What is “Super” in Superconductivity?

An *Informal* Overview of Experimental Facts

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Acknowledgements and References

Thanks to:

- Friends @physics, particularly HRK, TVR, AVMallik
- Abhishek Banerjee, Anindya Das

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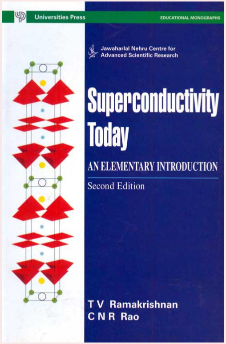
Must read

- Ramakrishnan, T. V., Rao, C. N. R. *Superconductivity Today*



Conductor to Super...

Conductor to Super...

- The phenomenon of conductors

(Google images)

Conductor to Super...

- The phenomenon of conductors

(Google images)

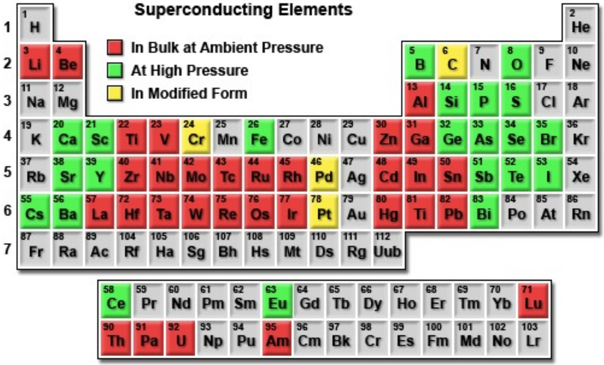
- ...going **SUPER**...

(Google images)

- ...is not so common among humans!

Superconductivity "everywhere"

- Most elemental metals yield to the charms of superconductivity...

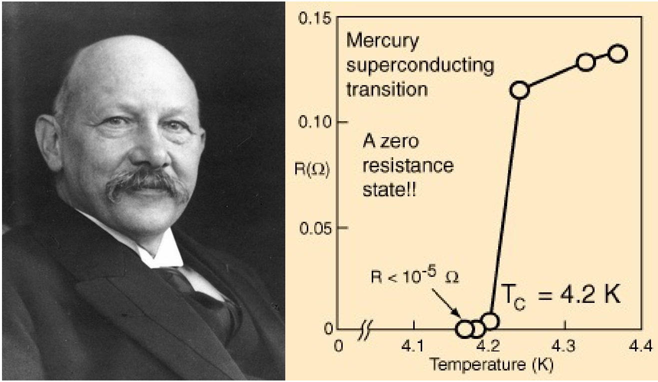


(From somewhere on the web!)

...perhaps under duress!

How it all started...

- Kamerlingh Onnes @ Leiden was obsessed with low temperatures...he liquefied helium!



(Wikipedia)

- ...and discovered (1911) that the resistance of mercury drops to “zero” below 4.2K!
- Aptly called *superconductivity* Not sure: By whom?

What Participants Should Expect to Gain

- Conductor in the superconductor: A review of the theory of metals
- An understanding of the *phenomenology* of superconductivity in metals...and why is it surprising
- A brief list of applications – how superconductors have the potential to be the next great thing!
- The challenge : Superconductors at ambient conditions

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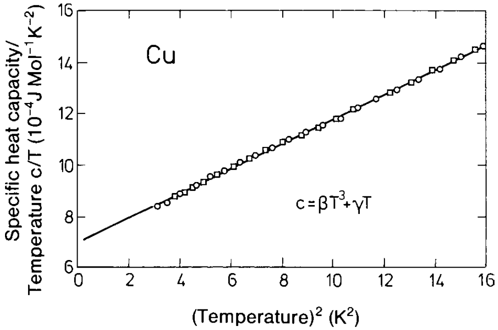
- Conductor in the superconductor: A review of the theory of metals
- An understanding of the *phenomenology* of superconductivity in metals...and why is it surprising
- A brief list of applications – how superconductors have the potential to be the next great thing!
- The challenge : Superconductors at ambient conditions
- Some necessary evil – theory and lack of it!

The “Conductor” in Superconductor

What is a Metal? – Survey of Metallic Properties

- Thermodynamic properties
- Magnetic properties
- Transport properties

Metals – Thermodynamic Properties



(Ibach and Lüth)

- Low temperature specific heat goes as

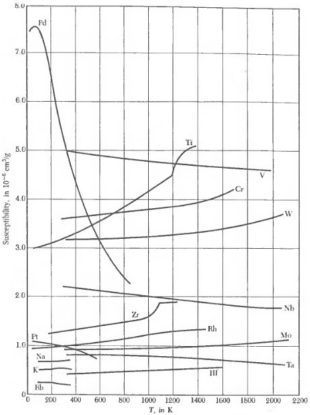
$$C_V^{metal} = \beta T^3 + \gamma T$$

- *Electronic* specific heat

$$C_V^{metal/electronic} \approx \gamma T$$

...**gapless** electronic excitations!

- Focus on "non-magnetic" metals

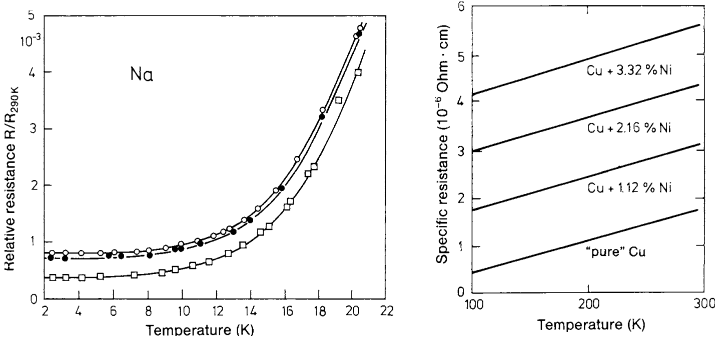


(Kittel)

- Magnetic susceptibility is essentially independent of temperature, and **paramagnetic**

Metals – DC Electrical Transport

- Resistivity of metals – increases with increasing temperature



(Ibach and Lüth)

- Resistivity regimes

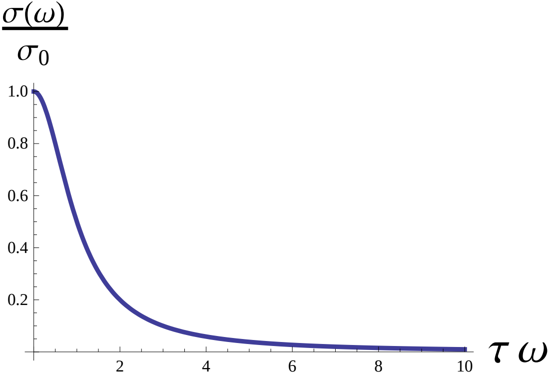
$$\rho = \rho_0 + A_1 T^2 \quad \text{“Low Temperature”}$$

$$\rho = \rho_0 + A_2 T^5 \quad \text{“Intermediate Temperature”}$$

$$\rho = \rho_0 + A_3 T \quad \text{“High Temperature”}$$

Metals: AC Conductivity

- All metals show a "Drude peak" in their AC conductivity



(Schematic)

- σ_0 is the DC conductivity, τ is "some" time scale

Metals: There's More!

- Widemann-Franz Law – Ratio of thermal conductivity and DC electrical conductivity is proportional to temperature

$$L = \frac{\kappa}{\sigma_0 T}$$

L is *INDEPENDENT* of the metal!!

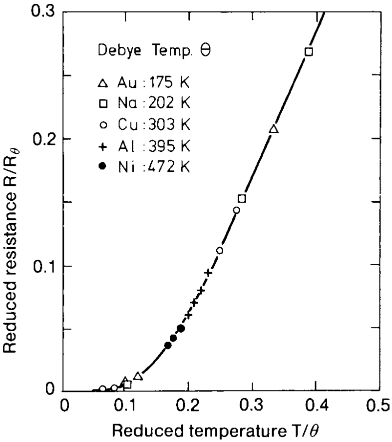
Metal	$L\,(10^{-8}\ \mathrm{W\Omega/K^2})$
Na	2.10
Ag	2.31
Au	2.35
Cu	2.23
Pb	2.47
Pt	2.51

(Ibach and Lüth)

- ...getting intriguing!

Metals: There's EVEN More!

- Universal resistivity!



(Ibach and Lüth)

- ...the metallicity of a metal

What is a Metal?

A ”liquid phase” of electrons with “universal” properties in

- Thermodynamics
- Magnetism
- Transport

Analogy with real liquids (on blackboard)

- ΔP vs Q compared to V vs I
- Liquid no shear stresses in “static condition” (takes the shape of the container) compared to no internal electric fields in “static condition (zero currents)” (screening charge on the surface to kill electric field inside)

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Before proceeding to superconductors, we will explore insulators

Insulators – The "solid phase" of electrons

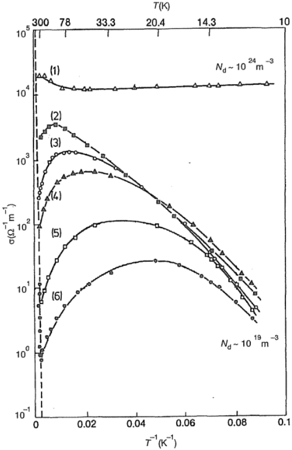
Insulators (Semiconductors)

- "Electronic solids" – do not conduct electricity at zero temperature
- Exponentially small electronic specific heat at low temperatures – **gapped** electronic excitations
- Weakly paramagnetic
- Poor electronic thermal conductors

(Wikipedia)

Insulators (Semiconductors)

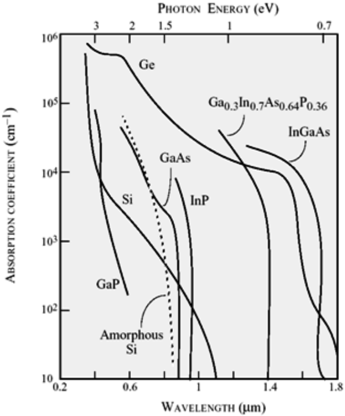
- Electrical conductivity *increases* with increasing temperatures at low temperatures

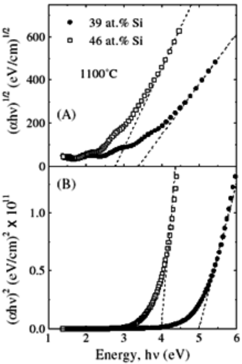


(Conductivity of doped Ge, Conwell (1952))

Insulators (Semiconductors)

- Electronic energy gap and optical absorption





(Google Images/NPTEL)

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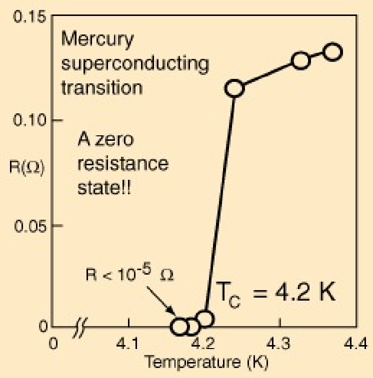
(Wikipedia)

...and The *Super*conductors

Perfect Conductor

- Kamerlingh Onnes's data



(Wikipedia)

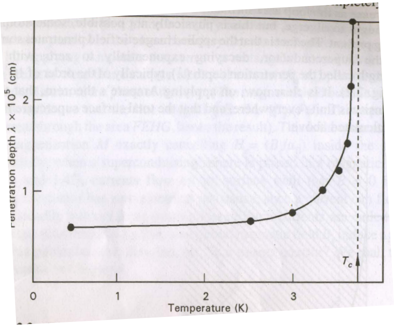
- Superconductors carry current without a voltage drop (think of "ideal fluid" flow) – zero resistance **perfect conductor**

Meissner Effect

- Superconductor does not like to have an electric field inside it (just like a normal metal)...
- Meissner-Ochsenfeld found that a superconductor also expels all *magnetic field*...superconductors hates electromagnetic fields!!
- The magnetic susceptibility $\chi = M/H = -1$ for a superconductor – **perfect diamagnet**
- ...
- This leads to spectacular effects...and technological applications!

Penetration Depth

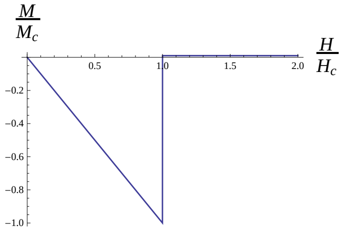
- The magnetic field can penetrate into the superconductor near the surfaces...but dies exponentially as we move into the bulk
- There is a length scale associated with this decay...called the *penetration* depth
- Most interestingly, the penetration depth is a function temperature...



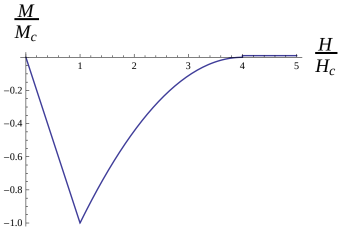
...and *diverges* at T_c!

Type I and Type II superconductors

- Superconductors do not remain perfect diamagnet for all magnetic fields...there are two types of behaviour
- Type I: At a critical magnetic field (H_c) superconductivity is lost and normal state is restored...typically found in elemental metals



Type I

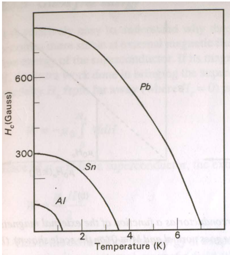


Type II

- Type II: There are two characteristic magnetic fields (H_{c1} and $H_{c2} < H_{c1}$)...at H_{c1} the magnetic field begins to penetrate the superconductor (not a perfect diamagnet) and at H_{c2} normal state is restored
- H_c (Type I) and H_{c1},H_{c2} are functions of temperature!

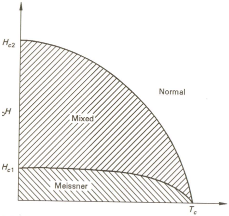
Phase Diagram

- Type I



(Ramakrishnan and Rao)

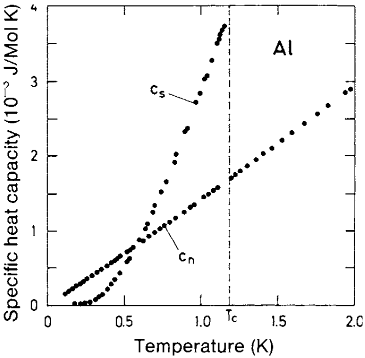
- Type II



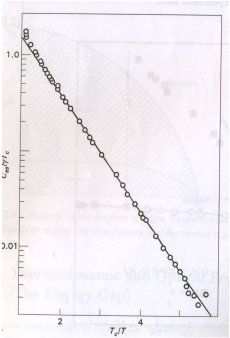
Thermodynamic Properties

Thermodynamic Properties

- *Electronic* specific heat goes to zero *exponentially* (like an insulator!!!)



(Ibach and Lüth)



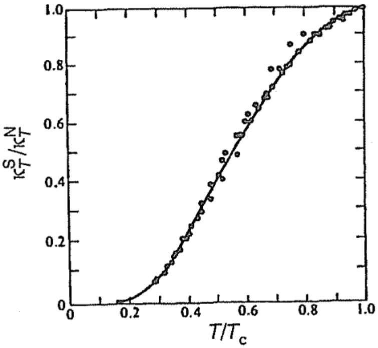
(Ramakrishnan and Rao)

- *Jump* in the specific heat at T_c – Phase Transition??

Thermal Conductivity

Thermal Conductivity

- (Electronic) Thermal conductivity also falls with temperature (approximately exponentially)

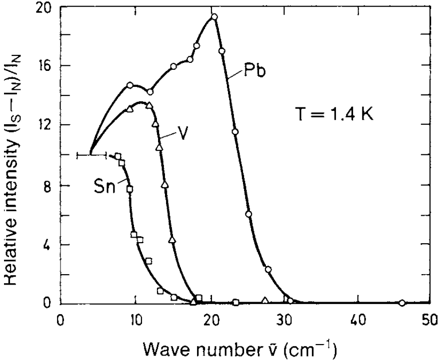


- Superconductors are poor thermal conductors!!...Widemann-Franz out!!

Optical Properties

Optical Properties

- Doesn't look like a metal...

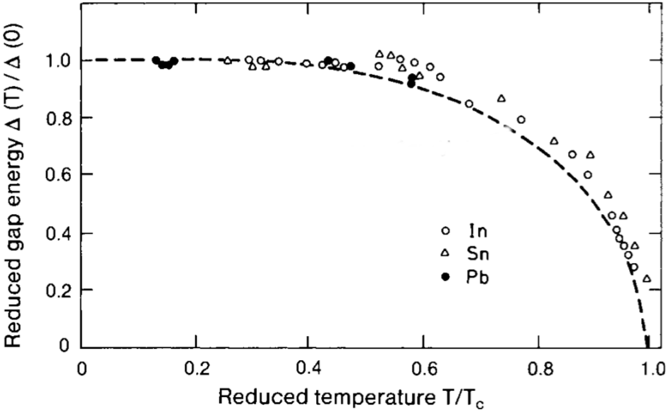


(Ibach and Lüth)

- ...looks more like a *semiconductor*! Has a GAP!!
- Superconductor HAS A GAP!!!!

Temperature Dependence of Gap

- Gap is temperature dependent

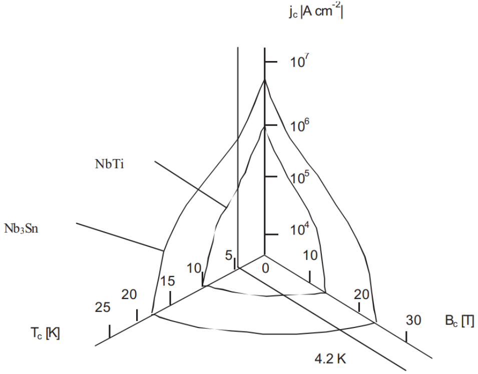


(Ibach and Lüth)

- Gap vanishes at T_c
- Also note "universal" behaviour

Critical Current

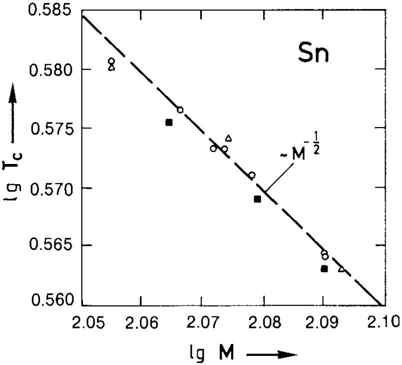
- A superconductor cannot support an arbitrary large current density...there is a critical current density j_c
- The critical current is temperature dependent
- Phase diagram in $B(H)$-T-I plane



(Poole et al.)

Isotope Effect

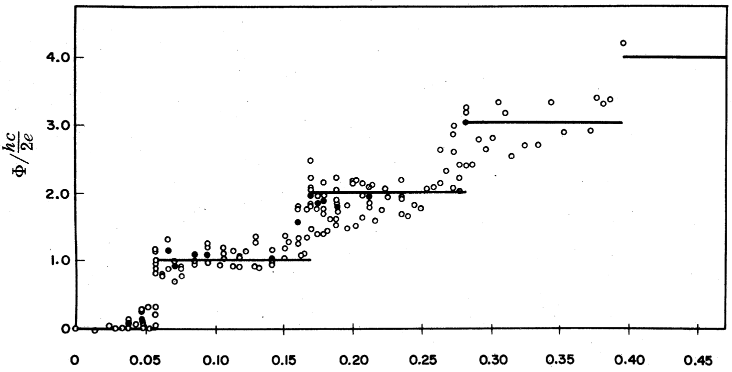
- The strangest thing...the T_c depends on the isotope!!



(Ibach and Lüth)

Flux Quantization

- The flux through a superconducting ring seems to be quantized



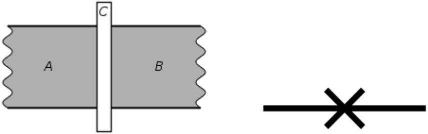
(Daever and Fairbank, 1961)

...based on measurements in small tin cylinders

- Some sort of "macroscopic quantum phenomenon" — note $\Phi_0 = \frac{h}{2e}$ (MKS units) appears, where Φ_0 is the *flux quantum*

Josephson Effect

- S-I-S structure – Joesephson Junction



(Wikipedia)

A, B – Superconductors, C – Insulator

- Josephson relations (t – time)

$$I(t) = I_c \sin(\varphi(t)), \quad V(t) = \frac{\Phi_0}{2\pi}\frac{\partial\phi}{\partial t}$$

gives the S-I-S current (I) voltage (V) relationship across the junction...effectively a nonlinear inductor

$$\frac{\Phi_0}{2\pi}\frac{1}{\sqrt{I_c^2 - I^2}}\frac{\partial I}{\partial t} = V$$

where I_c is a characteristic current of the Josephson junction

- Note appearance of h! **Macroscopic quantum phenomenon!**

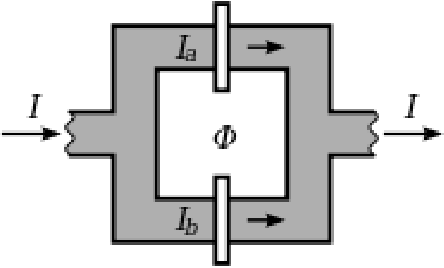
The “Super” in Superconductors

- Zero resistance
- Meissner effect (Penetration depth)
- Type I and II superconductors
- Vanishing specific heat
- Poor thermal conductivity
- Gap in excitations
- Critical current
- Isotope effect
- Flux quantization
- Josephson effects
- +other effects (Knight shift/Coherence peaks)

Superconductors
in Technology, Science and Beyond...

Quantum Phenomena for Measurement

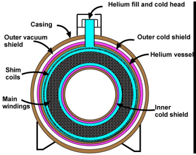
- AC Josephson effect – voltage standard (In fact, the Josephson effect and the quantum hall effect provide accurate measurement of ħ and *e*)
- Josephson effect used for magnetic measurements (SQUID – superconducting quantum interference device)

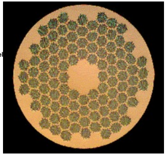


(Wikipedia)

Magnetic Resonance Imaging

- MRI imaging for medical diagnosis/scientific study (NMR)
- Superconducting coils used to produce high/uniform magnetic fields

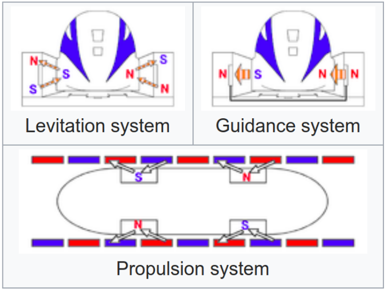




(Wikipedia)

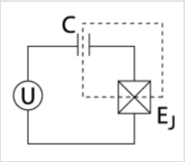
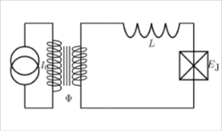
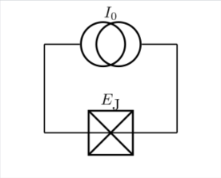
Magnetic Levitation Trains

- Technology is already in use in Japan (>600 km/hr achieved!)
- Superconducting magnets installed in the train



Quantum Computers

- Exploit the true quantum power (Race on at Google/MS/Intel...)
- Josephson effect – used to make qubits

Charge Qubit	RF-SQUID Qubit (prototype of the Flux Qubit)	Phase Qubit
A  Charge qubit circuit superconducting island (encircled with a dashed line) defined between the leads of a capacitor with capacitance C and a Josephson junction with energy E_J is biased by voltage U	A  Flux qubit circuit superconducting loop with inductance L is interrupted by a junction with Josephson energy E_J. Bias flux Φ is induced by a flux line with a current I_0	 Phase qubit circuit. Josephson junction with energy parameter E_J is biased by a current I_0

(Wikipedia)

- Can bring quantum speed-up to daily life
- **Potential for an *epoch changing* revolution**

Question

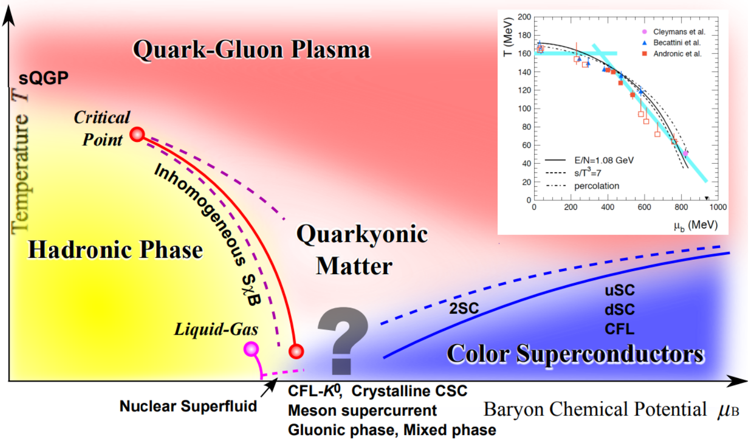
What can *you* think of to exploit the "super" of superconductors?

Superconductivity: Science for the Sciences...

- The idea of phenomenological Ginzburg-Landau theory (to be discussed) provides a **a paradigm for construction of physical theories** – identify symmetries of the problem (from experiment) and construct symmetry allowed (renormalizable) terms (examples: all of condensed matter physics, the standard model of particle physics)
- Notion of **spontaneous symmetry breaking**
- Provides a mechanism for providing masses to particles in the standard model...**mechanism posited by Brout-Englert-Higgs (also suggested by Anderson)** leading to the prediction of the Higgs boson – "the universe is a superfluid"

Superconductivity: ...and Beyond...

- ...in quantum chromodynamics...



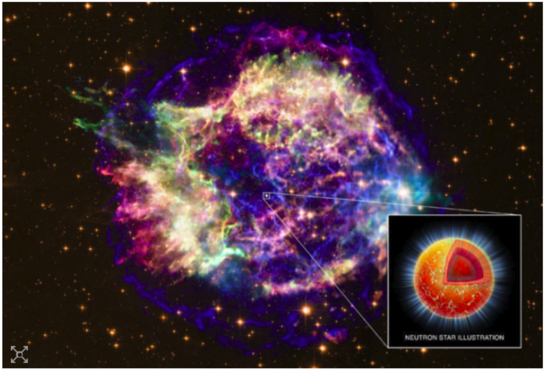
(Google Images)

...and even "Beyonder" to Neutron Stars!!

STARS AND SOLAR PHYSICS | RESEARCH UPDATE

Neutron star has superfluid core

02 Mar 2011



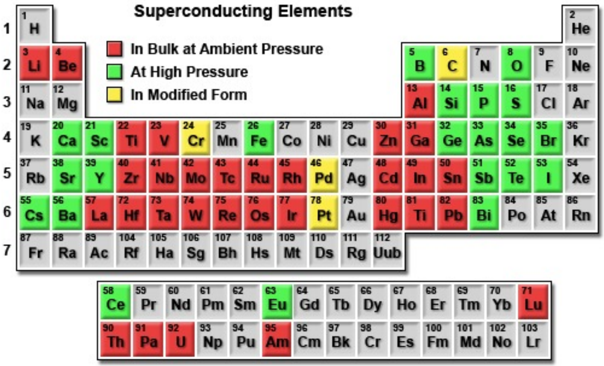
An extremely hot superfluid at the heart of Cassiopeia A

Neutron stars should exhibit both superfluidity and superconductivity, according to two independent groups of scientists. The researchers studied the neutron star in the supernova remnant known as Cassiopeia A, and found that its core should exist in a superfluid state at up to around a billion degrees kelvin, in contrast to the near absolute-zero temperatures required for superfluidity on Earth.

(Physics World)

The Real Challenge on Planet Earth: Superconductors with High T_c and H_c at Ambient Pressures

Elemental Metals



(From somewhere on the web!)

- Elemental metals have very low T_cs (liquid helium temperatures) and low H_c
- Nb is notable $T_c \approx 10\text{K}$ and $H_c \approx 1\text{T}$
- **Noble metals Cu, Ag, Au are *NOT* superconducting**

Alloys and Compounds etc...

- NbN ($T_c \approx 16$K) discovered in 1941
- **NbTi ($T_c \approx 10$K, $H_c \approx 15$T)** discovered in 1961 – most commercial superconducting technologies use this even today!
- 1960s-1970s many new materials, notably A15 materials of the type A_3B – Nb_3Se held the record for T_c

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- General consensus in 70s – T_c cannot exceed 30K
- Belief in 1970/early 80s (summarized by Matthias Rules) to look for good superconductors
  1. high symmetry is good, cubic symmetry is the best
  2. high density of electronic states is good
  3. stay away from magnetism
  4. stay away from insulators
  5. stay away from oxygen

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  6. **stay away from theorists**

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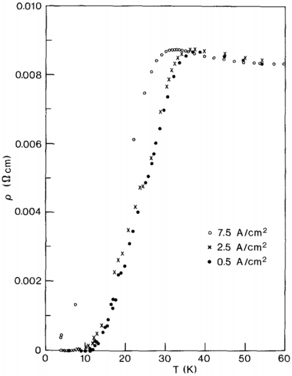
  4. stay away from insulators
  5. stay away from oxygen
  6. **stay away from theorists (the *only* rule that survives!)**

...smashed by the Cuprate Revolution...

- **Ceramic** copper oxide materials show *high temperature* superconductivity $T_c \approx 40K$!

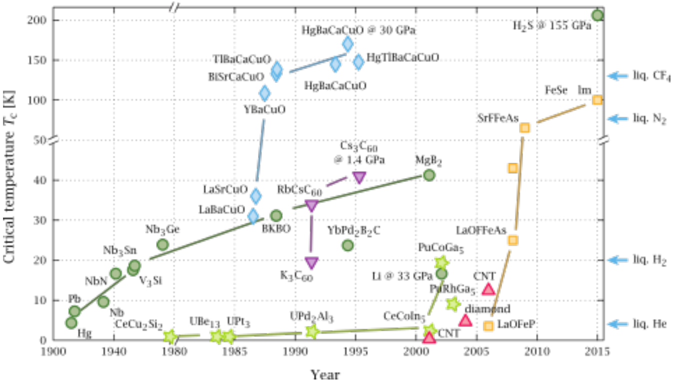


(Bednorz and Muller (1986), BaLaCuO system)

- 1987, YBCO compounds discovered with $T_c = 90K$ breaking the liquid nitrogen (77K) barrier!

...and other Discoveries

- MgB_2 (2001), $T_c \approx 39$
- Pnictides (Iron/Arsenic) compounds $T_c \sim 100K$
- ...latest H_2S (2015) (T_c ~200K at ≈150GPa)



(Wikipedia)

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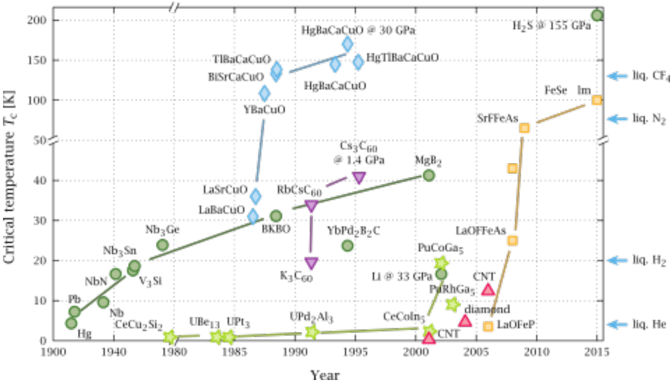
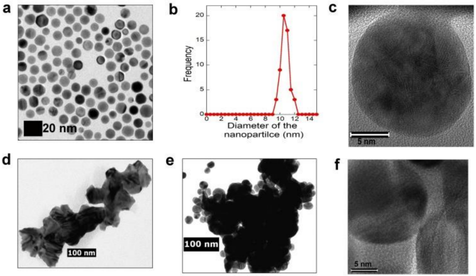


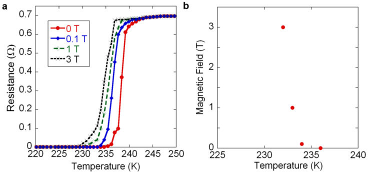
(Wikipedia)

- **Ambient condition superconductor?**

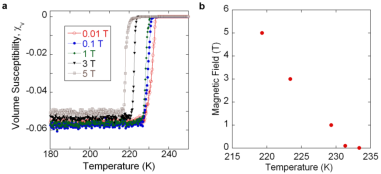
Ambient Condition Superconductor, Finally?

- Recent work from IISc: arXiv:1807.07572 Thapa and Pandey
- Magic material: **Sinter agglomerated Au nanoglobules (~ 10nm) infused with 1nm Ag nanoparticles**





$\Longrightarrow$



- Resistivity and susceptibility data suggestive of superconductivity
- $T_c \sim 150\text{K}$ to $> 300\text{K}$, large $H_c \gtrsim 5\text{T}$

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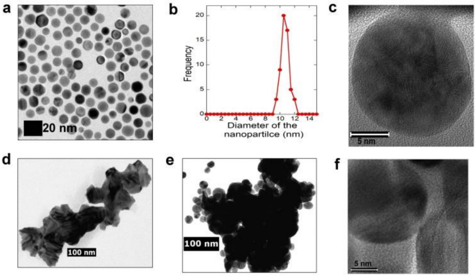
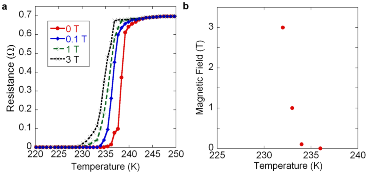
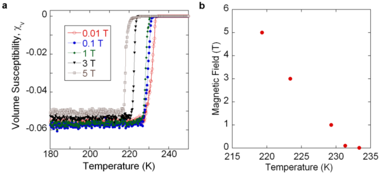




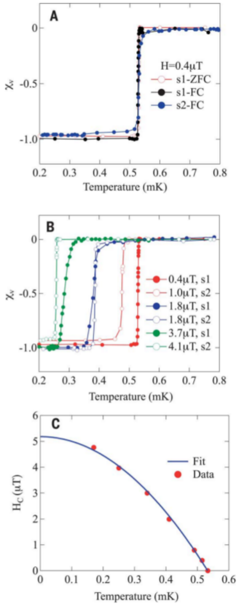


$\Longrightarrow$

- Resistivity and susceptibility data suggestive of superconductivity
- $T_c \sim 150\text{K}$ to $> 300\text{K}$, large $H_c \gtrsim 5\text{T}$
- **History in the making?**

Superconductor at Another Extreme!

- Lowest T_c superconductor – elemental Bi – discovered by TIFR group **(Ramakrishnan et al., (2017))**
- $T_c \sim 2 - 4$milliK !!
- $H_c \sim 1 - 4\mu$T !!
- Spectacular experiments



Theories
(Necessary Evil: Theorists!)

Phenomenological Theory - London Relation

- What is the phenomenological description of the “anti-light” stance of a superconductor?
- As an example, a metal is described by,

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$

  current density is proportional to applied electric field
- London brothers (mid 1940s) realized the correct phenomenological description for the superconductor

$$\boldsymbol{J} = -K\boldsymbol{A} = -\frac{n_s e^2}{m}\boldsymbol{A}$$

  $\boldsymbol{A}$ is the *vector potential* ($\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t}$)
- Captures *zero resistance* and *Meissner effect* in a single equation

Phenomenological Theory: Landau-Ginzburg

- Landau-Ginzburg (~1950) *posited* that the state superconductor is described by a ***complex number*** Ψ (analogous to magnetization $\boldsymbol{M}$ of a magnet)...manifestation of a symmetry ($U(1)$ symmetry)
- In the normal state equilibrium value of $\Psi = 0$ and in the superconducting state $\Psi \neq 0$
- A general state will have inhomogeneous $\Psi(\boldsymbol{r})$
- Landau-Ginzburg functional

$$\mathcal{F}[\Psi] = \int \mathrm{d}^d\boldsymbol{r} \left[c(T) \left(-i\hbar\boldsymbol{\nabla}\Psi + e^\star \boldsymbol{A}\right)^2 + a(T)|\Psi|^2 + \frac{b(T)}{2}|\Psi|^4 + \frac{1}{2\mu_o}\left(\boldsymbol{\nabla} \times \boldsymbol{A}\right)^2 \right]$$

- Superconducting state is obtained for $T \leqslant T_c$ if

$$a(T) = a_0(T - T_c) \quad b(T) = b_0, \quad c(T) = c_0 \quad (a_0, b_0, c_0 > 0)$$

$U(1)$ symmetry broken below $T \leqslant T_c$

Phenomenological Theory: Landau-Ginzburg

Explains...

- Miessner effect (London equation)
- ***Predicts*** two types of superconductors (Abrikosov 1950s)
- Explains flux quantization
- Explains Josephson effect

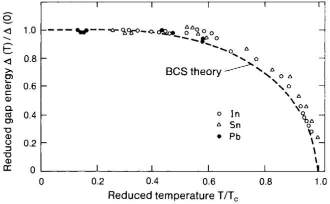
Does not explain...

- Gap in electron spectrum
- Coherence effects seen in NMR (not discussed)
- The value of T_c
- ...

Landmark theory of physics – provides a *paradigm* for construction of physical theories

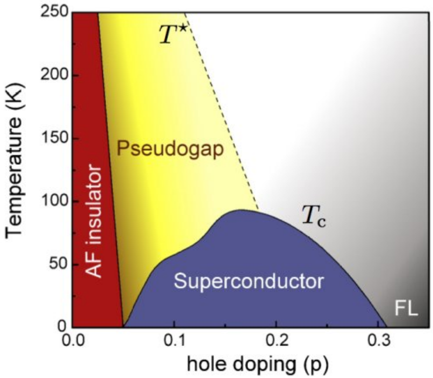
Microscopic Theory: Bardeen-Cooper-Schrieffer

- A theory with *electrons* as degrees of freedom
- Electrons are fermions ("avoid each other") and repel each other by Coulomb interactions
- Phonons induce a *retarded attractive interaction* between electrons
- Fermions form pairs (Morally: pairs are bosons, and can Bose condense) – **Superconductor is morally a Bose condensate of Cooper pairs**
- Obtains Landau-Ginzburg theory as an effective theory!
- Explains other phenomena including gap, coherence effects etc. in a quantitative fashion



- A spectacular success story, that took fifty years of writing!

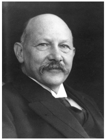
...smashed, again, by Cuprates!



(Google Images)

- Cuprates have smashed almost all paradigms of condensed matter physics...
- **A microscopic theory of cuprates (and other new systems)...remains a key open challenge**

Hall of Fame

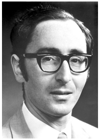


(Onnes, 1913)

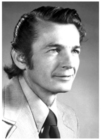
(Bardeen, 1972)

(Cooper, 1972)

(Schrieffer, 1972)



(Josephson, 1973)

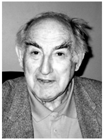


(Giaever, 1973)

(Bednorz, 1987)

(Muller, 1987)

(Abrikosov, 2003)



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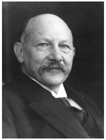

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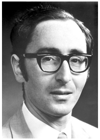

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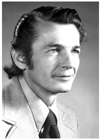

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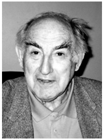


(Ginzburg, 2003)

(Leggett, 2003)

(Anderson, 1976)

Final Thought

Can Superconductors Shape the Future of Humanity?

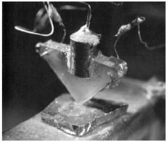
- Phases of many electrons have guided the evolution of humanity
- From the stone age...to metal age...to the present semiconductor age...can we harness true quantum effects (entanglement)?

(Fire)

(Wheel)

(Electricity)

(Vaccines)



(Transistor)

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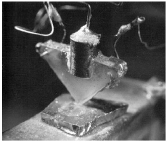

(Transistor)

(CCCookie?)

- **Chocolate-chip-cookie, anyone?**