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## Superconductivity in nanostructures Part I

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#### Electrical resistivity at low temperatures



Kelvin: Electrons will be frozen - resistivity grows till  $\infty$ .

Dewar: the lattice will be frozen – the electrons will not be scattered. Resistivity will decrese till 0.

Matthiesen: Residual resistivity because of contamination and lattice defects.

One of the scientific challenges at the end of  $19^{th}$ and beginning of the  $20^{th}$  century: How to reach temperatures close to 0 K?

> Hydrogen was liquefied (boiling point 20.28 K) for the first time by James Dewar in 1898

## Superconductivity- discovery I



1895 William Ramsay in Englanddiscovered helium on the earth1908 H. Kamerlingh Onnes liquefiedhelium (boiling point 4.22 K)

Resistivity at low temperatures- pure mercury (could repeatedly distilled producing very pure samples).



•Repeated resistivity measurements indicated zero resistance at the liquid-helium temperatures. Short circuit was assumed!

•During one repetitive experimental run, a young technician fall asleep. The helium pressure (kept below atmospheric one) slowly rose and, therefore, the boiling temperature. As it passed above 4.2 K, suddenly resistance appeared.

Hg  $T_C$ =4.2K

From: Rudolf de Bruyn Ouboter, "*Heike Kamerlingh Onnes's Discovery of Superconductivity*", Scientific American March 1997



## Superconductivity- discovery II

•Liquid Helium (4K) (1908). *Boiling point* 4.22K.

•Superconductivity in Hg T<sub>c</sub>=4.2K (1911)

"Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconducting state"

H. Kamerlingh Onnes 1913 (Nobel preis 1913)



Resistivity R=0 below  $T_c$ ; (R<10<sup>-23</sup>  $\Omega$ ·cm, 10<sup>18</sup> times smaller than for Cu)

#### How to measure very small resistivity ?

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# Is the resistivity of a superconductor really zero or just very small?



- A two-point probe measurement will not work because the the contact resistance and the resistance of the wires dominates everything.
- A four point probe measurement can be tried but it does not work either: one is limited by the smallest voltage one can measure.

## Is the resistivity of a superconductor really zero or just very small?



$$I(t) = I_0 e^{-t/\tau}$$

- A super-current can be induced in a superconducting ring.
- The decay of the current is given by the relaxation time (10<sup>-14</sup> s for a normal metal). For a superconductor it should be infinite. Experiments suggest that it is not less than 100.000 years.



#### Meissner-Ochsenfeld-effect

A superconductor is a perfect diamagnet. Superconducting material expels magnetic flux from the interior.

W. Meissner, R. Ochsenfeld (1933)

On the surface of a superconductor  $(T < T_c)$  superconducting current will be induced. This creates a magnetic field compensating the outside one.





#### Screening (shielding ) currents

#### Superconducting elements



- •Ferromagnetic elements are not superconducting
- •The best conductors (Ag, Cu, Au..) are not superconducting
- •Nb has the highest  $T_c = 9.2K$  from all the elements

#### What destroys superconductivity?

A current: produces magnetic field which in turn destroys superconductivity.



Magnetic field: the spins of the C-P will be directed parallel.

(should be antiparallel in C-P)

High temperatures:

strong thermal vibration of the lattice predominate over the electron-phonon coupling.

#### **High Temperature Superconductivity**



#### The Nobel Prize in Physics 1987

"for their important break-through in the discovery of superconductivity in ceramic materials"



J. Georg Bednorz



K. Alexander Müller

```
(La_{1.85}Ba_{.15})CuO_4

YBa_2Cu_3O_7

Bi_2Sr_2CaCu_2O_8

Tl_2Ba_2Ca_2Cu_3O_{10}

Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}
```



#### Tc = 203 K Superconductivity in Sulfur Hydride (H<sub>3</sub>S) @ P=200 GPa

#### Resistance



#### **Magnetization/ Meissner**



A.P. Drozdov, M.I. Eremets, I.A. Troyan, V. Ksenofontv & S.I. Shylin, Nature **525**, 73 (2015).

#### Superconductivity in pure Bi at ambient pressure



Prakash et al., Science **355**, 52–55 (2017)

## Magnetic shielding

Special alloy: mumetal

Very high magnetic permeability  $\mu \approx 100000$ 

77 % Ni, 16 % Fe, 5 % Cu, 2 % Cr or Mo

Shielding value 
$$S = \mu \frac{d}{D}$$

- d : materials thickness
- D : shielding diameter

## Magnetic shielding



https://mumetal.co.uk/?p=106



https://magneticshields.co.uk/

#### Detecting 100 fT magnetic fields using SQUIDs, Superconducting Quantum Interference Devices



Prototype of a SQUID-based magnetoencelography system developed at the Chieti University (courtesy of G.L. Romani).





## Creating strong magnetic fields



## Solenoid

მაგნეტორეზონანსული ტომოგრაფია (MRI) ზეგამტარობის გამოყენება მედიცინაში





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#### **FUSION and Superconductivity**





#### London model (Two fluid model)



• all free electrons of the superconductor are divided into two groups:

- superconducting electrons of density  $\,n_{
  m s}$
- normal electrons of density  $n_{
  m n}$ .
- The total density of free electrons is  $n=n_{
  m s}+n_{
  m n}$
- As the temperature increases from 0 to  $T_{\rm c},$  the density  $n_{\rm S}$  decreases from n to 0.



Heinz und Fritz London

### Magnetic field penetration depth $\lambda$

$$\vec{\nabla}^2 \vec{B} = \frac{1}{\lambda^2} \vec{B}$$

$$\lambda^2 = \frac{m}{\mu_0 n_s e^2}$$

$$B(x) = B_0 e^{-x/\lambda}$$

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• example: thin superconducting sheet of thickness d with B || sheet



## Estimate magnetic field penetration depth $\lambda$

$$\lambda^2 = \frac{m}{\mu_0 n_s e^2}$$

#### **Muon precession**

- beam of spin polarized muons μ<sup>+</sup> with polarization *P*<sub>μ</sub>(0)
- μ<sup>+</sup> precesses around the local field with Larmor frequency ω<sub>μ</sub>

local magnetic field



$$\omega_{\mu} = \gamma_{\mu} B_{loc}$$

gyromagnetic ratio  $\gamma_{\mu}$ = 135.5 MHz/T



#### Depth dependent µSR measurements in near surface regions



1.0 0.8

0.6

#### Field profile at the surface of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-8</sub>

Bext

c-axis

YBa,Cu,O,

700 nm film



T.J. Jackson, T.M. Riseman, E.M. Forgan, H. Glückler, T. Prokscha, E. Morenzoni, M. Pleines, Ch. Niedermayer, G. Schatz, H. Luetkens, and J. Litterst, Phys. Rev. Lett. 84, 4958 (2000).

First direct measurements of field profile on nm scale. Microscopic confirmation of London equations (local electrodynamics). Absolute determination of magnetic penetration depth ( $\lambda_{ab}$ ) without knowledge of superconducting state.

$$B(z,T)) = B_{ext}e^{-\frac{z}{\lambda_{ab}(T)}}$$

Field decay determined by shielding current flowing in **ab** planes  $\rightarrow \lambda_{ab}$ 



	$T_{c}$	$\lambda$ [nm]	ξ <b>[nm]</b>	К
Al	1.2	16	1600	0.01
Sn	3.7	34	230	0.16
Pb	7.2	37	83	0.4

	T <sub>c</sub>	λ <b>[nm]</b>	ξ <b>[nm]</b>	К
Nb	9.3	39	38	1
Nb <sub>3</sub> Sn	18	80	3	27
YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7</sub>	93	150	1.5	100
$Rb_3\bar{C}_{60}$	30	247	2.0	124
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	200	1.4	143

### Ginzburg-Landau theory (1950)

order parameter 
$$\Psi({f r})=\Psi_0 e^{i\phi({f r})}$$

$$n_s = |\Psi^*\Psi| = \Psi_0^2$$



#### The Nobel Prize in Physics 1972

"for their jointly developed theory of superconductivity, usually called the BCS-theory"







deen Leo





John Robert Schrieffer

Mechanism of superconductivity: pairing of electrons (Cooper pairs) due to interaction with lattice (Electron-Phonon interaction).



## The electron-phonon interaction/ Cooper pairs



 Polarization of the lattice by one electron leads to an attractive potential for another electron.

#### BCS: attractive e<sup>-</sup>-e<sup>-</sup> interaction



Lattice deforms slowly in the time of the electron

Maximum deformation of lattice at time  $\tau \sim \frac{2\pi}{\omega_{_D}} \sim 10^{-13} s$ 

In this time, first electron has travelled  $\sim v_{_F} au \sim 10^6 m s^{^{-1}} imes 10^{^{-13}} s \sim 1000$  Å

Lattice deformation attracts 2<sup>nd</sup> electron without it feeling the electron feeling Coulomb repulsion of 1<sup>st</sup>

 $\hbar \omega_{\vec{q}}$  phonon energy

 $\vec{q}$ 

 $\vec{k}_{2}'$ 

 $ec{k}_1$ 

 $\vec{k}_2$ 

electron–electron interaction via emission and subsequent absorption of a phonon of momentum  $\hbar \vec{q}$ 

$$\vec{k}_1 = \vec{k}'_1 + \vec{q} \implies \vec{k}_1 + \vec{k}_2 = \vec{k}'_1 + \vec{k}'_2$$

Scattering from state  $\vec{k}_1$  to the state  $\vec{k}_1'$  gives rise to local oscillations of electron density of frequency  $\omega = (\overline{\varepsilon}_{\vec{k}1} - \overline{\varepsilon}_{\vec{k}1'})/\hbar$ , where  $\omega < \omega_{\rm D}$  (Debye frequecy).

To enable an electron to go from the state  $\vec{k}_1$  to the state  $\vec{k}_1'$ , the latter must be free (Pauli principle) that is possible only in the vicinity of the Fermi surface.

#### BCS theory of superconductivity

1957 John Bardeen, Leon Cooper, and John Robert Schrieffer

An electron on the way through the lattice interacts with lattice sites (cations). The electron produces **phonon**.



The lattice deformation creates a region of relative positive charge which can attract another electron.

During one phonon oscillation an electron can cover a distance of  $\sim 10^4$ Å. The second electron will be attracted without experiencing the repulsing electrostatic force.

# Important length scales in a superconductor Coherence length $\boldsymbol{\xi}$



Coherence length is the distance between the carriers creating a Cooper-Pair.

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# Important length scales in a superconductor Magnetic penetration depth $\lambda$

$$\Delta \mathbf{B} = \frac{1}{\lambda^2} \mathbf{B}$$

$$\Delta \mathbf{j} = \frac{1}{\lambda^2} \mathbf{j}$$



The solution of the London Eq. (2.12a) can be written as

$$B(x) = B_1 \exp\left(-\frac{x}{\lambda_L}\right) + B_2 \exp\left(+\frac{x}{\lambda_L}\right)$$

The boundary conditions are

$$B\left(-\frac{d}{2}\right) = B_0: \quad B_1 \exp\left(\frac{d}{2\lambda_L}\right) + B_2 \exp\left(-\frac{d}{2\lambda_L}\right) = B_0$$
$$B\left(+\frac{d}{2}\right) = B_0: \quad B_1 \exp\left(-\frac{d}{2\lambda_L}\right) + B_2 \exp\left(+\frac{d}{2\lambda_L}\right) = B_0$$

From here we calculate

$$B_1 = B_2 = \frac{B_0}{\cosh\left(\frac{d}{2\lambda_L}\right)}$$

Thus, the final expression for the field B(x) inside the superconducting film is

$$B(x) = B_0 \frac{\cosh\left(\frac{x}{\lambda_L}\right)}{\cosh\left(\frac{d}{2\lambda_L}\right)}.$$