.02 \cdot \frac{\rho [g/cm^3]}{\chi} \]

organic materials:

\( B \cdot \nabla B \approx 1000 \left[ \frac{T^2}{m} \right] \)

can be achieved with strong magnet:
\( B = 20 \text{ Tesla}, \ \text{grad} \ B = 100 \ T/m \)
Levitated tomatoes, strawberries, ....

Source: http://www.hfml.ru.nl/

Tomato

Frog

Grasshopper

Strawberry

Water droplet
1.3 Perfect Diamagnetism

- **organic materials:** $\rho \approx 1 \text{ g/cm}^3$, $\chi \approx -1 \cdot 10^{-5}$

  \[ \mathbf{B} \cdot \nabla \mathbf{B} \approx 1000 \quad \text{T}^2 \text{m}^{-1} \]

- **superconductors:** $\rho \approx \text{a few g/cm}^3$, $\chi \approx -1$

  \[ \mathbf{B} \cdot \nabla \mathbf{B} \approx 0.01 \quad \text{T}^2 \text{m}^{-1} \]

**Permanent magnet**

**Superconductors:**

*ideal materials for magnetic levitation*
Chapter 1

1. Basic Properties of Superconductors

1.1 History of Superconductivity
1.2 Perfect Conductivity
1.3 Perfect Diamagnetism
1.4 Type-I and Type-II Superconductors
1.5 Flux Quantization
1.6 Superconducting Materials
1.7 Transition Temperatures
1.4 Type-I and Type-II Superconductors

- **Meißner-Phase** for $B_{\text{ext}} < B_{\text{cth}}$
- no Shubnikov-Phase

**Type-I Superconductor**

- $\mu_0 H_{\text{ext}}$
- $T$ (K)
- $B_{\text{cth}}$
- Meißner-Phase

**Type-II Superconductor**

- $\mu_0 H_{\text{ext}}$
- $T$ (K)
- $B_{c1}$, $B_{c2}$
- Meißner-Phase
- Shubnikov-Phase for $B_{c1} < B_{\text{ext}} < B_{c2}$

$B_{c1} < B_{\text{cth}} < B_{c2}$
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1.4 Flux Quantization

- discovered 1961 by
  - Robert Doll and Martin Nääbauer (WMI)
  - B.S. Deaver and W.M. Fairbanks (Stanford University)

- experiment by Doll and Nääbauer (WMI)
  - trapping of magnetic flux in hollow cylinder
  - apply torque \( \mathbf{D} = \mathbf{\mu} \times \mathbf{B}_p \) by probing field \( \mathbf{B}_p \)
  - increase sensitivity by resonance technique

- number of trapped flux quanta:
  \[
  N = B_{\text{cool}} \pi (d/2)^2
  \]
  \[
  N \approx 1 \quad @ \quad B_{\text{cool}} = 10^{-5} \text{ T}, \quad d = 10 \mu\text{m}
  \]
1.4 Flux Quantization

Flux Quantization

\[ F_0 = \frac{\hbar}{2e} \]

prediction by F. London: \( h/e \)

\[ \Phi_0 = \frac{\hbar}{2e} \]

experimental proof for existence of Cooper pairs

**R. Doll, M. Näbauer**

**B.S. Deaver, W.M. Fairbank**

Paarweise im Fluss
Chapter 1

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1.7 Transition Temperatures
1.6 Superconducting Materials

- discovery of superconductivity in chemical element Hg
- since then thousands of further superconducting compounds found
- classification into families:

1. elemental superconductors (Hg, 1911)
2. alloys and intermetallic compounds
3. heavy Fermion superconductors (1979)
4. organic superconductors (1981)
5. fullerides (1991)
6. oxides superconductors, cuprates (1986)
7. iron pnictides (2006)

MgB$_2$ (2001)
1.6 Superconducting Materials

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<th>Mass Number</th>
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<th>Superconducting at $p &gt;&gt; 1 \text{ bar}$</th>
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<th>Magnetic Ordering</th>
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</table>

**Elemental Superconductors**
1.6 Superconducting Materials

• elemental superconductors
  - highest \( T_c \): Nb, 9.2 K
  - lowest \( T_c \): Rh, 0.32 mK
  - many elements become superconducting under pressure
    e.g. Li: \( T_c \) almost 20 K @ \( p = 0.5 \) Mbar
    non-magnetic high pressure Fe phase: \( T_c = 2 \) K

• problem related to observation of superconductivity in materials with very low \( T_c \):

\[
k_B T_c = 1.38 \cdot 10^{-26} \text{ J @ } T_c = 1 \text{ mK}
\]

requires small pair breaking rate \( \Rightarrow \) very pure materials

\[
\tau^{-1} \leq \frac{k_B T_c}{\hbar} = 1.38 \cdot 10^{-26} \frac{\text{J}}{\hbar} @ T_c = 1 \text{ mK} \Rightarrow \tau \geq 10^{-8} \text{ s}
\]
## 1.6 Superconducting Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$</th>
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<tbody>
<tr>
<td><strong>@ 1 bar</strong></td>
<td></td>
</tr>
<tr>
<td>Ru</td>
<td>0.35 K</td>
</tr>
<tr>
<td>Al</td>
<td>1.2 K</td>
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<tr>
<td>In</td>
<td>3.4 K</td>
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<tr>
<td>Sn</td>
<td>3.7 K</td>
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<td>Hg, Ta</td>
<td>4.2 K</td>
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<tr>
<td>Pb</td>
<td>7.2 K</td>
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<tr>
<td>Nb</td>
<td>9.2 K</td>
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<tr>
<td><strong>@ &gt; 120 kbar</strong></td>
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<tr>
<td>Si</td>
<td>6.7 K</td>
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<tr>
<td>Ge</td>
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<tr>
<td>S</td>
<td>17 K</td>
</tr>
<tr>
<td>Li</td>
<td>16 K</td>
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<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$</th>
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<tbody>
<tr>
<td>amorphous:</td>
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<tr>
<td>Pt</td>
<td>0.6 .. 0.9 K</td>
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<tr>
<td>quartzite</td>
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<tr>
<td>quenched condensed:</td>
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</tr>
<tr>
<td>Ga</td>
<td>8.0 K (orthorhombic phase: 1.09 K)</td>
</tr>
<tr>
<td>Bi</td>
<td>6.0 K (crystalline phase: semimetal, no SC)</td>
</tr>
</tbody>
</table>
1.6 Superconducting Materials

- **alloys and intermetallic compounds**

  - more than 1000 systems found until today
  - some have high relevance for applications:

    e.g. A15 compounds (1953) with β-tungsten structure
    \[ \text{Nb}_3\text{Ge}: T_c = 23.2 \, \text{K}, \text{Nb}_3\text{Sn}: T_c = 18 \, \text{K}, \text{V}_3\text{Si}: T_c = 17 \, \text{K} \]

    e.g. NbTi: \[ T_c = 10 - 11 \, \text{K} \]

    e.g. NbN: \[ T_c = 13 - 16 \, \text{K} \]

- Chevrel phases: \[ M_x\text{Mo}_6X_8 \] \( M = \text{Ca, Sr, Ba, Sn, Pb, Au, RE} \)
  \( X = S, \text{Se, Te (chalcogenides)} \)

  e.g. PbMo\(_6\)S\(_8\): \[ T_c = 15 \, \text{K} \]

- boron carbides: \[ RM_2B_2C \] \( R = \text{rare earth elem. (e.g. Tm, Er, Ho)} \)
  \( M = \text{Ni, Pd} \)

  e.g. (Lu/Y)Ni\(_2\)B\(_2\)C: \[ T_c = 16 \, \text{K} \]

- \[ \text{MgB}_2 \] \( T_c \) almost 40 K

(1994)
(2001)
1.6 Superconducting Materials

• heavy Fermion superconductors

- found by Frank Steglich et al. in 1979
  - CeCu$_2$Si$_2$ \( T_c = 0.5 \) K
  - today many systems known

- electrons in these compounds have very large effective mass
  \( \rightarrow \) heavy Fermions: \( m^* \sim 100 - 1000 \) \( m_e \)

- mechanism of superconductivity still under debate
1.6 Superconducting Materials

- **organic superconductors**

- found by *Jerome* et al. in 1980

- TMTSF (tetramethyl-tetraselenafulvalen) \( T_c = 0.9 \text{ K} \)
- today many systems known with \( T_c \) up to 12 K

  e.g. \((\text{BEDT-TTF})_2\text{Cu[N(CN)]}_2\text{Br}\)
  \( T_c = 11.2 \text{ K} \)

  bis(ethylenedithio)-tetrathiafulvalene

BEDT-TTF-molecule:

- most systems are highly anisotropic
1.6 Superconducting Materials

- **fullerides**

  - doping of $C_{60}$ molecules (fullerene), arrangement in regular structure $\rightarrow$ fullerides

  - superconductivity found in 1991 by Robert Haddon at Bell Labs
    
    $K_3C_{60}$ with $T_c = 18$ K

  - until today $T_c$ up to 40 K found

    $Cs_2RbC_{60}$ $\quad T_c = 33$ K
    $Cs_3C_{60}$ $\quad T_c = 40$ K @ $p = 15$ kbar
1.6 Superconducting Materials

- *oxide superconductors*

- discovered by **Georg Bednorz** and **Alex Müller** in 1986 in La$_{2-x}$Ba$_x$CuO$_4$ (Zurich oxide)

- until today several compounds found with $T_c$ up to 135 K (165 K under pressure)

- layered crystal structure formed by CuO$_2$ planes and charge reservoir layers
1.6 Superconducting Materials

4 component systems

\[ A_m B_2 Ca_{n-1} Cu_n O_{2+m+2n} \]

Bi, Tl, Hg   \( Ba, Sr = \text{alcaline earth metals} \)

examples

\[ Bi_2 Sr_2 Ca_2 Cu_3 O_{10} = Bi-2223 \ (110 \text{ K}) \]
\[ Tl_2 Ba_2 Ca_2 Cu_3 O_{10} = Tl-2223 \ (127 \text{ K}) \]
\[ Hg Ba_2 Ca_2 Cu_3 O_9 = Hg-1223 \ (135 \text{ K}) \]
1.6 Superconducting Materials

- **iron pnictide superconductors**
  - discovered in 2006 by *Hideo Hosono* et al.
    in La[O$_{1-x}$F$_x$]FeAs, $T_c = 26$ K
  - until today several compounds/families found with $T_c$ up to 55 K

LaFeAsO (1111)  
BaFe$_2$As$_2$ (122)  
LiFeAs (111)  
FeSe (11)

Yoichi Kamihara, Hidenori Hiramatsu, Masahiro Hirano, Ryuto Kawamura, Hiroshi Yanagi, Toshio Kamiya, and Hideo Hosono
1.6 Superconducting Materials

BaFeAs$_2$

1 mm
Chapter 1

1. Basic Properties of Superconductors

1.1 History of Superconductivity
1.2 Perfect Conductivity
1.3 Perfect Diamagnetism
1.4 Type-I and Type-II Superconductors
1.5 Flux Quantization
1.6 Superconducting Materials
1.7 Transition Temperatures
1.7 Transition Temperatures

![Graph showing transition temperatures over time]
1.7 Transition Temperatures

- recently discovered materials with very high transition temperatures

- **2015:**
  Eremets and co-workers report that $\text{H}_2\text{S}$ becomes a metallic conductor under high pressure (100–300 GPa) and shows a transition temperature of $T_c = -70^\circ\text{C}$ (203 K).

- **2019:**
  Eremets *et al.* measured for $\text{LaH}_{10}$ under high pressure (170 GPa) a transition temperature of $T_c \approx 250\;\text{K}\; (\approx -23^\circ\text{C})$
1.7 Transition Temperatures

- recently discovered materials with very high transition temperatures
  - 2020:
    Snider et al. measured for CH$_8$S under high pressure (267 GPa) a transition temperature of $T_c \approx 288$ K ($\approx 15$ °C), Nature 586, 373 - 377 (2020)

material with the so far highest transition temperature
1.7 Transition Temperatures

- recently reported but not confirmed room temperature superconductors

2023:

- The First Room-Temperature Ambient-Pressure Superconductor

- Consideration for the development of room-temperature ambient-pressure superconductor (LK-99)
  J. Korean Crystal Growth and Crystal Technology 33 (2), 61–70 (2023)

- Material: LK-99 (named after Lee and Kim and the year of discovery)
  LK-99 is decidedly weird for a putative high-temperature superconductor:
  - it’s a greyish-black phosphate mineral called apatite containing copper and lead
  - while most superconductors are pretty good normal electrical conductors before they turn superconducting, LK-99 is an insulator above its purported $T_c = 127^\circ$C
1.7 Transition Temperatures

The graph illustrates the transition temperatures ($T_c$) of various superconducting materials over time. The x-axis represents the year, ranging from 1920 to 2020, and the y-axis represents the temperature in Kelvin ($K$), with markers indicating $10^1$, $10^2$, and $10^3$ K. The graph shows a trend of increasing transition temperatures with time, with some materials such as Pb, Nb, and Hg having lower transition temperatures, while others like HgBaCaCuO @ 30 GPa have higher transition temperatures.

Materials such as Pb, Nb, NbN, V$_3$Si, Hg, BaKBiO, LaBaCuO, MgB$_2$, YbPd$_2$B$_2$C, Li, SmFeAsO, YbC$_6$, LaFeAsO, and diamond are plotted on the graph, each represented by a symbol or color-coded marker.

The graph also indicates various phases of liquid nitrogen (LN$_2$), liquid hydrogen (LH$_2$), and liquid helium (LHe) along the x-axis, with corresponding pressures marked on the right side of the graph.
relevant material parameters for technical applications:

- high transition temperatures $T_c$
- high critical current densities $J_c$
- high critical magnetic fields $B_c$