Introduction to Superconductivity

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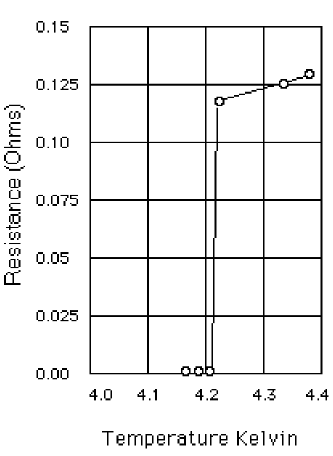
What is superconductivity

Most spectacular manifestation:

Complete disappearance of electric resistance

Birthday of SC: April 28, 1911
Discovered by H. Kamerlingh-Onnes

Physics Nobel Prize 1913



resistance of Hg:
R=0 below T=4.15K≈-269ºC

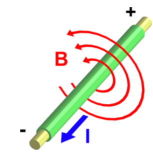
absolute zero
of temperature: 0K=-273.15ºC

degrees Kelvin = degrees Celsius + 273.15

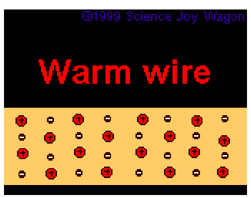
Electric resistance:

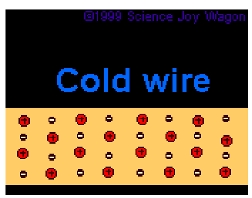
Useful: glowing filaments in incandescent bulbs
heating elements in electric kettles and cookers

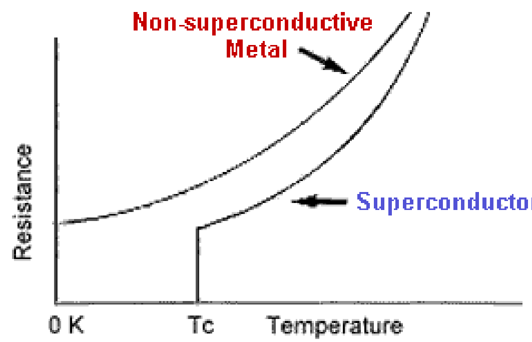
Harmful: 7-10% of electric power is lost for heating in power grids
prevents building powerful electromagnets



Resistance of metals gradually decreases when temperature decreases





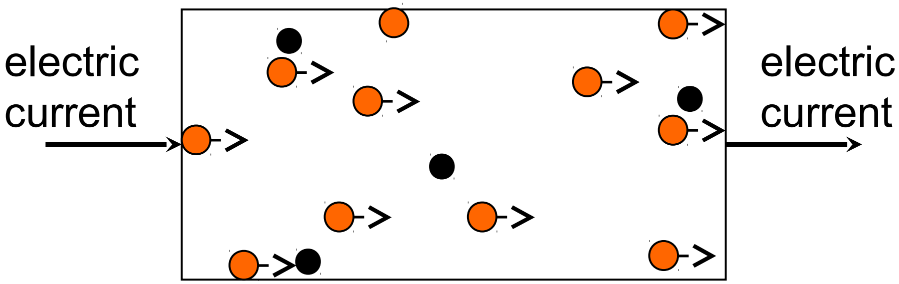


In superconductors: **R=0** below **the critical temperature T_c** → no heating losses

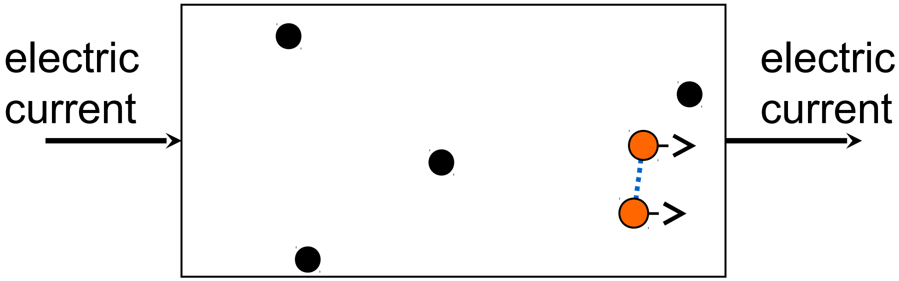
Electric current in a SC circuit would circulate indefinitely
Experimentally: no loss detected for 2 years

Why superconductors superconduct

Origin of electric resistance in ordinary metals: **scattering of electrons**



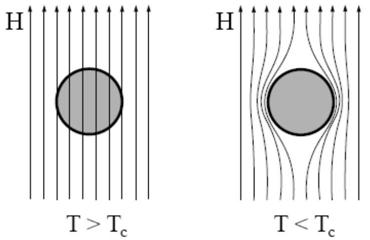
Origin of superconductivity: **electron teamwork**



all electrons are in the same collective state

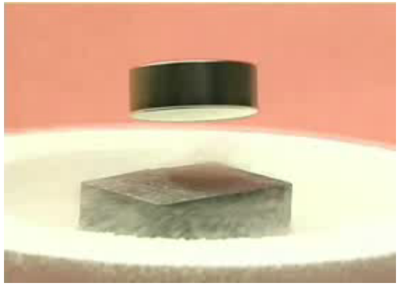
Magnetic properties of superconductors

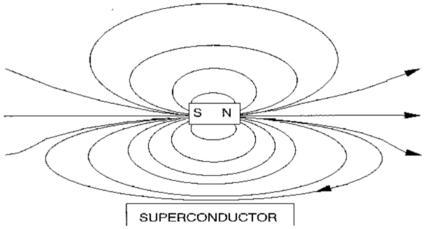
- **Meissner effect** (1933):
  complete expulsion of weak magnetic field



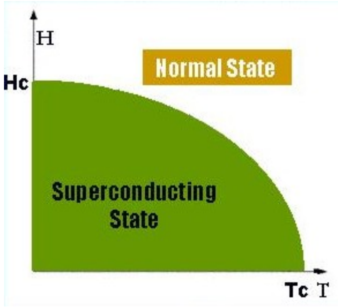
field=0
in SC bulk

Meissner effect causes
magnetic levitation





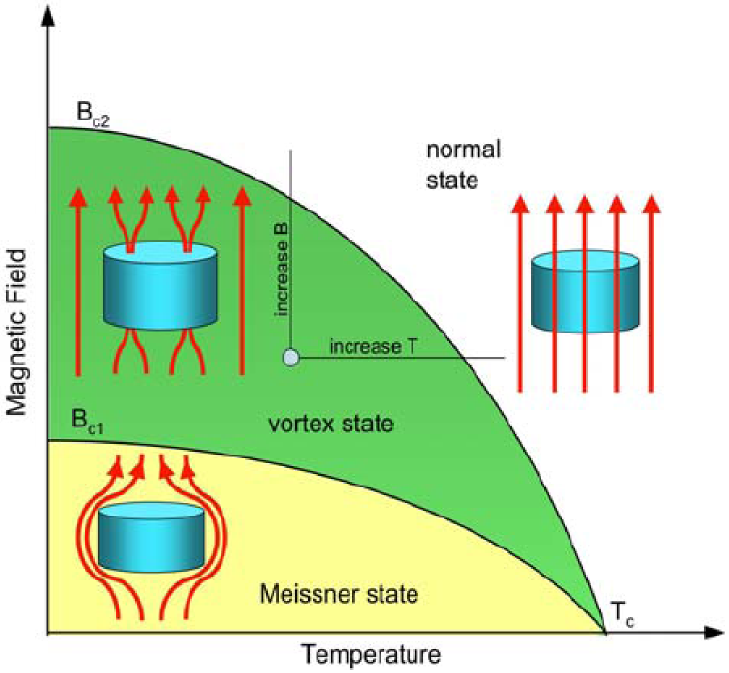
- Superconductivity is destroyed by magnetic field above **the critical field H_c**



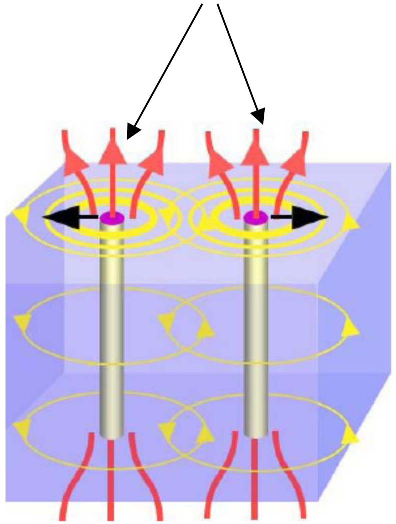
Magnetic phase diagram
of Type I superconductors

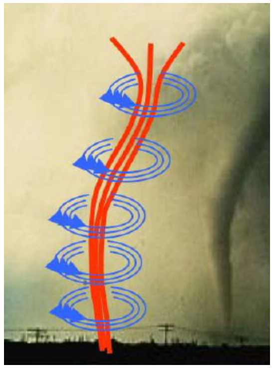
Magnetic properties of superconductors

Magnetic phase diagram
of Type II superconductors



Magnetic field in SC bulk forms
an array of magnetic flux lines, or
Abrikosov vortices





Abrikosov 1957, Nobel Prize 2003

Brief history of superconductivity

- **1911** – discovery in Hg (Kamerlingh-Onnes)
- **1933** – Meissner effect (Meissner, Ochsenfeld)
- **1950** – macroscopic theory of SC (Ginzburg, Landau)
- **1957** – type II SC, superconducting vortices (Abrikosov)
- **1957** – theory of SC (Bardeen, Cooper, Schrieffer)
- **1957 to late 1970s** – Golden Age of Classical Superconductivity
- **1976** – first exotic SC: heavy-fermion $CeCu_2Si_2$ (Steglich)
- **1979** – organic SC: $(TMTSF)_2PF_6$ (Jerome)
- **1986** – high-temperature SC: LaBaCuO (Bednorz, Müller)
- **since 1986** – focus on exotic SCs

Superconducting materials

Classical SCs: **Pb, Sn, In, Nb, …**
highest T_c pre-HTSC: **Nb_3Ge** (T_c=23.2K≈-250 ºC)

Heavy-fermion SCs: **$CeCu_2Si_2$, UBe_{13}, UPt_3, $CeCoIn_5$**, …
and Organics: **$(TMTSF)_2X$, $(BEDT\text{-}TTF)_2X$, fullerenes, C-nanotubes**
typically T_c ~ 1K (but for **Cs_3C_{60}** T_c=40K, and for **$PuCoGa_5$** T_c=18.5K)

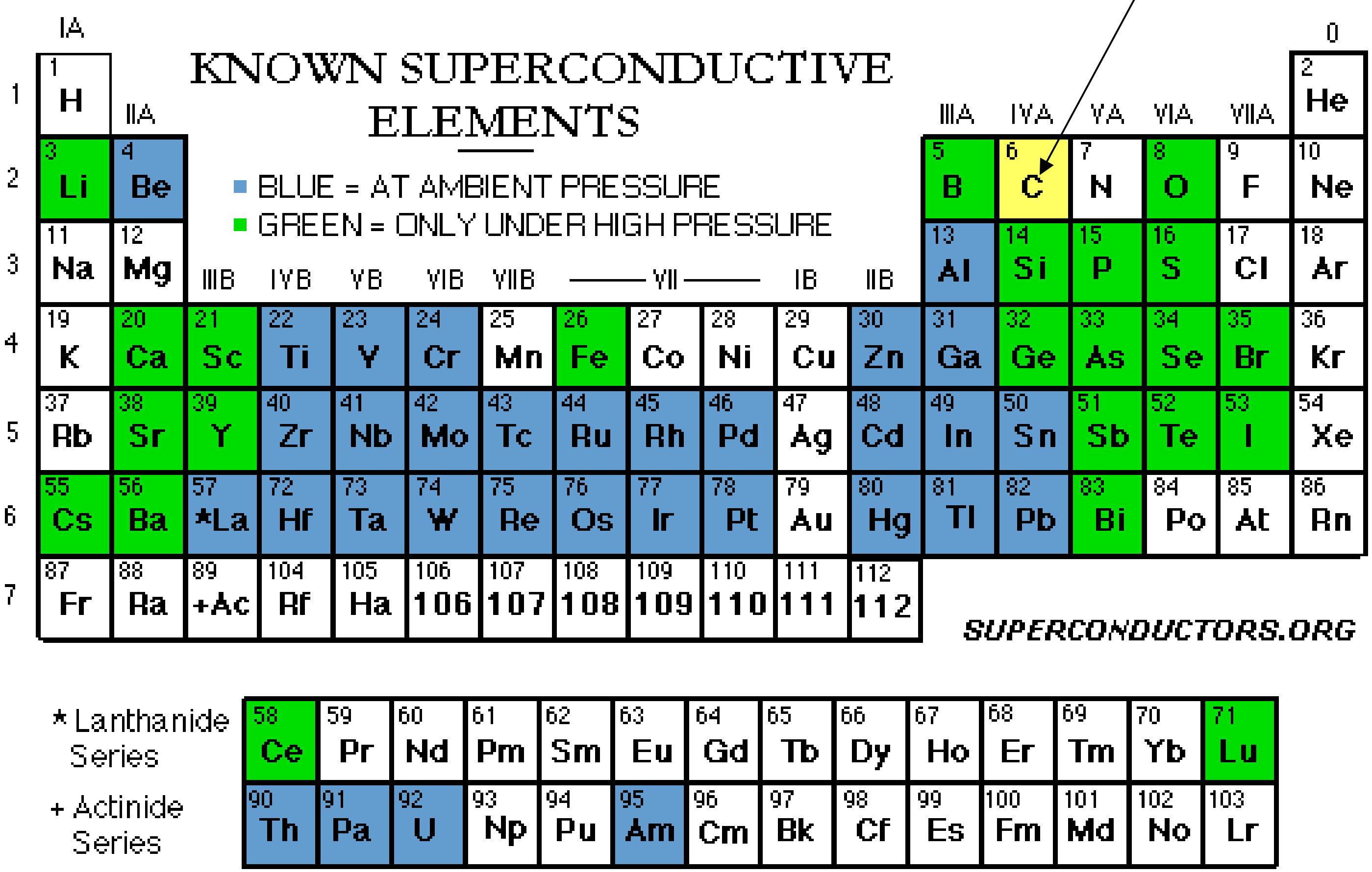
High-temperature SCs: **YBCO, BSCCO, …**
T_c record holder: **$HgBa_2Ca_2Cu_3O_{8+\delta}$** : T_c=164K=-109 ºC at P=3×10^5 atm
T_c=133K=-140 ºC at P=1 atm

Latest additions to the family:

- Triplet SC with intrinsic magnetism: **Sr_2RuO_4**
- Two-gap SC: **MgB_2**
- Ferromagnetic SCs: **UGe_2, URhGe, borocarbides**
- Iron-based HTSCs: **REOFeAs** (for **SmOFeAs** T_c=55K)
- Noncentrosymmetric SCs: **$CePt_3Si$, UIr, Li_2Pt_3B, Li_2Pd_3B**

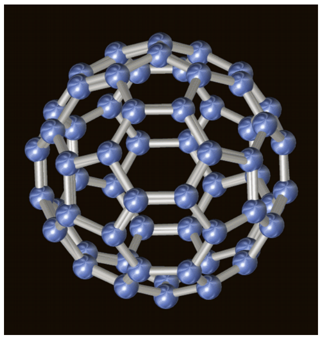
Elemental superconductors

carbon-based SCs



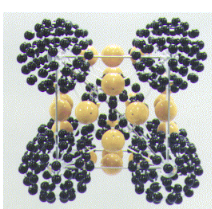
Carbon-based superconductors

"buckyball": fullerene C_{60}

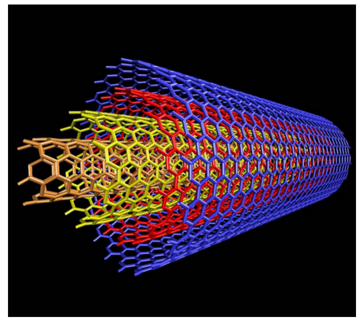


Kroto, Curl, Smalley
Chemistry Nobel Prize 1996

superconductivity at up to T_c=40 K in alkali-doped fullerenes



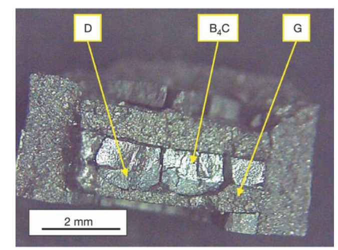
carbon nanotubes



diameter ~ 1 nanometer
=1/1000000000 meter
length up to a few mm

superconductivity at T_c=12 K in array of multi-walled carbon nanotubes

diamond



superconductivity upon doping with boron T_c=4 K

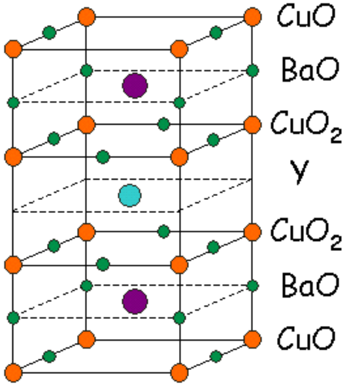
Superconducting superstars: High-temperature cuprates

Discovered in 1986 by G. Bednorz and K. Müller
Physics Nobel Prize 1987

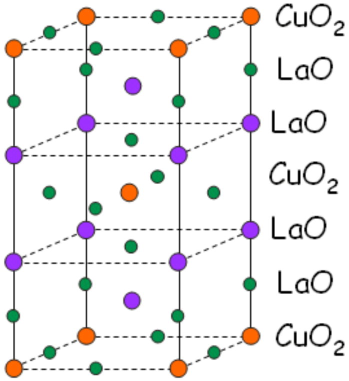
All known high-T_c superconductors are **layered metal oxides**

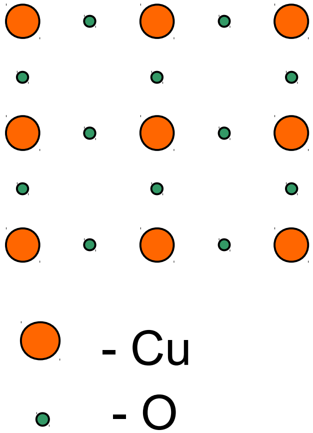
most important are **Cu-O_2 planes**:

Y-Ba-Cu-O



La-Sr-Cu-O





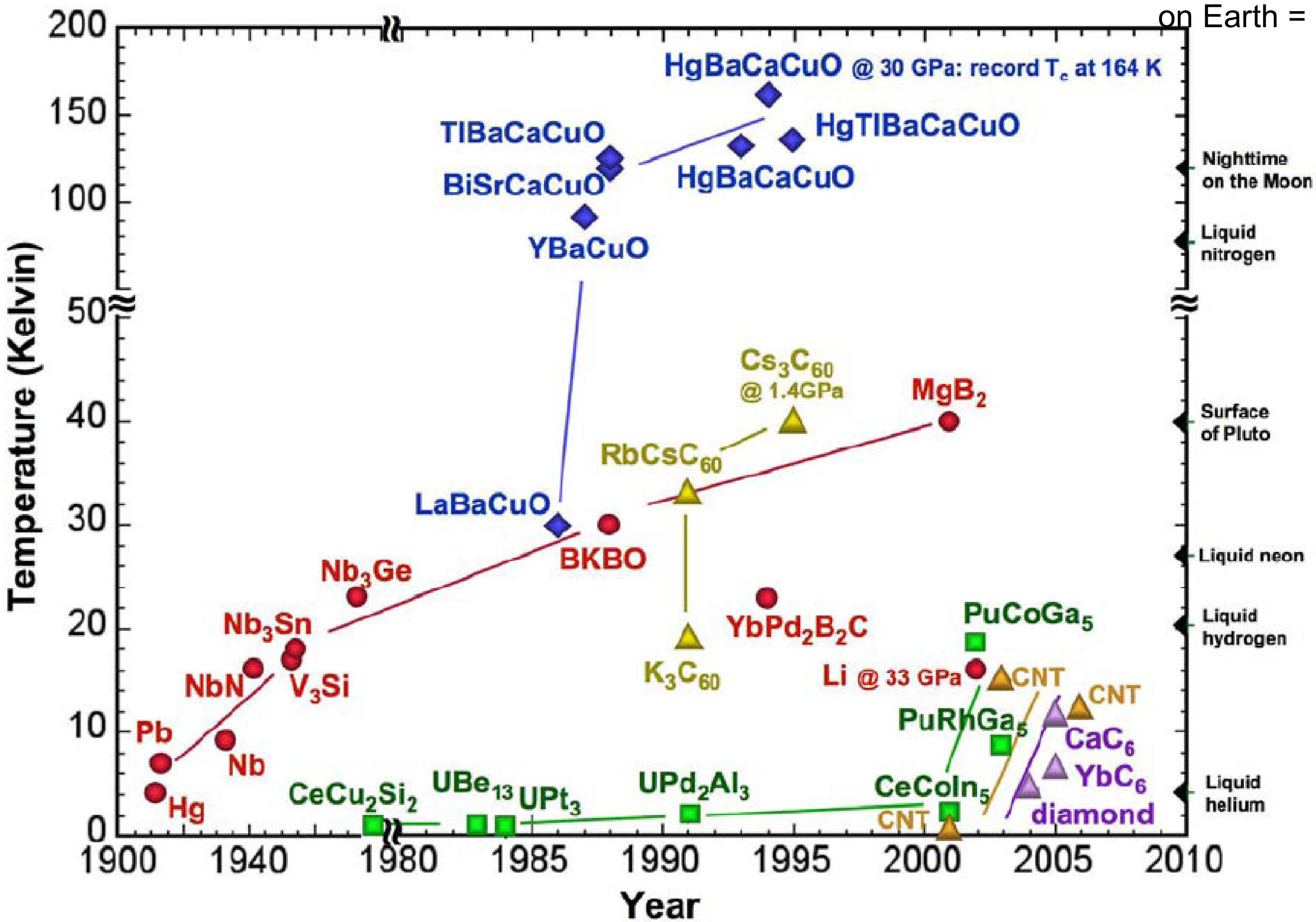
Brock contribution

Canada's first high-T_C superconductor – Dec 1986

La-Ba-Cu-O, T_C= 27 K (Mitrovic, Razavi, and Koffyberg)

T_c vs. year of discovery

coldest surface temperature on Earth = −89.2°C=184 K



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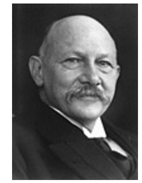
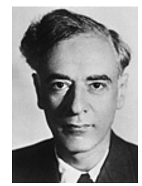
Nobel Prizes 

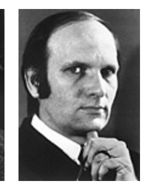
- 1913 **H. Kamerlingh-Onnes**
  (discovery of superconductivity)



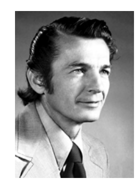
- 1962 **L. Landau**
  (explanation of superfluidity of He-4)



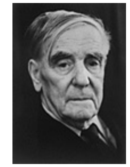
- 1972 **J. Bardeen, L. Cooper, J. R. Schrieffer**
  (pairing theory of superconductivity)

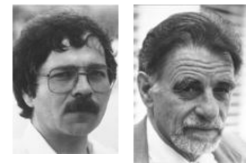
- 1973 **B. Josephson, L. Esaki, I. Giaever**
  (electron tunneling and phase coherence phenomena)

- 1978 **P. Kapitza**
  (discovery of superfluidity of He-4)

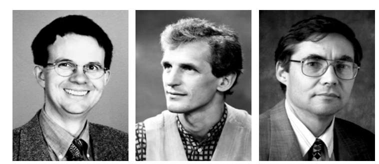


- 1987 **G. Bednorz, K. Mueller**
  (discovery of high-T_c superconductors)



- 1996 **D. Lee, D. Osheroff, R. Richardson**
  (discovery of superfluidity of He-3)

- 2001 **E. Cornell, W. Ketterle, C. Wieman**
  (discovery of BEC in cold gases)



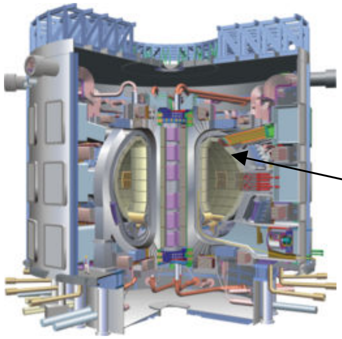
- 2003 **A. Abrikosov, V. Ginzburg, A. Leggett**
  (Ginzburg-Landau theory, vortices, He-3)

Note for taxpayers: Applications of superconductivity

- Coils for **powerful electromagnets**:
  - Magnetic Resonance Imaging (MRI)
  - Particle accelerators
  - Thermonuclear fusion power reactors

MRI scanner

MRI of human brain



International Thermonuclear Experimental Reactor (ITER)

Nb_3Sn superconducting magnets

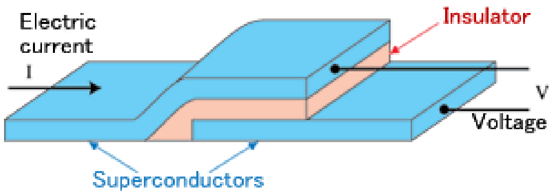
- **Magnetic levitation** devices

Maglev train

Note for taxpayers: Applications of superconductivity

- **SQUIDs** (Superconducting Quantum Interference Devices):

  - Ultrasensitive magnetometers
  - Photon detectors



Josephson effect,
Nobel Prize 1973

- Other possible applications:

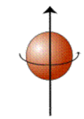
  - **Power transmission** lines
  - **Power storage** devices
  - **Quantum computing** hardware

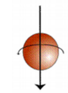
Why superconductors superconduct

Origin of superconductivity:
Electrons are in a collective state of motion

How can electrons form such a state?

Collectivization of electrons

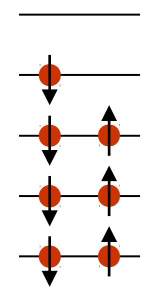
Elementary particles have internal angular momentum − **spin** 

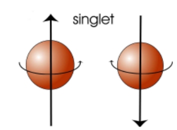
Electrons are **Fermions**: spin=1/2 − can point up  or down 

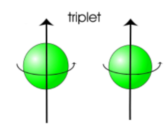
Pauli principle: no more than one fermion in any state

↓

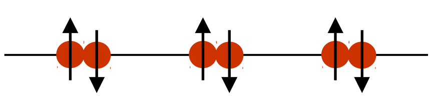
electrons cannot form a coherent many-particle state



Electron pairs are **Bosons** → spin=0 (singlet pair) 

→ spin=1 (triplet pair) 

Bosons can condense all into the same state
(**Bose-Einstein condensation**)



Explanation of superconductivity

At low temperature, electrons in metals form pairs (**Cooper pairs**)

↓

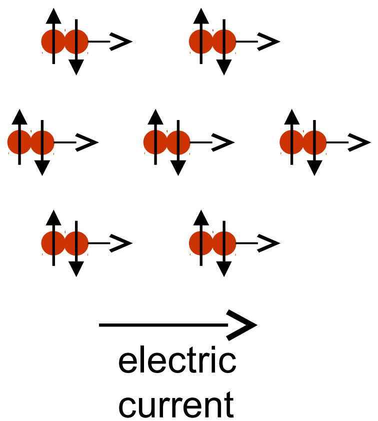
Cooper pairs condense into the same state

↓

Macroscopic coherence suppresses scattering of individual particles

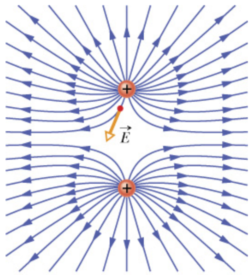
↓

Electron liquid can flow as a whole without resistance



Big question: **What is the glue that holds Cooper pairs together?**

Pairing of electrons seems impossible
because of like-charge repulsion:



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Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity

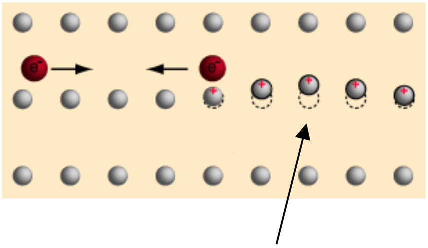
Proposed in 1957 by J. Bardeen, L. Cooper, J. R. Schrieffer
Physics Nobel Prize 1972

BCS theory is based on two ideas:

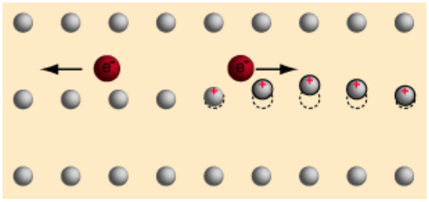
1) **Superconductivity = Bose-Einstein condensation of Cooper pairs**

2) **Pairs are formed due to phonon-mediated attraction between electrons**

an electron creates a cloud
of positive lattice charge



another electron is
attracted by the cloud



phonon = wave of lattice distortion

Broader impact of superconductivity

BCS-like pairing of neutrons or protons also occurs in **atomic nuclei** and **neutron stars**

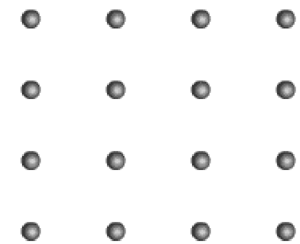
Fundamental physical concepts:

Nonperturbative emergent states of matter:
superfluidity, strongly-correlated electron systems, quantum Hall effect

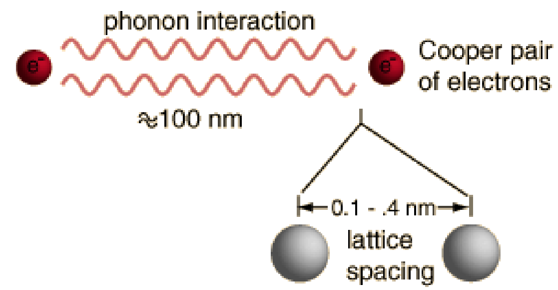
Spontaneous symmetry breaking:
at the center of the Standard Model of elementary particles

Cooper pairs

Paired electrons help each other
to move through the lattice



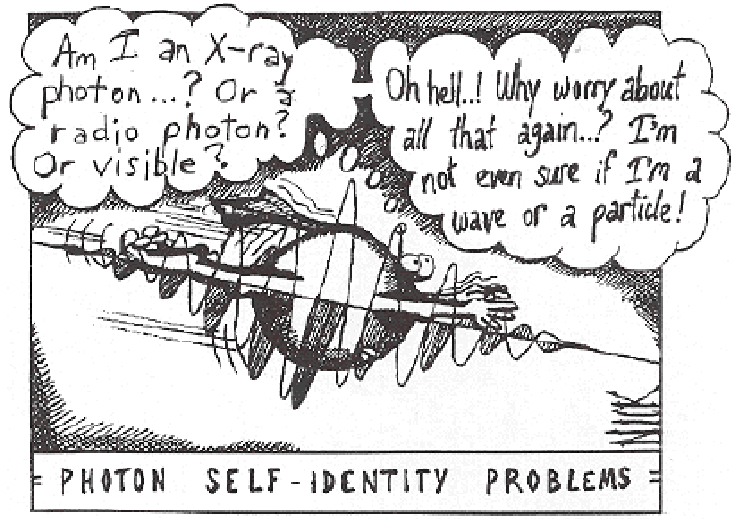
Attraction due to exchange by phonons is weak,
pairs are loosely bound
break-up energy ~ T_c



Quantitative measure of superconductivity:
wave function of Cooper pairs

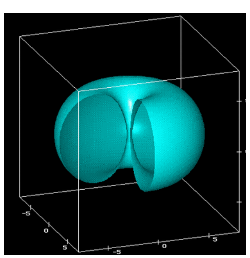
Wave functions

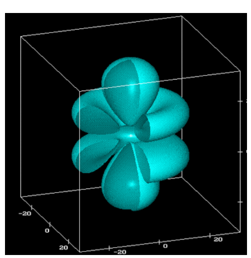
Light and matter exhibit properties of both waves and particles, quantitatively described by **the wave function $\Psi(\boldsymbol{r})$**



Interpretation: wave function describes the probability to find an electron near point $\boldsymbol{r}$

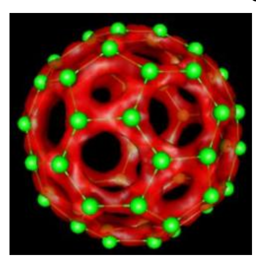
For example: wave functions of hydrogen atom orbitals



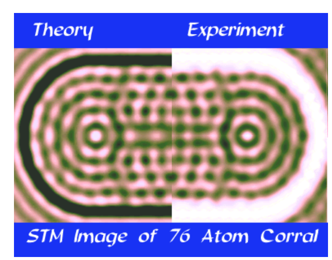


n=2,l=1,m=1 n=3,l=3,m=0

“buckyball” C_{60}

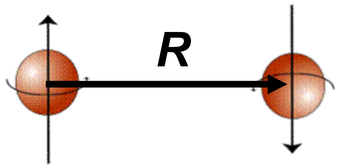


atoms in nanostructures



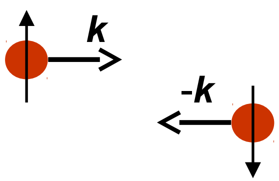
Wave function of Cooper pairs

For single electron: wave function = $\Psi(\boldsymbol{r})$
For a Cooper pair (2 electrons): wave function = $\Psi(\boldsymbol{r}_1,\boldsymbol{r}_2) = \Delta(\boldsymbol{R})$, $\boldsymbol{R}=\boldsymbol{r}_1-\boldsymbol{r}_2$



In normal metal: no pairs, $\Delta(\boldsymbol{R})=0$
In superconductor: electrons are paired, $\Delta(\boldsymbol{R})\neq 0$

Paired electrons move in opposite directions:

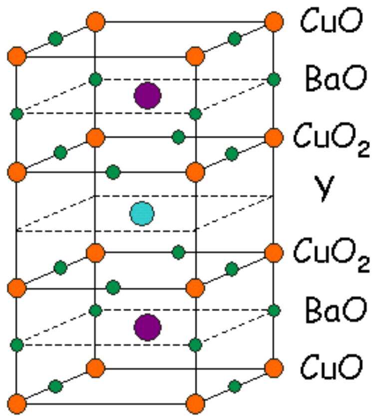


$\Delta(\boldsymbol{R}) \rightarrow$ **the gap function** $\Delta(\boldsymbol{k})$ = pairing strength of electrons ($\boldsymbol{k}$,↑) and ($-\boldsymbol{k}$,↓)

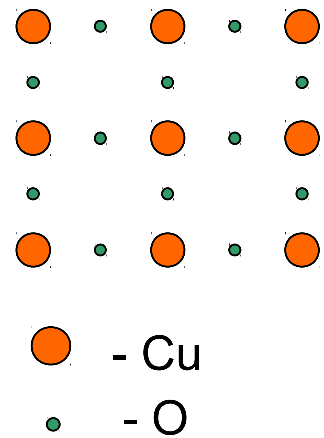
In BCS theory: $\Delta(\boldsymbol{k})$ same for all directions of $\boldsymbol{k}$: **isotropic pairing**
But, if $\Delta(\boldsymbol{k})$ depends on the direction of $\boldsymbol{k}$: **anisotropic pairing**

Example: Cooper pairing in HTSC

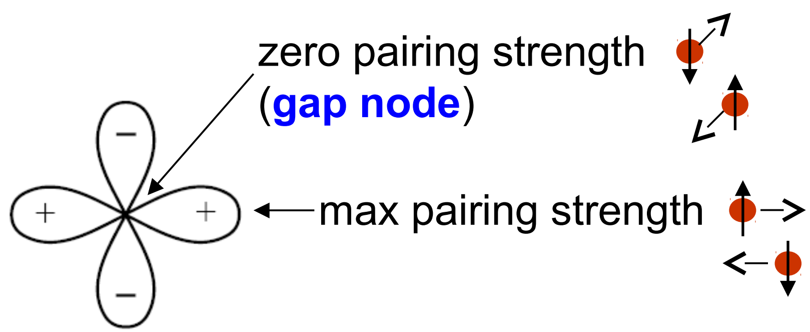
Y-Ba-Cu-O
layered crystal



electrons mostly move
in Cu-O planes



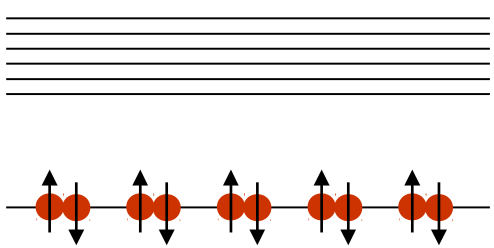
Superconducting pairing is described
by anisotropic gap function $\Delta(\boldsymbol{k})$



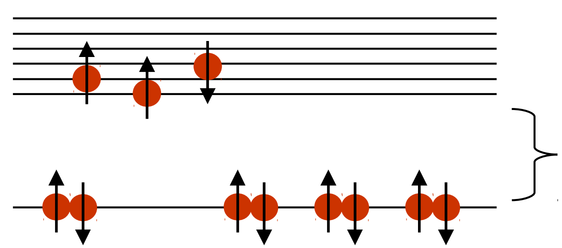
Probing Cooper pairs

How to look inside a superconductor: **measure the excitation energy gap $|\Delta(\boldsymbol{k})|$**

ground state, T=0:
electrons are paired

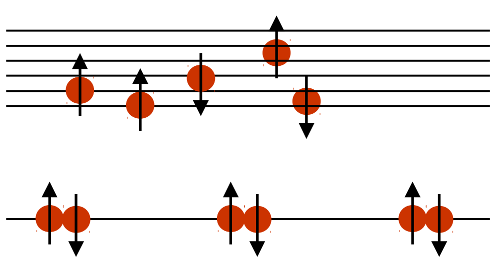


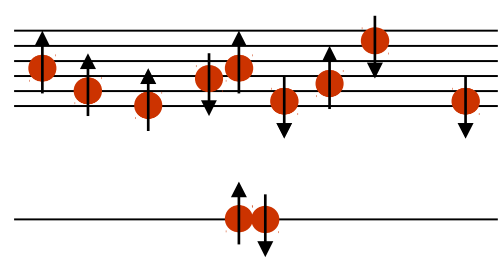
T>0, excited state:
unpaired electrons appear



energy gap ~ $|\Delta(\boldsymbol{k})|$

temperature increases → more pairs are broken



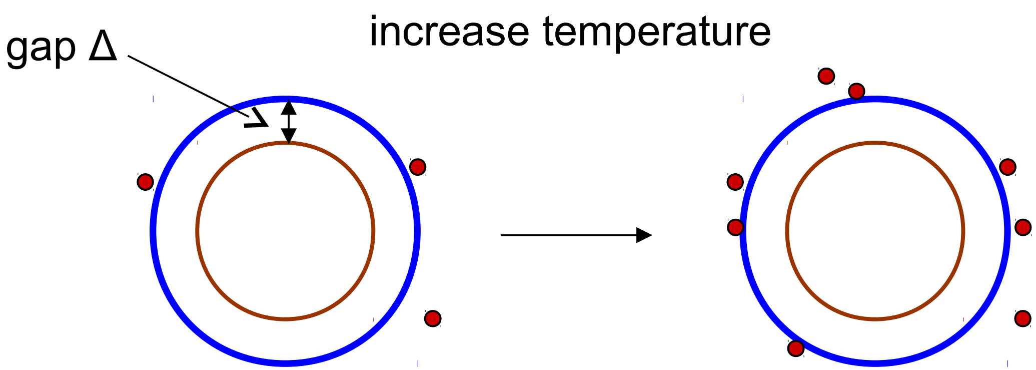


eventually, at $T>T_c$
there are no pairs left,
metal is no longer SC

Probing Cooper pairs

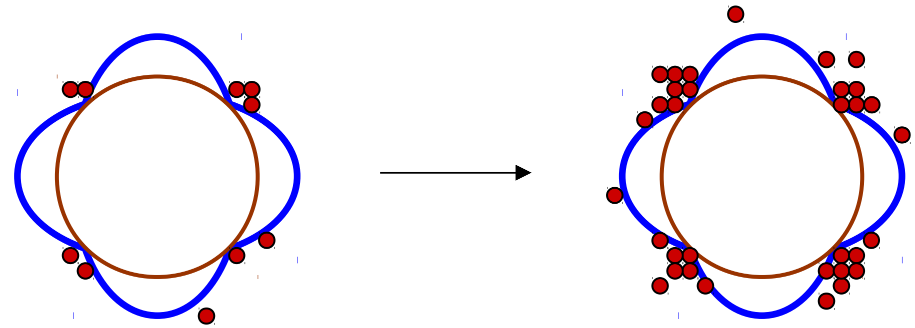
Probe the excited electrons near **the gap nodes**:

isotropic pairing,
no nodes



few excited electrons　　more excited electrons

anisotropic pairing
with gap nodes

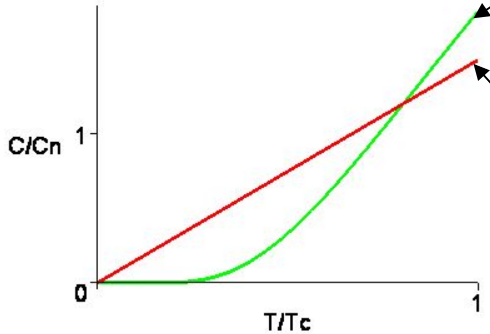


excitations near gap nodes　　a lot of excitations near gap nodes

Probing Cooper pairs

Thermal measurements:

e.g. specific heat

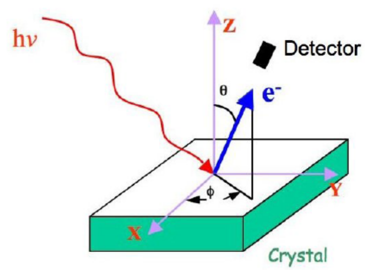


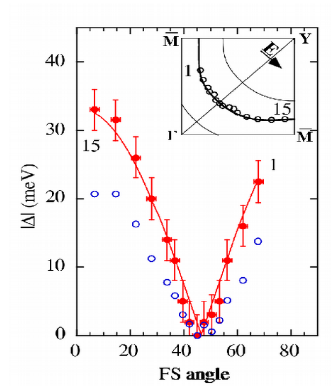
isotropic pairing, no nodes:
specific heat $C(T) \sim e^{-\Delta/T}$,
very small at low temperatures

anisotropic pairing with gap nodes:
$C(T) \sim T^2$ (for HTSCs),
not very small at low temperatures

Direct measurements of $\Delta(\boldsymbol{k})$:

e.g. ARPES (Angle-Resolved PhotoEmission Spectroscopy)





HTSC gap

Other methods: **magnetic measurements, NMR, Josephson effect, …**

Exotic Superconductivity

Conventional superconductors:

Cooper pairs are isotropic

no gap nodes

pairing mechanism is phononic

Quantitative theory − BCS model

Unconventional, or exotic, superconductors:

Cooper pairs are anisotropic

gap nodes are present

pairing mechanism is likely non-phononic

No quantitative theory yet!

Understanding superconductors

Experiment

$\downarrow$

Type and location of gap nodes

$\downarrow$

Gap function $\Delta(k)$

$\downarrow$

Pairing mechanism

$\downarrow$

Applications: from SC by serendipity to SC by design