Introduction to superconductivity

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Superconductivity in relativistic heavy ion collisions

The Large Hadron Collider (LHC) is currently operating at the energy of 6.5 TeV per beam. At this energy, the trillions of particles circle the collider's 27-kilometre tunnel 11,245 times per second. The magnet system on the ATLAS detector includes eight huge superconducting magnets (grey tubes) arranged in a torus around the LHC beam pipe (Image: CERN).

All the magnets on the LHC are superconducting. There are 1232 main dipoles, each 15 metres long and weighing in at 35 tonnes. If normal magnets were used in the 27 km-long LHC instead of superconducting magnets, the accelerator would have to be 120 kilometres long to reach the same energy.
Superconductivity in cosmology

The link between superconductivity and black holes

An electron thrown into superconductor disappears immediately, in a similar way to what happens to an object which falls into a black hole. The descriptions in terms of quantum fields (without gravity), such as the ones describing the interactions of the electrons in the superconductor, are equivalent to some quantum gravitational theory descriptions in an exotic higher dimensional space-time.

“Clockwork Dreams” by NitroX72

http://mappingignorance.org/2015/06/10/the-link-between-superconductivity-and-black-holes/
Superconductivity in cosmology

‘Somewhat more interesting is the possibility of the superconductivity of metallic hydrogen in the depths of large planets — Jupiter and Saturn’: V.L. Ginzburg.

Superconductivity and dark matter

Superconductors could detect superlight dark matter.

The dark matter particles that are thought to be constantly flowing through the Earth will scatter off a free electron in the superconductor. If a dark matter particle has enough energy to pull an electron above the material's band gap, it will break the Cooper pair. A second device (a calorimeter) measures the heat energy deposited in the absorber, providing direct evidence of the dark matter particle.


Superconductivity in cancer therapy

Making cancer treatment more accessible:
Alexey Radovinsky, Joe Minervini, Phil Michael, and Leslie Bromberg of the Plasma Science and Fusion Center MIT collaborates on a smaller, lighter delivery system for proton-beam radiotherapy.

Joseph Minervini: “Using superconductivity in a cyclotron design can reduce its mass an order of magnitude from conventional, resistive magnet machines,”

http://thesilicongraybeard.blogspot.no/2015/07/techy-tuesday-using-superconductors-to.html
Primary energy solution: thermonuclear energy, ITER?

‘ITER (International Thermonuclear Experimental Reactor, and is also Latin for "the way") is an international nuclear fusion research and engineering megaproject, which will be the world's largest magnetic confinement plasma physics experiment.’

https://en.wikipedia.org/wiki/ITER

‘Without superconductivity, ITER would go from being a "net energy positive" machine to a "net energy negative" machine.’

https://www.iter.org/newsline/146/408
Discovery of Superconductivity

- Discovered by **Kamerlingh Onnes** in 1911 during first low temperature measurements to liquefy helium.

- Whilst measuring the resistivity of "pure" Hg he noticed that the electrical resistance dropped to zero at 4.2K.

- In 1912 he found that the resistive state is restored in a magnetic field or at high transport currents.
The superconducting elements

Transition temperatures (K)
Critical magnetic fields at absolute zero (mT)

- Transition temperatures (K) and critical fields are generally low
- Metals with the highest conductivities are not superconductors
- The magnetic 3d elements are not superconducting

...or so we thought until 2001
Superconductivity in alloys and oxides

- HgBa$_2$Ca$_2$Cu$_3$O$_9$
- Hg$_2$Ca$_2$Cu$_3$O$_9$
- TlBaCaCuO
- BiCaSrCuO$_2$
- YBa$_2$Cu$_3$O$_7$
- (LaBa)CuO
- (LaBa)CuO

Other compounds:
- HgBa$_2$Ca$_2$Cu$_3$O$_9$
- Nb$_3$Ge
- Nb$_3$Sn
- V$_3$Si
- NbC
- NbN
- Pb
- Hg

Graph showing the superconducting transition temperature (K) from 1910 to 1990, with the liquid nitrogen temperature (77K) as a reference.
Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

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General properties

- Zero resistance (Kammerlingh-Onnes, 1911) at $T < T_c$. The temperature $T_c$ is called the critical one.

- Superconductivity can be destroyed also by an external magnetic field $H_c$ which is also called the critical one (Kammerlingh-Onnes, 1914). Empirically,

$$H_c(T) = H_c(0) \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right].$$

- If the superconductivity is destroyed by a current the critical current is just the one which produces the field $H_c$ at the surface (the Silsby rule).

- The Meissner-Ochsenfeld effect (1933)

Magnetic field does not penetrate superconductor

Only for long samples!
Meissner effect

Perfect Conductor $R=0$

1. $B_z = 0$
2. Room temperature
3. Cooled
4. Low temperature
5. $B_z \rightarrow 0$

Perfect Diamagnet $B=0$

1. $B_z = 0$
2. Room temperature
3. Cooled
4. Low temperature
5. $B_z \rightarrow O$

Meissner Effect

Ideal conductor! Ideal diamagnet!
Type I superconductors: Magnetization curve

SI: \( B/\mu_0 = H + M \)

- \( H \) – magnetic field strength
- \( M \) – magnetization
- \( B \) – magnetic induction

\[ B, M \]

\[ H, M \]

\( H_c \)

\( M \)

Meissner state

Normal state
Type II superconductors

Dashed lines – type I superconductor
Solid lines – type II superconductor

In type II superconductors the Meissner effect is incomplete in the region $H_{c1} < H < H_{c2}$

$\Phi_0 = \frac{h}{2e} \approx 2.067833758(46) \times 10^{-15}$ Wb

In CGS units

Vortex lattice
A. A. Abrikosov

2003
**Ginzburg-Landau Theory (1950)**

**Order parameter**

\[ |\Psi|^2 \ll 1 \quad \Rightarrow \quad G_s = G_n + a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + \cdots. \]

\[ \tilde{G} = G_s - G_n \]

\[ a > 0 \]

\[ a < 0 \]

\[ \Psi = 0 \quad \text{at} \quad T > T_c, \]

\[ |\Psi|^2 = -(\alpha/b)\tau = |\Psi_0|^2 \quad \text{at} \quad T < T_c. \]

\[ \text{Introduce } \tau = \frac{T - T_c}{T_c}. \quad \text{Near } T_c, |\tau| \ll 1: \quad a = \alpha \tau, \quad \alpha > 0. \]

*a should change the sign at the transition point*
\[ \Psi = \tanh \frac{x}{\xi \sqrt{2}} \]

\[ \xi = \frac{\lambda}{k} \quad \text{the coherence length.} \]

\[ \delta \text{ is just the London penetration depth near } T_c. \]

Surface energy:

\[ \sigma_{ns} = \begin{cases} 
> 0, & \kappa < \frac{1}{\sqrt{2}} \\
= 0, & \kappa = \frac{1}{\sqrt{2}} \\
< 0, & \kappa > \frac{1}{\sqrt{2}} 
\end{cases} \quad \kappa = \frac{\lambda}{\xi} \]

Depending on GL parameter \( k \) there is a tendency either to create, or not to create new surfaces.
Two types of superconductors

Surface energy is positive:
Type I superconductivity

Surface energy is negative:
Type II superconductivity

(Abramov lattice, 1952)
### Characteristic parameters of superconductors

<table>
<thead>
<tr>
<th>Superconductor</th>
<th>$T_c$ (K)</th>
<th>$\lambda(0)$ (Å)</th>
<th>$\xi(0)$ (Å)</th>
<th>$H_{c2}(T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>9.2</td>
<td>450</td>
<td>380</td>
<td>0.2</td>
</tr>
<tr>
<td>NbTi</td>
<td>9.5</td>
<td>1600</td>
<td>50</td>
<td>14</td>
</tr>
<tr>
<td>NbN</td>
<td>16</td>
<td>2000</td>
<td>50</td>
<td>16</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.4</td>
<td>800</td>
<td>35</td>
<td>24</td>
</tr>
<tr>
<td>Nb$_3$Ge</td>
<td>23</td>
<td>-</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>Ba$<em>{0.6}$K$</em>{0.4}$BiO$_3$</td>
<td>31</td>
<td>2200</td>
<td>35</td>
<td>32</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>39</td>
<td>850</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>UPt$_3$</td>
<td>0.5</td>
<td>7800</td>
<td>200</td>
<td>2.8</td>
</tr>
<tr>
<td>UBe$_{13}$</td>
<td>0.9</td>
<td>3600</td>
<td>170</td>
<td>8</td>
</tr>
<tr>
<td>URu$_2$Si$_2$</td>
<td>1.2</td>
<td>-</td>
<td>130</td>
<td>8</td>
</tr>
<tr>
<td>CeIrIn$_5$</td>
<td>0.4</td>
<td>5300</td>
<td>250</td>
<td>1.0</td>
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<tr>
<td>CeCoIn$_5$</td>
<td>2.3</td>
<td>-</td>
<td>80</td>
<td>11.9</td>
</tr>
<tr>
<td>TmNi$_2$B$_2$C</td>
<td>11</td>
<td>800</td>
<td>150</td>
<td>10</td>
</tr>
<tr>
<td>LuNi$_2$B$_2$C</td>
<td>16</td>
<td>760</td>
<td>70</td>
<td>7</td>
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<tr>
<td>K$_3$C$_6$O$_7$</td>
<td>19.5</td>
<td>$\sim$4800</td>
<td>35</td>
<td>$\sim$30</td>
</tr>
<tr>
<td>Rb$_3$C$_6$O$_7$</td>
<td>30</td>
<td>$\sim$4200</td>
<td>30</td>
<td>$\sim$55</td>
</tr>
<tr>
<td>YBa$_2$Cu$_3$O$_7$</td>
<td>93</td>
<td>1450</td>
<td>13</td>
<td>150</td>
</tr>
<tr>
<td>HgBa$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td>135</td>
<td>1770</td>
<td>13</td>
<td>190</td>
</tr>
</tbody>
</table>

Critical temperature $T_c$, the penetration depth $\lambda(0)$, the Cooper-pair size $\xi(0)$ and the upper critical magnetic field $H_{c2}$ for type-II superconductors (for layered compounds, the in-plane values are given).
Magnetic field penetrates to or 'exit' from the sample with constant gradient and current equal to critical current. There is no current in flux-free region.
Meissner effect: field decrease

First increasing $B$ to a value $B_o$ then reducing $B$ to zero again. Because the flux density gradient must remain constant, flux is trapped inside the superconducting sample, even at $B=0$. 

\[
\begin{align*}
\text{current density:} & \\
\text{superconductor:} & \\
B=0 & \quad D & B=0 & \\
\end{align*}
\]
Magnetic field penetrates to or 'exit' from the sample with a varying gradient. Current is equal to critical current in region with magnetic flux. There is current in flux-free region.
Superconductivity: seeing is believing

Faraday effect and magneto-optical imaging

The Faraday effect is a rotation of the polarization of light in presence of magnetic field. The effect was discovered by Michael Faraday in 1845.
Magneto-optical imaging of YBa$_2$Cu$_3$O$_x$ thin films

Magneto-optical image of an YBCO film at magnetic field of 85 mT and temperature of 13 K (a), 30 K (b) and 70 K (c).

Magnetic flux penetration in superconducting films

T = 70 K, ideal YBCO

T = 4 K, YBCO

T = 4 K, MgB$_2$

T = 20 K, YBCO
Magnetic flux penetration on intrinsic defects

Dendritic flux avalanches in superconducting NbN films

The avalanches propagate with very high speed up to 100km/s.

Oslo International School for Master and PhD Students

15-26 May 2017 Oslo, Norway
Trapped magnetic flux in melt grown sample at 79 K

The sample was zero field cooled to 79 K. At this temperature magnetic field of 85 mT was applied and then removed. A set of magneto-optical images was recorded at different positions in the sample.
Magneto-optical imaging of bulk YBa$_2$Cu$_3$O$_x$

Magneto-optical image of flux penetration into a melt-grown bulk YBCO at magnetic field of 85 mT and temperatures of 20 K (a) and 77.3 K (b), respectively. The screening of the magnetic flux is considerably better at liquid hydrogen (a) than at liquid nitrogen (b) temperature.
Properties of MgB$_2$

- High critical temperature (~40 K, twice above boiling temperature of liquid hydrogen, 20.3 K)
- High critical current in bulk (~ $10^6$ A/cm$^2$ at 20 K)
- Low mass density (2.62 g/cm$^3$)

MgB$_2$ is an excellent material for liquid-hydrogen superconducting applications.
Synergy of superconductivity and hydrogen economy

• *Superconductivity* offers compactness, high efficiency, savings in energy and a range of new applications in liquid hydrogen

• *Superconducting* pipelines can provide infrastructure for hydrogen economy

• Fully *superconducting vehicles* (cars, planes, ships, submarines) could be developed featuring *superconducting* motors, generators, energy storage units; loss-free wiring, current limiters, electronics, computers *etc.*

• *Superconducting* Home Energy Units can be designed

• *Superconductivity* could help addressing *global* problems on the planetary scale
Rise of renewable energy sources

- Hydrogen and electricity can easily be produced by renewable energy sources solving simultaneously problem of energy storage.
- Hydrogen can release full potential of superconductivity starting with building infrastructure for hydrogen economy.
Superconducting pipelines: transport of liquid hydrogen and electrical energy, levitating train

Magnetic field ~ 1 Tesla
Flexible Flat Cables

by reactive evaporation

Magnesium Diboride Flexible Flat Cables for Cryogenic Electronics

Chris S. Yung and Brian H. Moeckly
Advanced MgB$_2$ techniques: thin films deposition

RAPID COMMUNICATION

Growth of high-quality large-area MgB$_2$ thin films by reactive evaporation

B H Moeckly and W S Ruby

Superconductor Technologies, Inc., 460 Ward Drive, Santa Barbara, CA 93111, USA
Hydrostatic extrusion of MgB$_2$ pipes of small diameter

Return of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO)

http://www.aerogel.org/

https://en.wikipedia.org/wiki/Aerogel

Aerogel: progress in non-vacuum thermal insulation.

MOI images of metalorganic YBCO films at 20 K.

YBCO can significantly relax cooling requirements for liquid hydrogen economy.

Global applications of superconductivity

Magnetic field protection of Earth during poles reversal

The superconducting pipeline would need to withstand a current of $10^9$ A

Prevention of super-volcano eruption

The superconducting pipeline encircling super-volcano could be used to extract energy and prevent its eruption

The liquid hydrogen-cooled superconducting pipeline encircling planet could be built

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Space applications of superconductivity

Superconductors can be used for the protection of space stations and space ships from cosmic radiation and in the asteroid defence.
Four-electrodes transport measurements

Optical image of a slice of brain exposed to water solution of graphene flakes and connected to the wires. The electrical current was passed between leads 1 and 4 and potential was measured between 2 and 3. The red arrow marks narrow constriction between the leads 1 and 2. A dark spot close to the sample contains remnants of graphene leaked from the slice. White area is an insulating polytetrafluoroethylene (PTFE) tape.
IV curves of the muscles tissue recorded in the process of the drying of the sample. Small black arrows show direction of the record. Large red arrow indicates increase of resistance in the process of measurement.
Transport measurements of brain tissue

Current-voltage characteristic of the brain tissue measured in the four-probe configuration. Small black arrows show direction of the record.

Current-voltage characteristic of the brain slice shown in three-probe configuration with current leads 2 and 4, and potential leads 2 and 3.
Superconductivity in brain?

Advances in Cryogenic Engineering

VOLUME 17

A Collection of Invited Papers and Contributed Papers Presented at National Technical Meetings During 1970 and 1971

K. D. TIMMERHAUS, Editor
Engineering Research Center
University of Colorado
Boulder, Colorado

SPECULATIONS OF SUPERCONDUCTIVITY IN BIOLOGICAL AND ORGANIC SYSTEMS**†

E. H. Halpern and A. A. Wolf
Naval Ship Research and Development Center
Annapolis, Maryland

SPECULATIONS AS TO WHERE SUPERCONDUCTIVITY CAN BE FOUND IN BIOLOGICAL SYSTEMS

It may be reasonable to expect superconductivity in regions of highest organization in biological systems. This would be found in the central nervous system and brain, where information is stored and processed, and where complex functions such as long-term memory and consciousness are centered. Consciousness is controlled by an energy flow through the brain, which is, in turn, controlled by blood flow bringing oxygen to the brain. This flow creates order in the molecular structure of various centers of the brain. John [12] described the mechanism of memory in terms of decreasing entropy with time in the higher-order centers of the brain.

It is certainly conceivable to explain long-term memory (70 to 100 years lifetime of a person) in terms of persistent currents. That persistent currents exist seems to have been established by the response of living systems to strong magnetic fields. No theories of memory today seek to explain this phenomenon in terms of superconductivity. Certainly the work of Ladik et al. [5] on DNA as a room-temperature superconductor has bearing on the problem. DNA is critical to information storage and transfer of cell functions and reproduction of molecules.
Quantum behaviour in brain

$R_q = \frac{h}{e^2}$

Current-voltage characteristic of the brain slice re-plotted as voltage dependence of the resistance.
Link between energy gap and critical temperature

Possibility of Synthesizing an Organic Superconductor
W. A. Little
Phys. Rev. 134, A1416 – Published 15 June 1964

$T_c = 1644 \text{ K}$

$T_c = 2200 \text{ K}$

$T_c = 1906 \text{ K}$

$2\Delta = 3.53 \ k_B T_c$

Link between energy gap and critical temperature

\[ 2\Delta = 3.53 \, k_B \, T_c \]

- \( T_c = 1380 \, K \)
- \( T_c = 1940 \, K \)
- \( T_c = 2200 \, K \)

W. A. Little, 1964
Conclusions

• Superconductivity is important phenomenon in condensed matter physics that enables rapid progress in different areas of science and technology including cosmology, cancer therapy, relativistic heavy ion collisions and dark matter research.

• Superconductivity plays special role in building fossil fuel-free renewable energy economy. A concept of Smart Superconducting Grid is suggested for delivering simultaneously losses-free electricity and liquid fuel (hydrogen).

• Development of superconducting materials and techniques for renewal economy is well under the way

• There is impressive progress in the synthesis of new superconducting materials and the search for superconductors with a higher critical temperature.