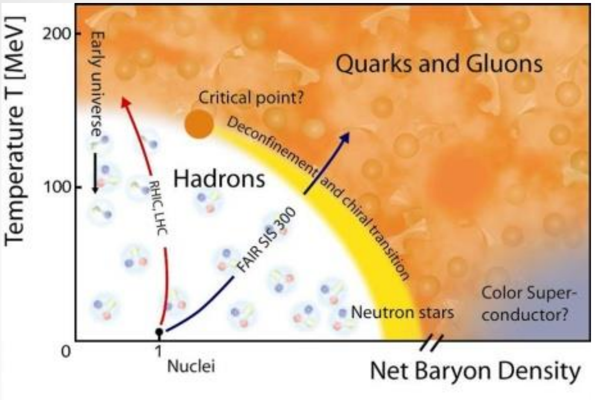
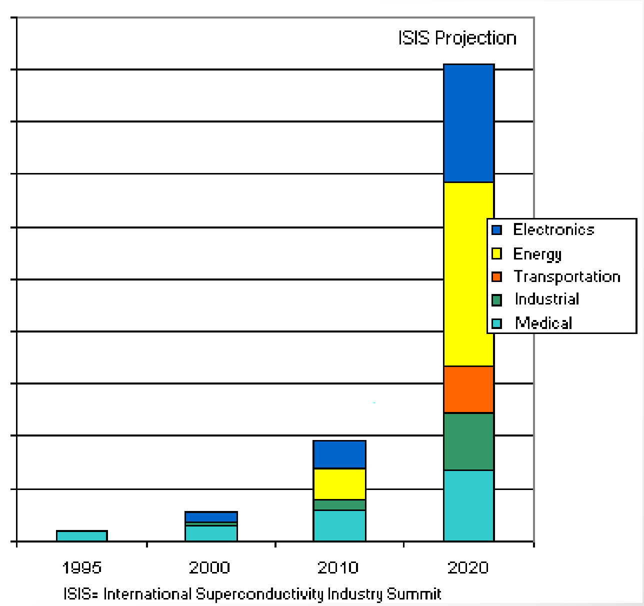


$6\ 10^{11}$ K

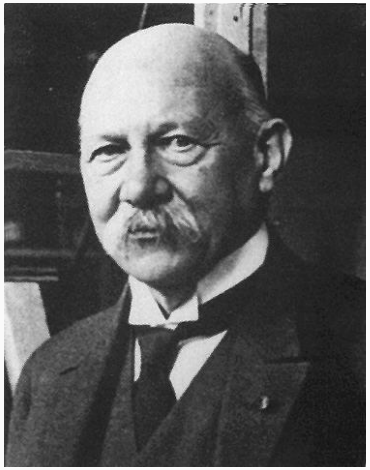
http://www.aftenposten.no/amagasinet/Hvorfor-Tilbake-til-Fremtiden-II-tok-feil-7885865.html

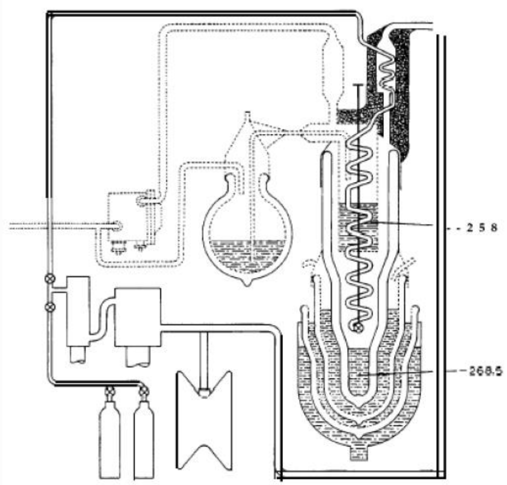
Superconductivity



14. What are practical applications of superconductors?

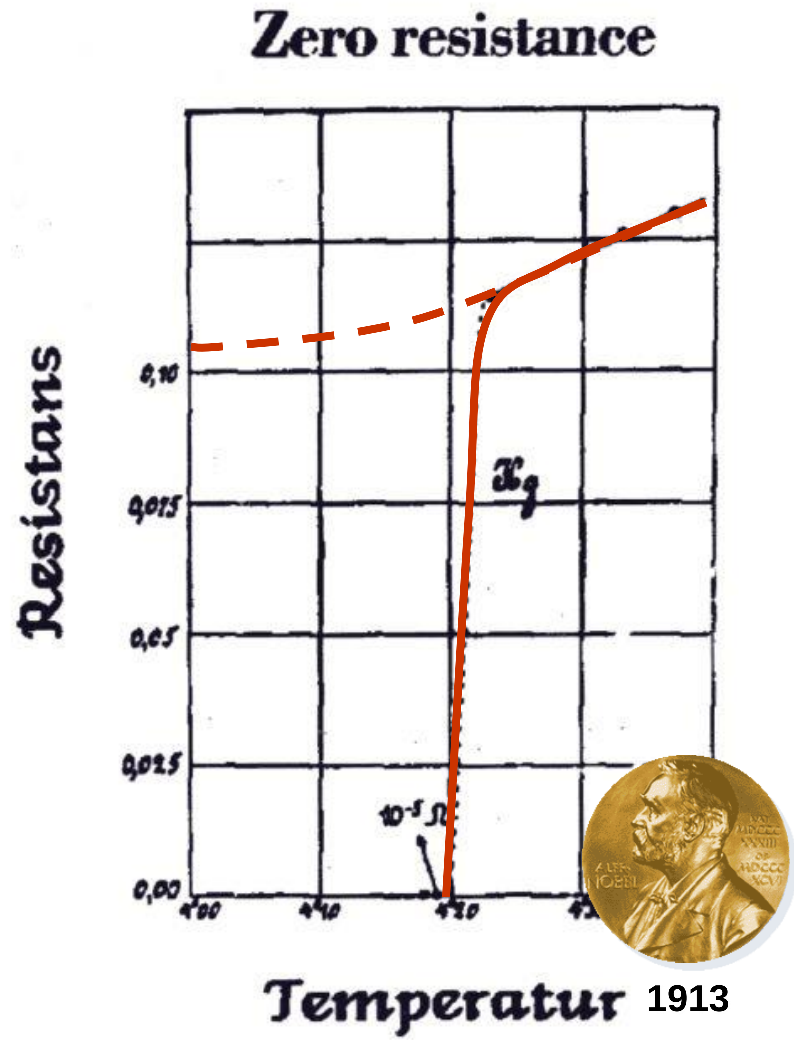
Discovery of Superconductivity





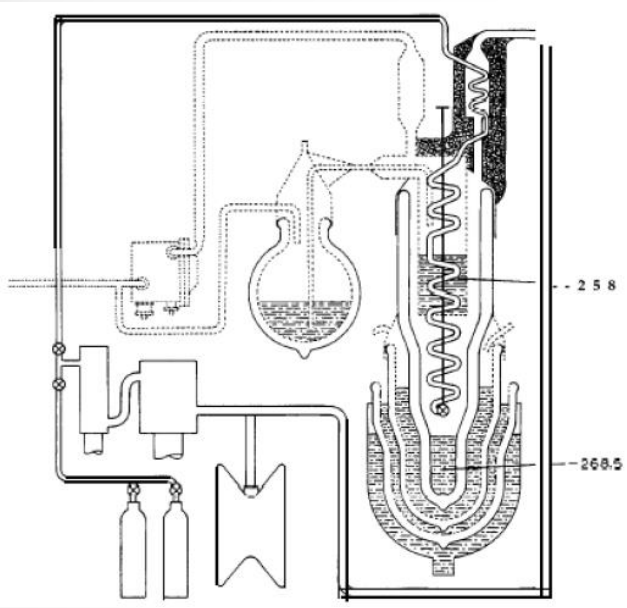
- Discovered by **Kamerlingh Onnes** in 1911 during first low temperature measurements to liquefy helium

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

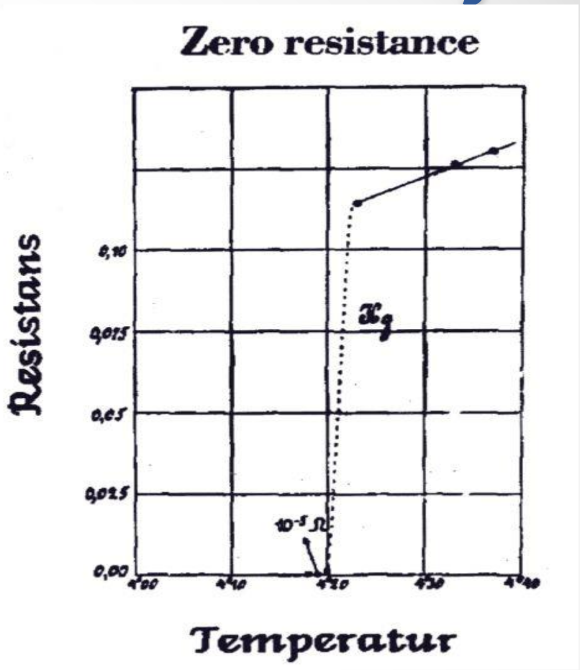


1913

Discovery of Superconductivity



1913



‘The phenomenon of superconductivity was discovered in 1911 by the Dutch physicist H. Kamerlingh Onnes and his assistant Gilles Holst in Leiden. They found that *dc* resistivity of mercury suddenly drops to zero below 4.2 K, as shown in Fig. 1.1. Gilles Holst actually made this measurement [1]. However, his name has become lost in the recesses of history, as is often the case with junior researchers working under a famous scientist.’

ROOM-TEMPERATURE SUPERCONDUCTIVITY
Andrei Mourachkine
University of Cambridge, Cambridge, United Kingdom
CAMBRIDGE INTERNATIONAL SCIENCE PUBLISHING, 2004

Failed theories of superconductivity

by Jörg Schmalian

Albert Einstein
(1879-1955)

Niels Bohr
(1885-1962)

Ralph Kronig
(1905-1995)

Lev D. Landau
(1908-1968)

Felix Bloch
(1905-1983)

Léon Brillouin
(1889 -1969)

Einstein, Bohr, Kronig, Landau, Bloch, and Brillouin made proposals for microscopic theories of superconductivity prior to the ground breaking experiment by Meissner and Ochsenfeld in 1934.

https://arxiv.org/ftp/arxiv/papers/1008/1008.0447.pdf

General properties

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

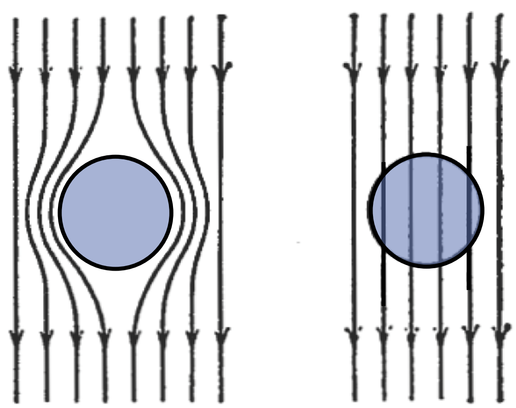
- Superconductivity can be destroyed also by an external magnetic field H_c which is also called the *critical* one (*Kammerlingh-Onnes, 1914*). Empirically,

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

- 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)

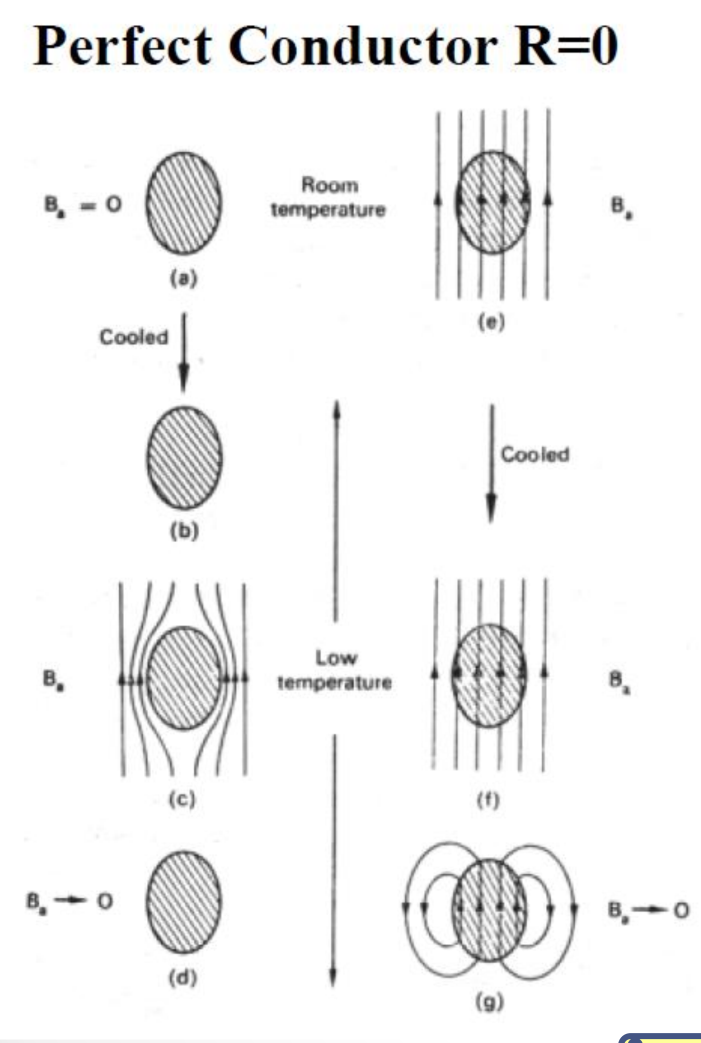
Magnetic field is expelled from the superconductor

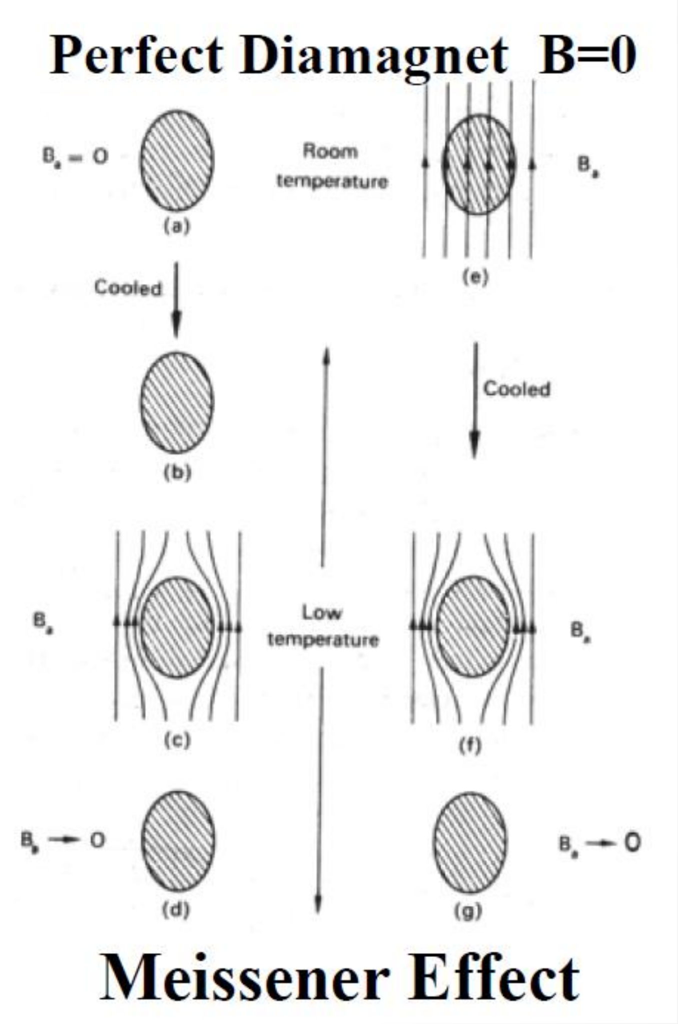


Ideal conductor! Ideal diamagnet!

2. How could superconductivity be destroyed?

Meissner effect





4. What is the Meissner effect? Is this consequence of zero resistance or not?

Ideal conductor! Ideal diamagnet!

The superconducting elements

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

Li	Be 0.026											B	C	N	O	F	Ne
Na	Mg											Al 1.14 10	Si	P	S	Cl	Ar
K	Ca	Sc	Ti 0.39	V 5.38	Cr				Ni	Cu	Zn 0.875 5.3	Ga 1.091 5.1	Ge	As	Se	Br	Kr
Rb	Sr	Y							Pd	Ag	Cd 0.56 3	In 3.4 29.3	Sn 3.72 30	Sb	Te	I	Xe
Cs	Ba	La 6.0 110				Re 1.4 20	Os 0.655 16.5	Ir 0.14 1.9	Pt	Au	Hg 4.153 41	Tl 2.39 17	Pb 7.19 80	Bi	Po	At	Rn

Fe
(iron)
T_c=1K
(at 20GPa)

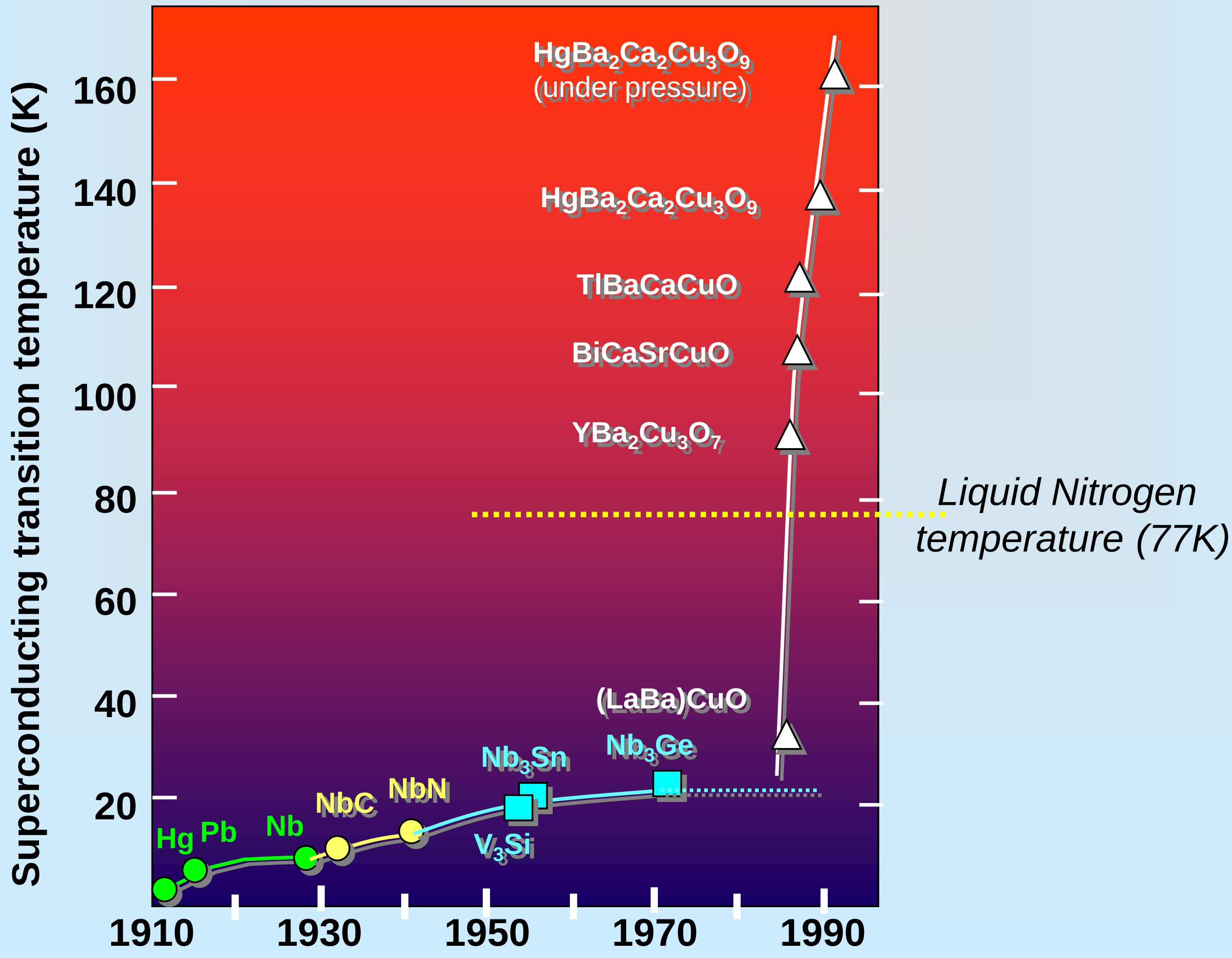
Nb
(Niobium)
T_c=9K
H_c=0.2T

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

11. What is critical temperature of superconductor? How large it could be?

...or so we thought until 2001

Superconductivity in alloys and oxides

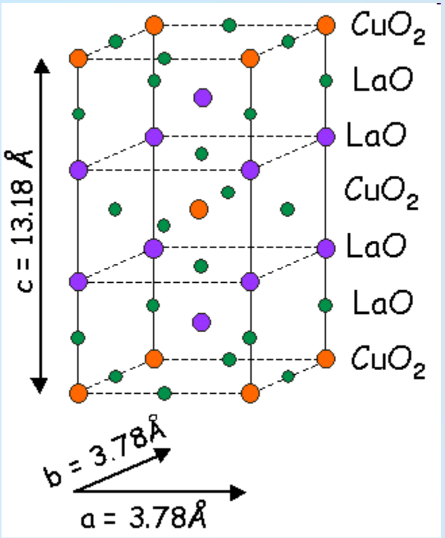


New materials, new discoveries ...

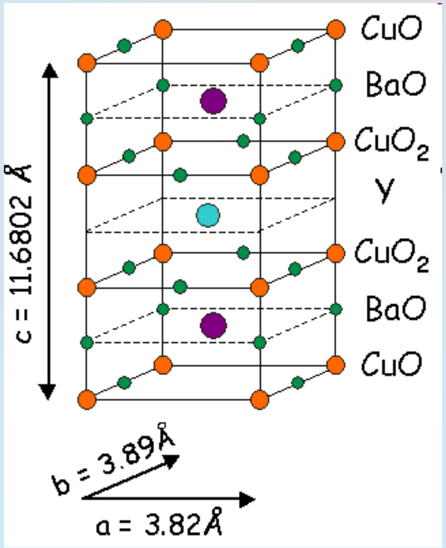
High-T_c superconductors

Alex Müller
Georg Bednorz

1987



$La_{2-x}Sr_xCuO_2$



YBCO

Mechanisms are still under discussion

Magnetic field penetration in YBCO film

13. What is high temperature superconductivity? When it was discovered? In what materials does it take place?

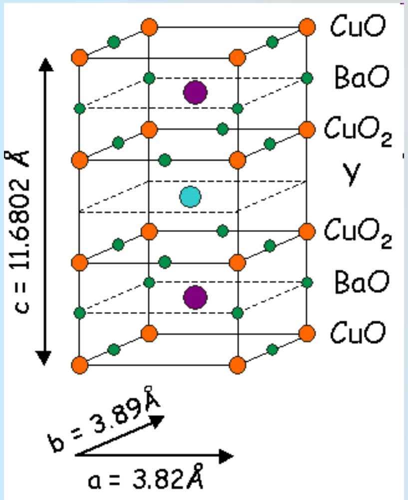
YBCO - Jim Ashburn (at the University of Alabama in Huntsville)

Discovery of YBCO

First-Hand:Discovery of Superconductivity at 93 K in YBCO: The View from Ground Zero

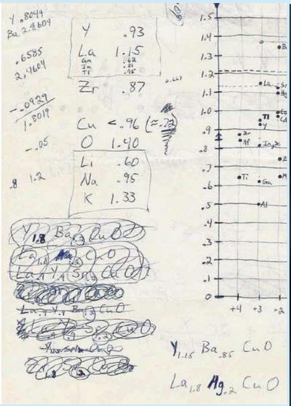
1987

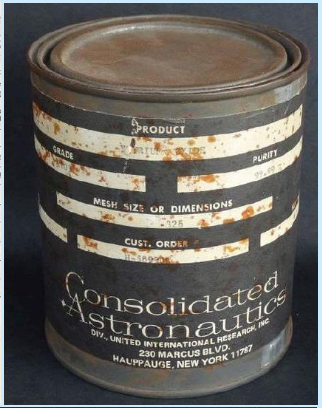
Jim Ashburn



$YBa_2Cu_3O_{7-x}$

A photo from the fall of 1987 showing from left to right: Pei-Herng Hor (Houston), Ruling Meng (Houston), Laura Greene (AT&T Bell Labs), Jim Ashburn (Huntsville), Maw-Kuen Wu (Huntsville), and Ching-Wu "Paul" Chu (Houston).





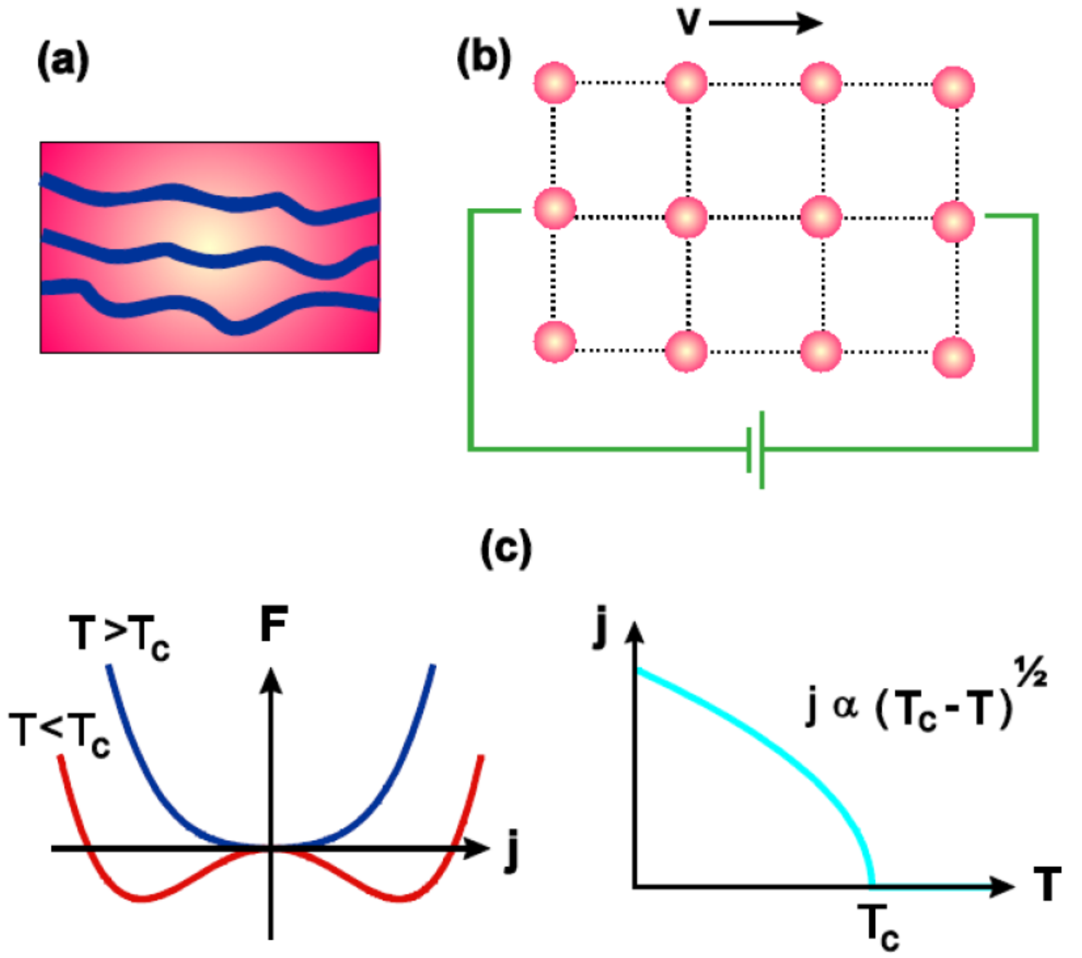
Can of Yttrium Oxide borrowed from Ed Ethridge, NASA Space Sciences Lab.

...the event that attracted everyone's attention [came when] the story began to circulate that M. K. Wu at the University of Alabama [in Huntsville] and Paul Chu at the University of Houston (Wu was one of Chu's former students) had found a superconducting copper oxide with a transition temperature of 90 K...

For those at least marginally familiar with some version of the YBCO discovery story, it will quickly become obvious that what I relate below has very little in common with the most widely disseminated accounts (perhaps consistent with Cava's sentiment). Confined to the events having a causal relationship to finding the YBCO superconductor, the true story is, in fact, not particularly difficult to tell, as causality constrains us largely to a two-month period. It also can (and will) be corroborated with great precision by the evidence, and, unlike most accounts, is *not* one of brilliant scientists or their insightful vision (again in line with Cava's perspective). The "science" (if one can call it that) is dirty and ugly, fraught with mistakes, blunders, and failures – many of them, which are, in my understanding, the basis on which success is often achieved.

Failed theories of superconductivity

by Jörg Schmalian



(a) Sketch of Einstein's molecular conduction chains. (b) Kronig's electron crystal that was supposed to slide as a whole in an external electric field. (c) Landau's expansion of the free energy with respect to the equilibrium current.

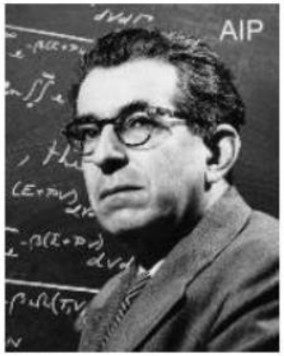
https://arxiv.org/ftp/arxiv/papers/1008/1008.0447.pdf

Failed theories of superconductivity

by Jörg Schmalian

John Bardeen
(1908-1991)

Werner Heisenberg
(1901-1976)



Fritz London
(1900-1954)

Max Born
(1882-1970)

Herbert Fröhlich
(1905-1991)

Richard Feynman
(1918-1988)

Between the second world war and the formulation of the BCS theory, unsuccessful attempts to formulate microscopic theories of superconductivity were made by Bardeen, Heisenberg, London, Born, Fröhlich, and Feynman.

https://arxiv.org/ftp/arxiv/papers/1008/1008.0447.pdf

UiO : University of Oslo

Theories of superconductivity

from Jörg Schmaian

The microscopic theory of superconductivity (**Bardeen–Cooper–Schrieffer**): **1957**. NP1972.

Albert Einstein(1922): "with our far-reaching ignorance of the quantum mechanics of composite systems we are very far from being able to compose a theory out of these vague ideas". His understanding of superconductivity was based on the concept of "molecular conduction chains" that carry supercurrents: "supercurrents are carried through closed molecular **chains** where electrons undergo continuous cyclic exchanges".

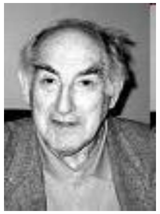
Joseph John Thompson(1915): fluctuating electric dipole **chains**.

Kamerlingh Onnes(1921): superconducting **filaments**.

Fröhlich(1953): a beautiful theory for **one dimensional system** with electron lattice coupling. Coherent excitations in biological systems known as Fröhlich coherence. Nominated for the Nobel Prize in Physics in 1963 and in 1964.

William Little(**1964**): model for **quasi one-dimensional superconductivity**.

https://arxiv.org/ftp/arxiv/papers/1008/1008.0447.pdf



Ginzburg-Landau Theory (1950)

$$F(T,M) = F(T,0) + a(T - T_{Cur})M^2 + bM^4 + c|\nabla M|^2$$

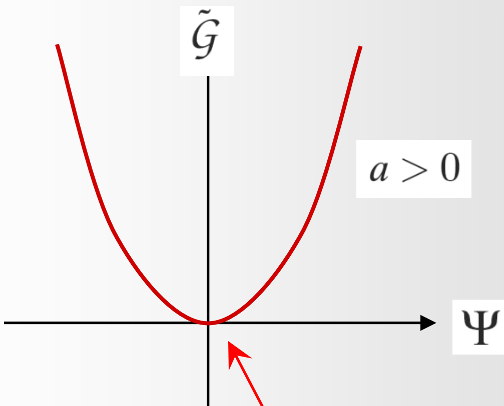
Order parameter? Hint: wave function of Bose condensate (complex!)

2003

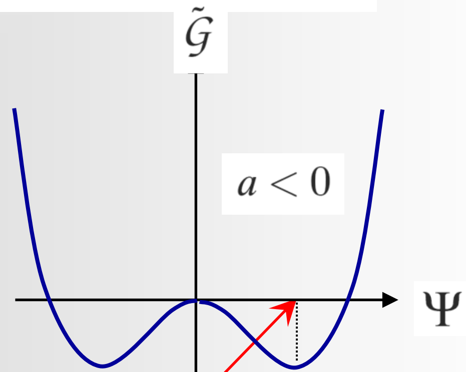
$|\Psi|^2 \ll 1$ ⇨

$$\mathcal{G}_s = \mathcal{G}_n + a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + \cdots.$$

1962



$$\tilde{\mathcal{G}} \equiv \mathcal{G}_s - \mathcal{G}_n$$



a should change the sign at the transition point

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

$$\begin{array}{ll} \Psi = 0 & \text{at} \quad T > T_c, \\ |\Psi|^2 = -(\alpha/b)\tau = |\Psi_0|^2 & \text{at} \quad T < T_c \end{array}.$$

Ukrainian institute of Physics and Technology, Kharkiv (former capital of Ukraine), 1934. Most scientists were 24-26 years old, the oldest 35 years old.

Lev Landau's office

https://www.pravda.com.ua/articles/2021/02/12/7283087/

Ukrainian institute of Physics and Technology, Kharkiv (former capital of Ukraine). March 10, 2022 - bombed and partially destroyed by Russian Military Forces after large-scale invasion on Ukraine early morning on February 24, 2022.

Lev Landau’s office

https://www.pravda.com.ua/articles/2021/02/12/7283087/

Microscopic mechanism

John Bardeen, Leon Cooper, and Robert Schrieffer

1972

Conventional mechanism – phonon-mediated attraction

‘The electrons are bound into Cooper pairs… Therefore, in order to break a pair, one has to change energies of all other pairs. This means there is an energy gap for single-particle excitation, unlike in the normal metal (where the state of an electron can be changed by adding an arbitrarily small amount of energy). The energy gap is most directly observed in tunnelling experiments and in reflection of microwaves from superconductors.’

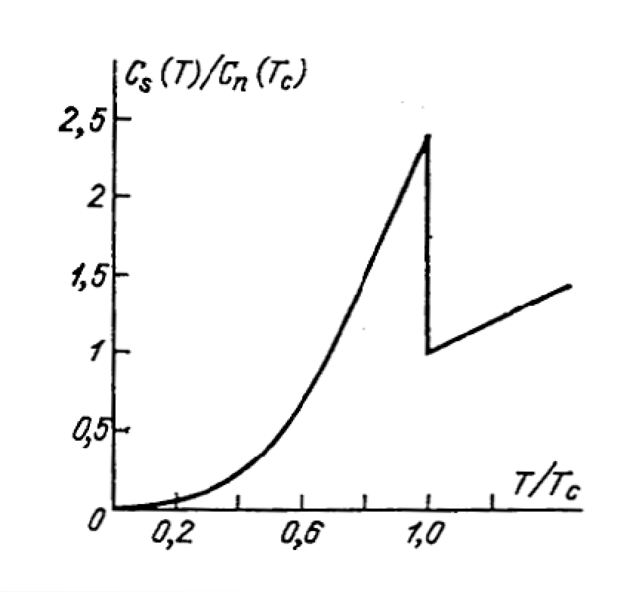
‘The theory describes superconductivity as a microscopic effect caused by a condensation of Cooper pairs into a boson-like state. The theory is also used in nuclear physics to describe the pairing interaction between nucleons in an atomic nucleus.’

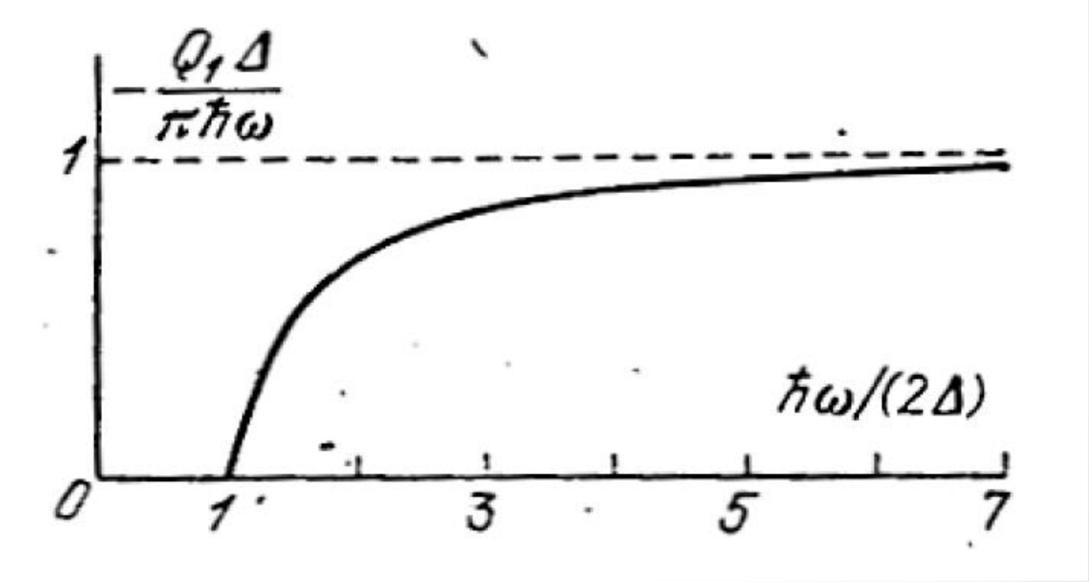
https://en.wikipedia.org/wiki/BCS_theory

12. What is the mechanism of superconductivity? Is it linked to Fermi or Bose statistics?

The gap in the quasiparticle energy spectrum leads to crucial consequences.

It is the gap that determines most of thermal, magnetic, and electrical properties of superconductors.





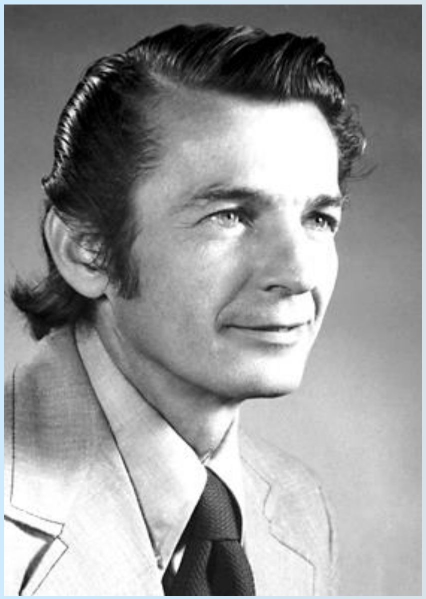
Specific heat

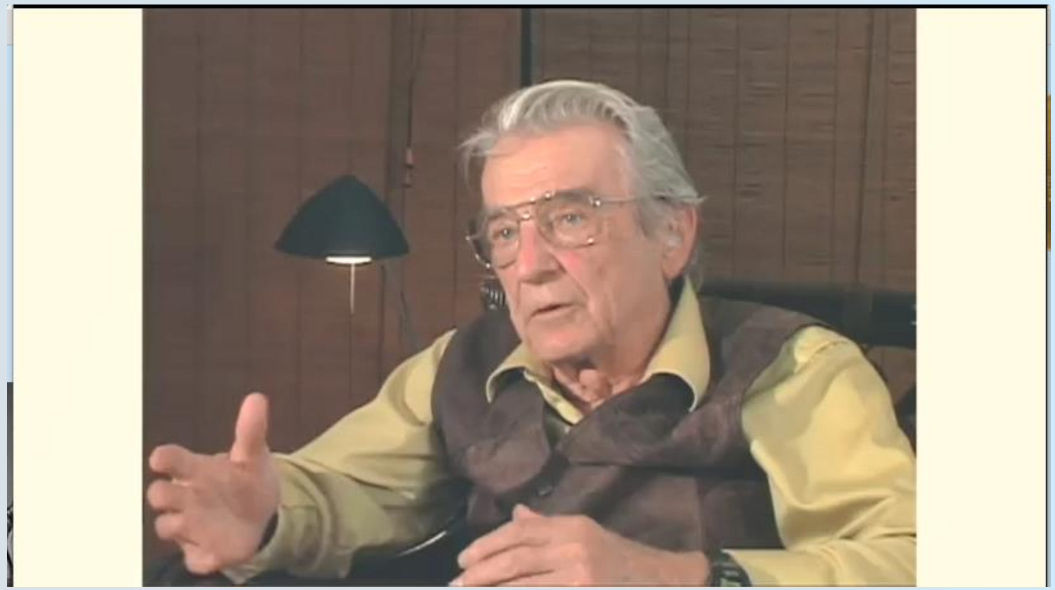
Microwave absorption

Tunneling effect

The Nobel Prize in Physics 1973
Leo Esaki, Ivar Giaever, Brian D. Josephson

1973





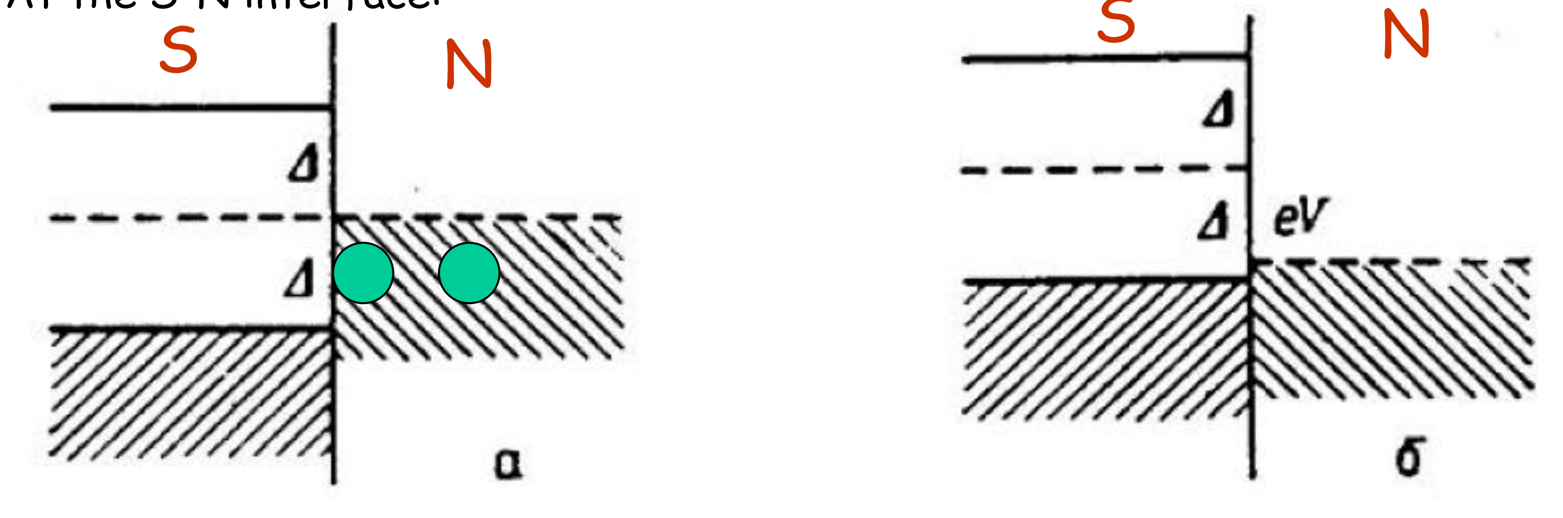
How Quantum Tunneling Works - by Ivar Giaever - YouTube

Ivar Giaever

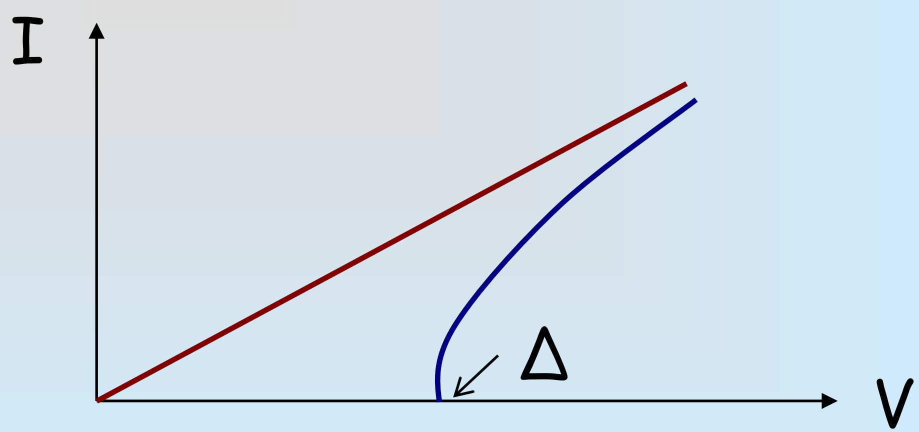
Prize motivation: "for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"
Field: condensed matter physics, semiconductors

Energy gap in superconductors

At the S-N interface:



No single-electron tunneling possible until $eV \leq \Delta$



3. Describe principle of tunnelling between superconductor and normal metal. What are the implications of this nanoscale phenomenon? What could be role of spin in this process?

http://www.iggl.no/

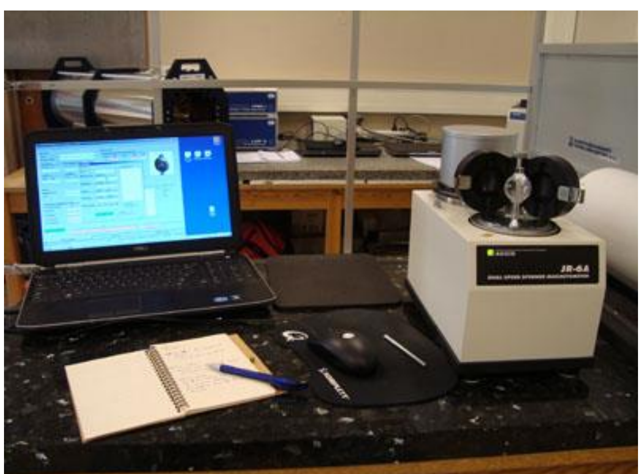
IGGL

Ivar Giæver Geomagnetic Laboratory

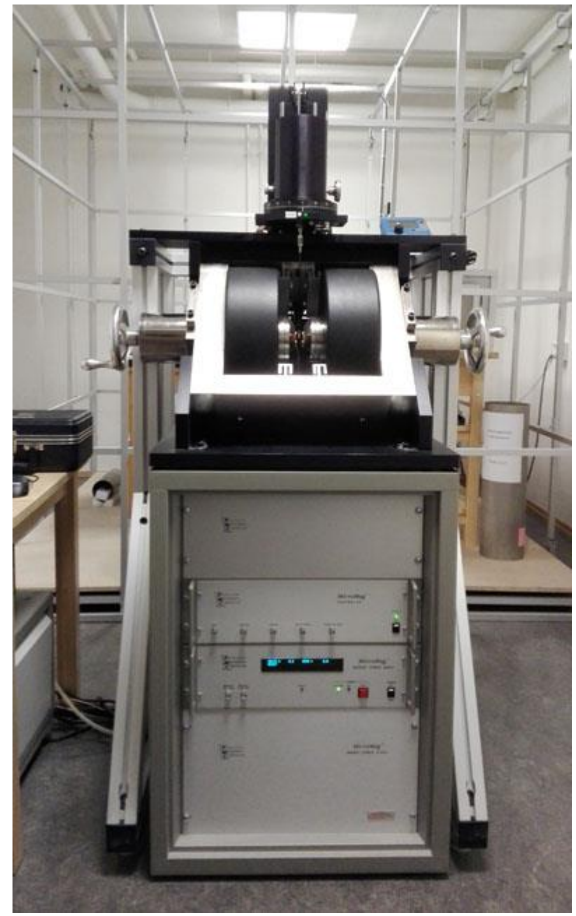
http://www.mn.uio.no/geo/om/aktuelt/aktuelle-saker/2016/geomagnetisme.html

Official opening on 7 September 2016

Instruments for Paleomagnetic Measurements and Rock Magnetic Analyses



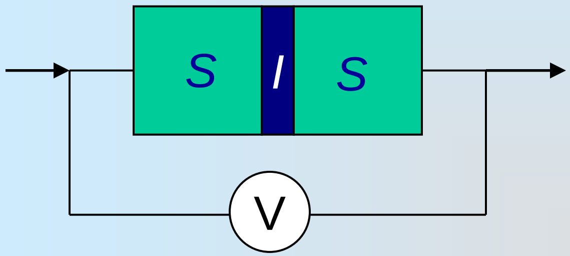
AGICO JR-6A Spinner Magnetometer



Lake Shore PMC MicroMag 3900
Vibrating Sample Magnetometer (VSM)

Josephson effects

Is it possible to convey Cooper pairs between superconductors?



Weak link – two superconductors divided by a thin layer of insulator or normal conductor

What is the resistance of the junction?

For small currents, the junction is a superconductor!

Reason – order parameters overlap in the weak link

1973

B. Josephson

8. Describe stationary Josephson Effect. What kind of tunnelling does it represent? What is its nature and what does its amplitude depend on? How is Josephson Effect linked with the phase of the order parameter of superconductor?

UiO : University of Oslo

Superconductivity

$$\Psi(\mathbf{r}) = \frac{1}{\sqrt{2}}\sqrt{n_s(\mathbf{r})}\,\mathrm{e}^{i\theta(\mathbf{r})}$$

$$\mathbf{J} = -\left(\frac{e\hbar n_s}{2m}\right)\boldsymbol{\nabla}\theta - \left(\frac{n_s e^2}{mc}\right)\mathbf{A}$$

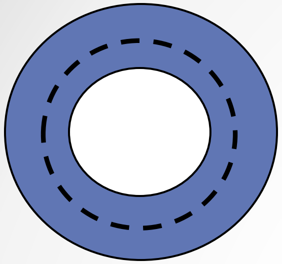
$$\frac{\partial\theta}{\partial t} = \frac{2e}{\hbar}V$$

$$\omega_j = \frac{2e}{\hbar}V$$

$$\theta = kx = \frac{px}{\hbar} = \frac{Et}{\hbar} = \frac{2eVt}{\hbar}$$

The Nobel Prize in Physics 1933 was awarded jointly to Erwin Schrödinger and Paul Adrien Maurice Dirac "for the discovery of new productive forms of atomic theory."

Quantization of magnetic flux:



Long hollow cylinder

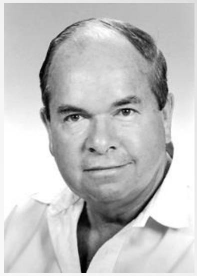
The current inside is zero

$$\Psi = |\Psi| e^{i\chi}$$

$$|\Psi| = \text{const} \Rightarrow \mathbf{j} = -\frac{e\hbar}{m}|\Psi|^2\left[\nabla\chi + \frac{2e}{\hbar c}\mathbf{A}\right]$$

$$\underbrace{\oint \frac{\mathbf{j}}{|\Psi|^2} d\mathbf{l}}_{0} = -\frac{e\hbar}{m}\left[\underbrace{\oint \nabla\chi\, d\mathbf{l}}_{-2\pi k} + \frac{2e}{\hbar c}\underbrace{\oint \mathbf{A}\, d\mathbf{l}}_{\text{flux}}\right]$$

$$\Phi = k\Phi_0, \quad \Phi_0 = \pi\hbar c/e = 2.07\cdot 10^{-7}\,\text{G}\cdot\text{cm}^2.$$

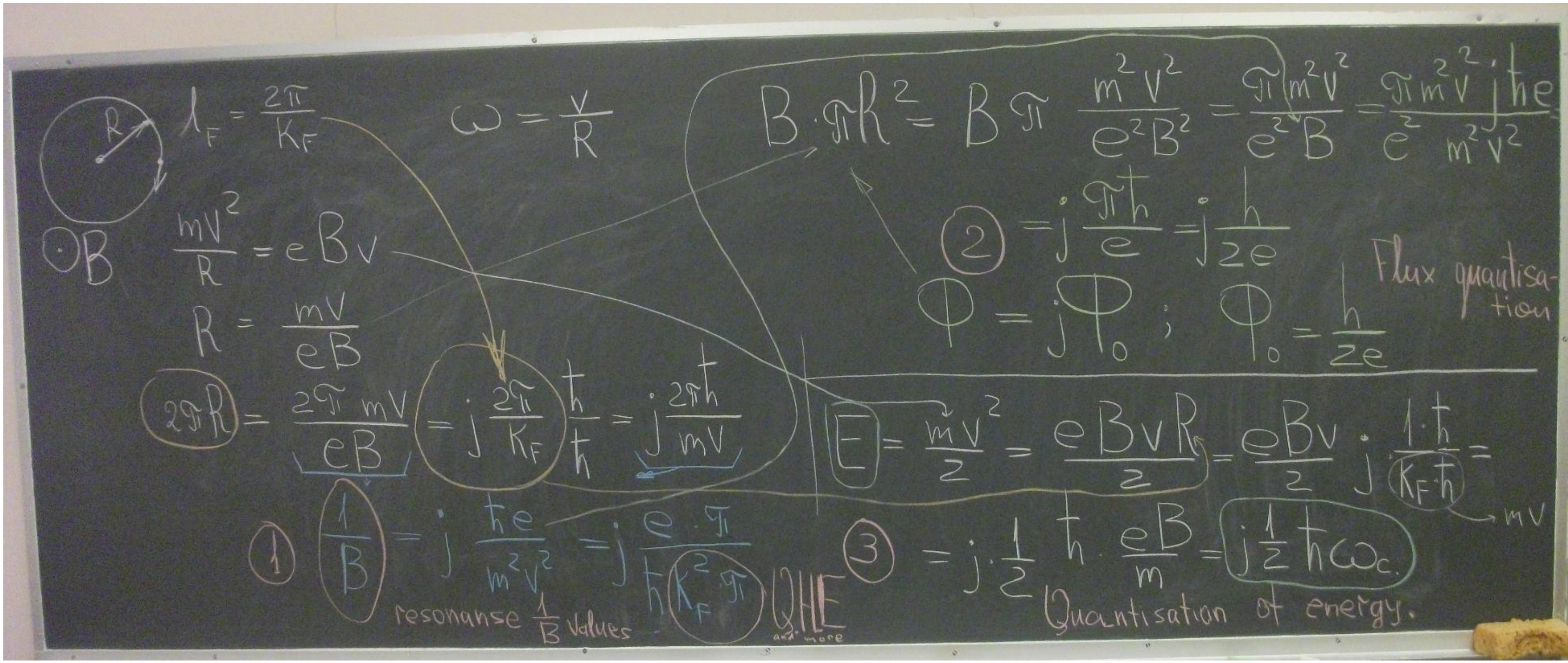


Alexei A. Abrikosov

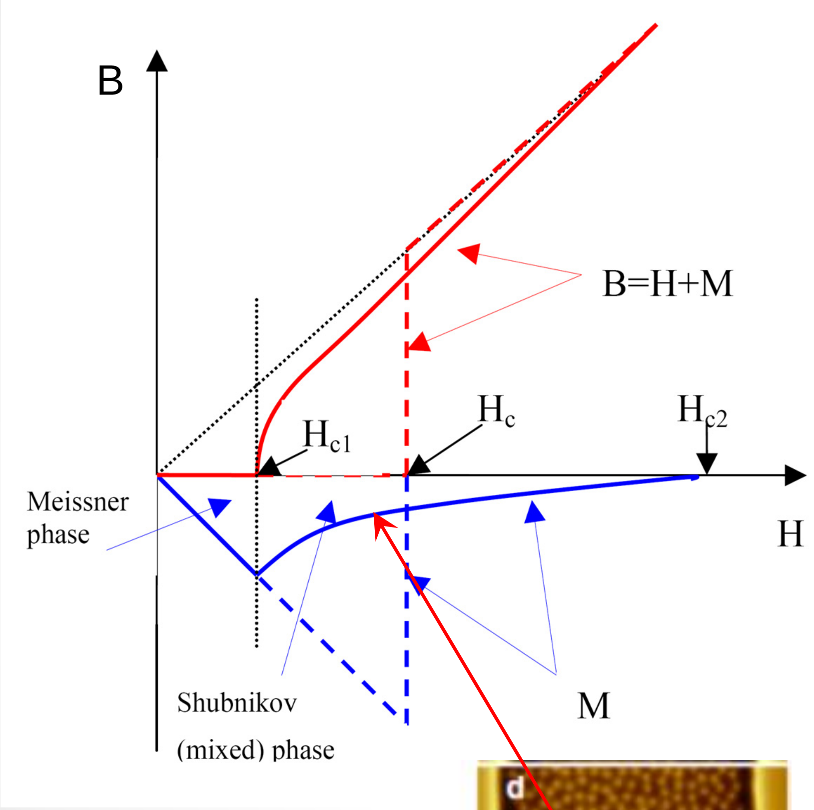
2003

http://en.wikipedia.org/wiki/SQUID

Landau quantization and it's consequences



Type II superconductors



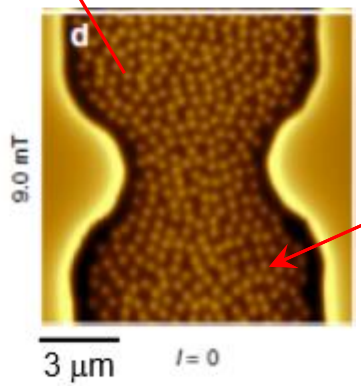
Dashed lines – type I superconductor

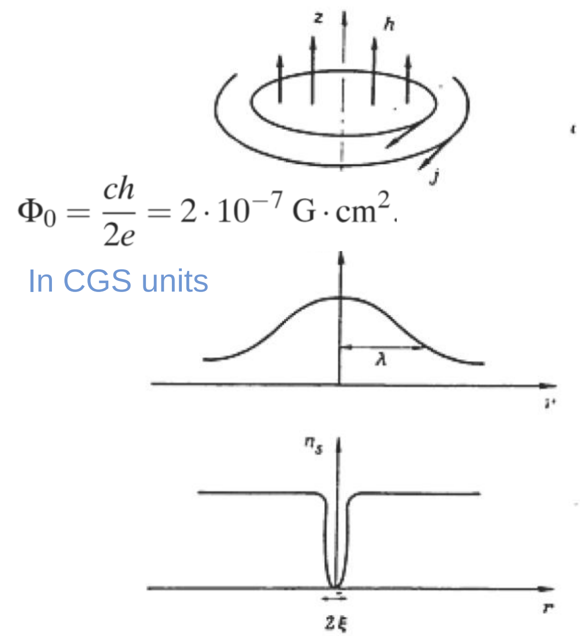
Solid lines – type II superconductor

In type II superconductors the Meissner effect in incomplete in the region

$H_{c1} < H < H_{c2}$

$\Phi_0 = h/(2e) \approx 2.067833758(46)\times10^{-15}$ Wb





Vortex lattice

A. A. Abrikosov

2003

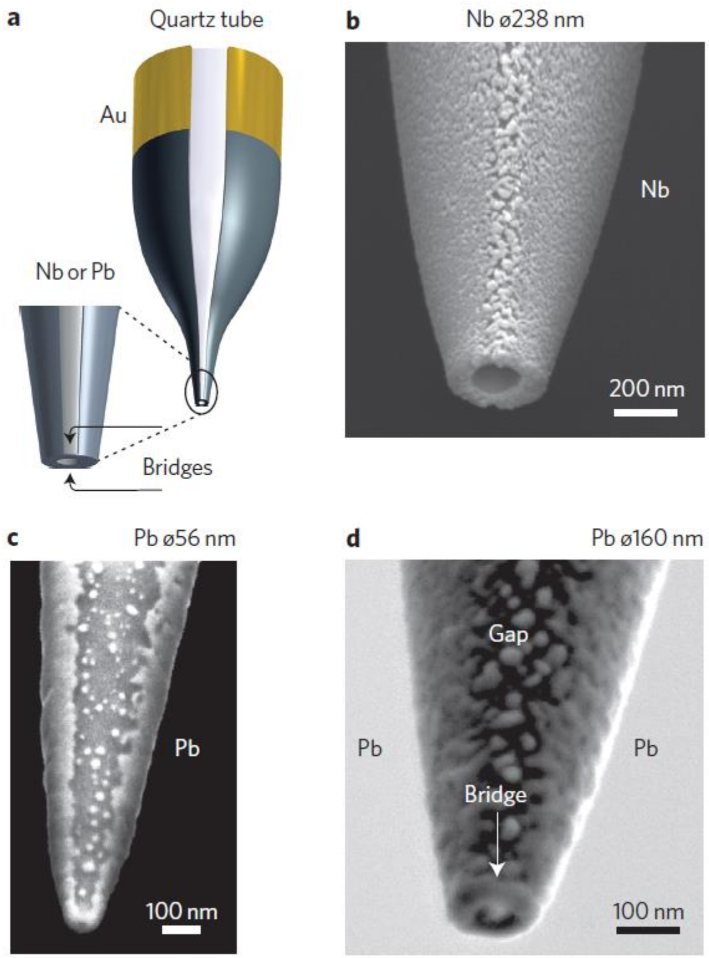
https://www.nature.com/articles/s41467-017-00089-3

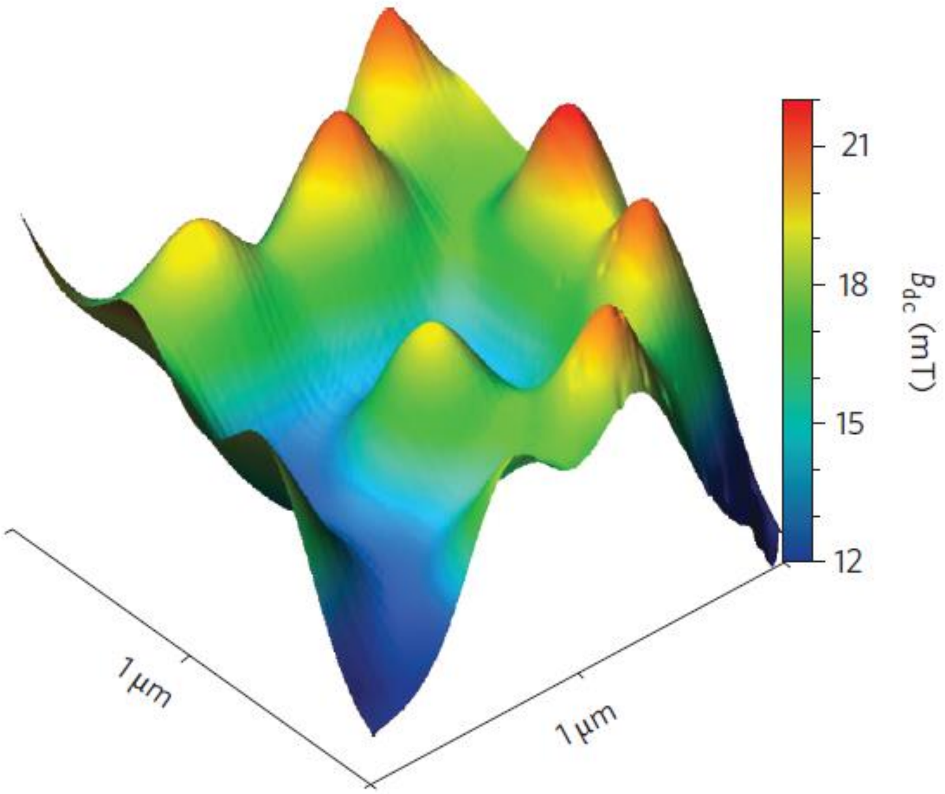
7. What are first and second critical fields of superconductor? Are they related to quantization of magnetic flux?

Nano SQUID on tip (SOT)

NATURE NANOTECHNOLOGY | VOL 8 | SEPTEMBER 2013 |

Weizmann Institute of Science, Department of Condensed Matter Physics, Rehovot 76100, Israel, Department of Physics, University of Colorado Denver, Denver, Colorado 80217, USA





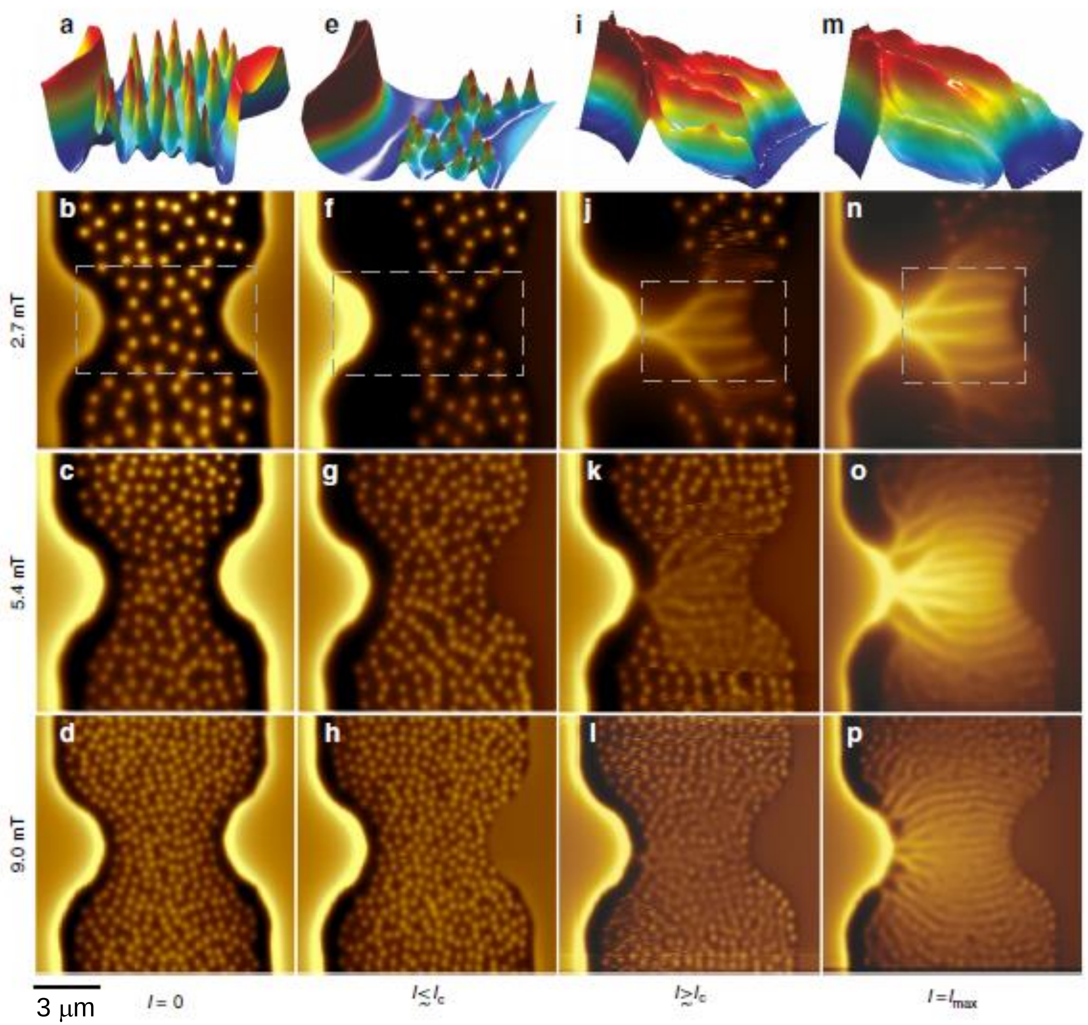
SEM images of SOT devices.

Scanning SOT microscopy images of vortex matter.

Imaging of super-fast dynamics and flow instabilities of superconducting vortices

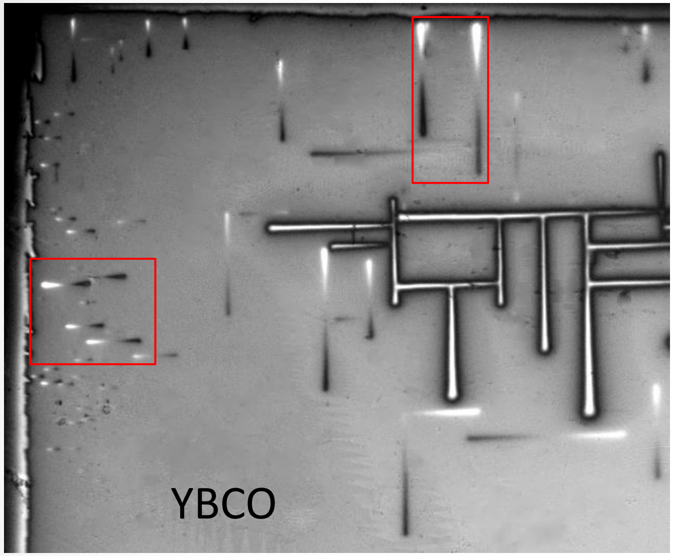
NATURE COMMUNICATIONS 2017

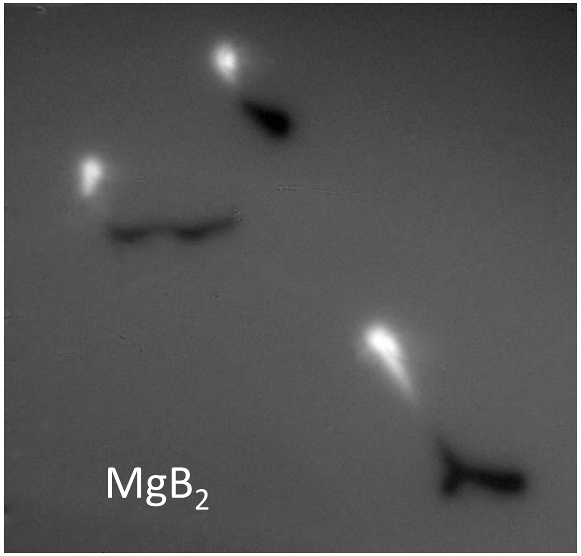
Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 7610001, **Israel**, The Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 9190401, **Israel**, Departement Fysica, Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, **Belgium**, Département de Physique, Université de Liège, B-4000 Sart Tilman, **Belgium**, Departments of Physics and Electrical Engineering, University of Colorado Denver, Denver, Colorado 80217, **USA**, Verkin Institute for Low Temperature Physics & Engineering, Ukrainian Academy of Sciences, Kharkov 61103, **Ukraine**, Department of Physics, Old Dominion University, Norfolk, Virginia 23529-0116, **USA**.

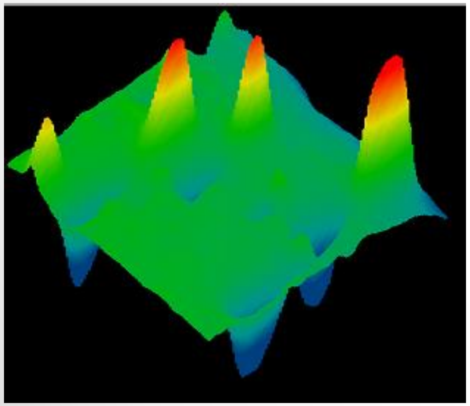


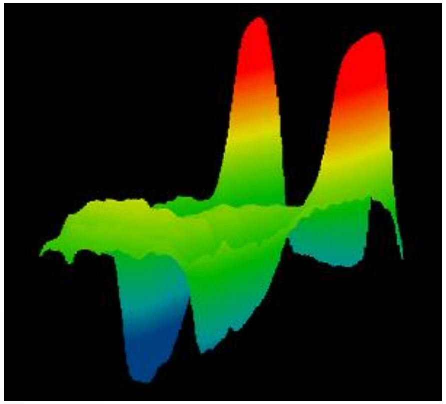
Magnetic imaging of stationary and fast moving vortices in Pb film at 4.2 K.

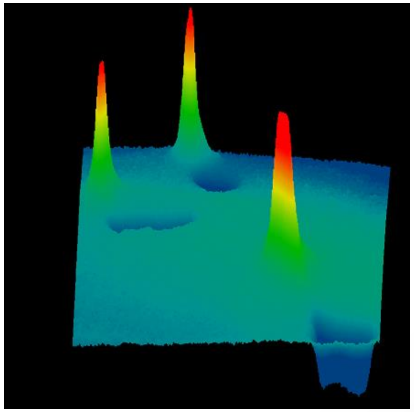
Magnetic flux penetration on intrinsic defects

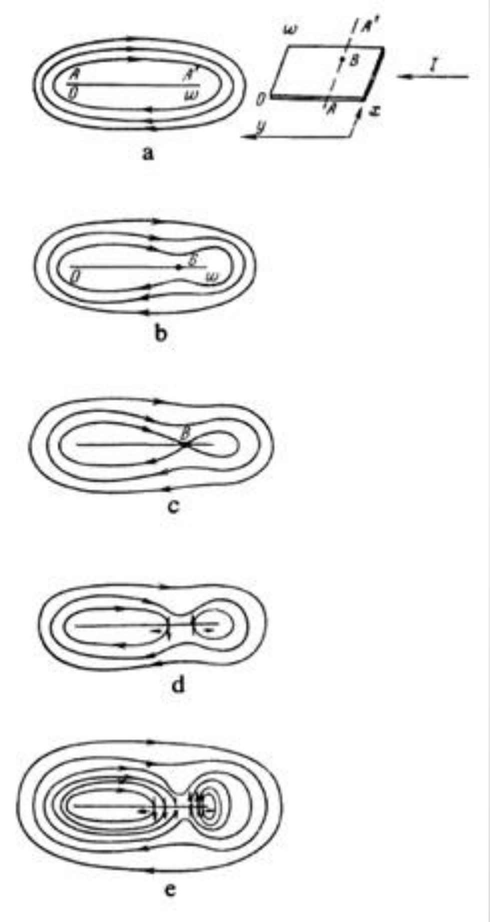








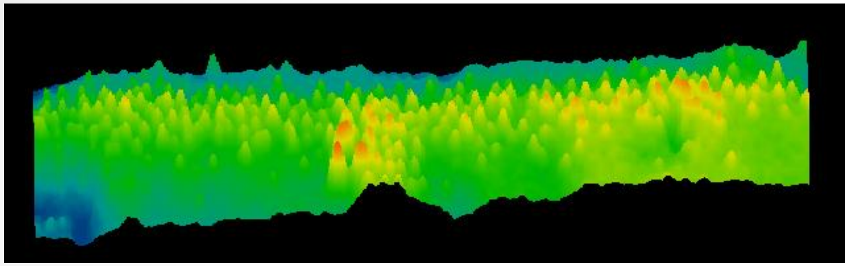


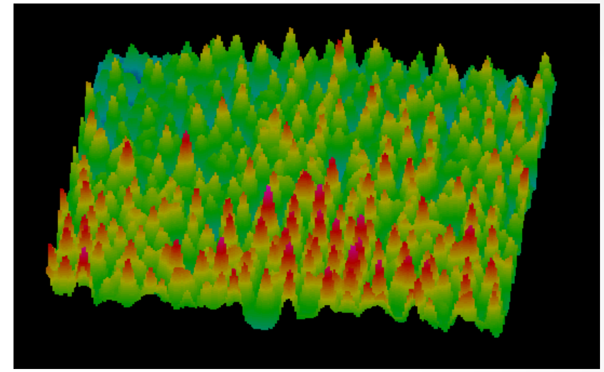


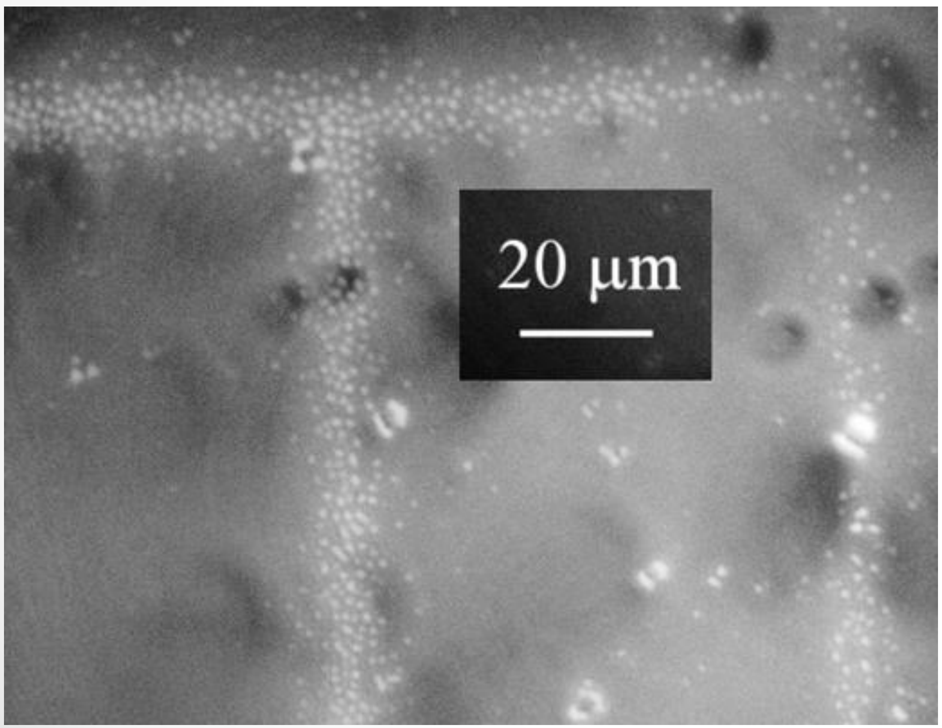
Yu. M. Ivanchenko and P. N. Mikheenko, New mechanism of penetration of vortices into current-saturated superconducting films, Zh. Eksp. Teor. Fiz. 85,2116-2127 (1983)

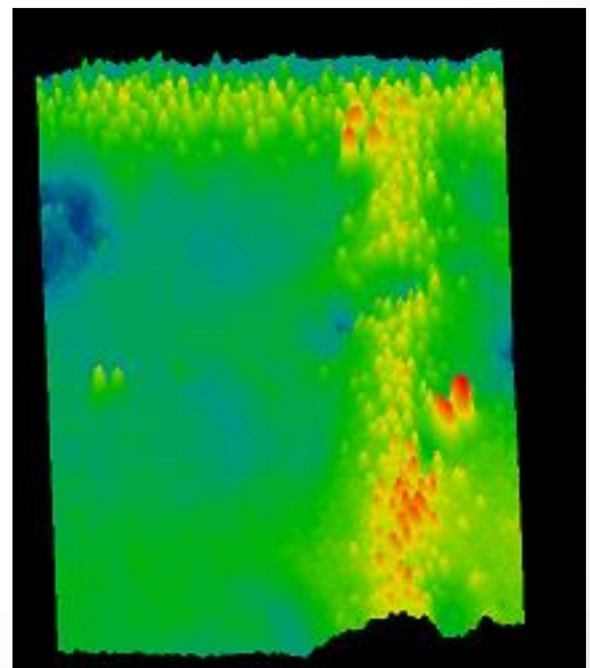
UiO University of Oslo | UNIVERSITY OF CAMBRIDGE | UNIVERSITY OF BIRMINGHAM | JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

Single vortex imaging in $YBa_2Cu_3O_x$ films



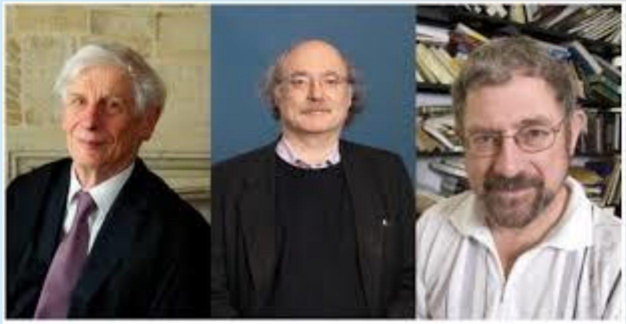




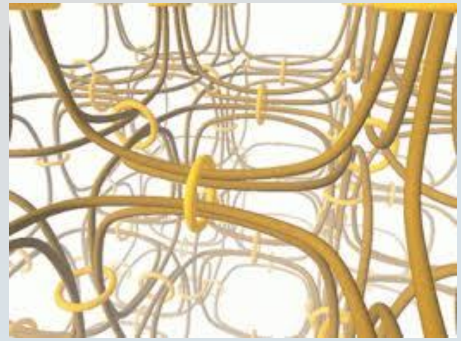


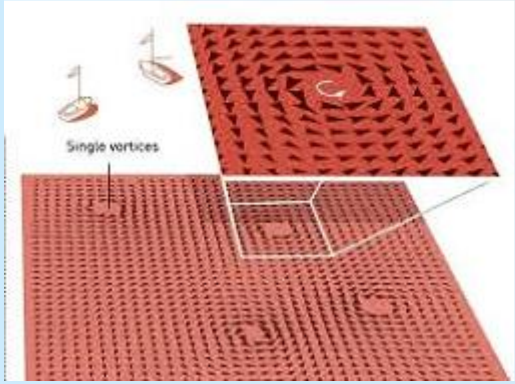
Channels in YBCO can be used for imaging of individual vortices.

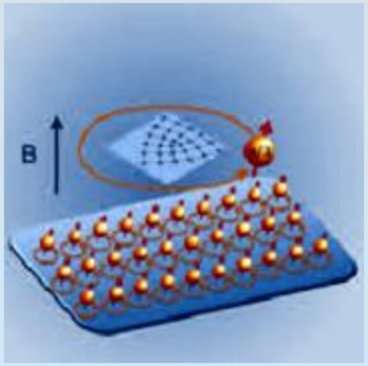
Physics Nobel Prize 2016 for topological phase transitions and topological phases of matter

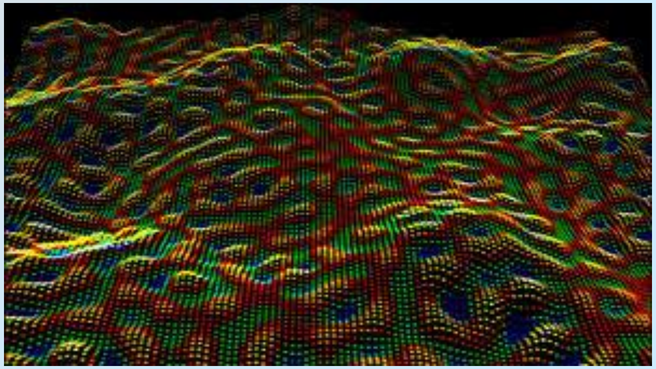


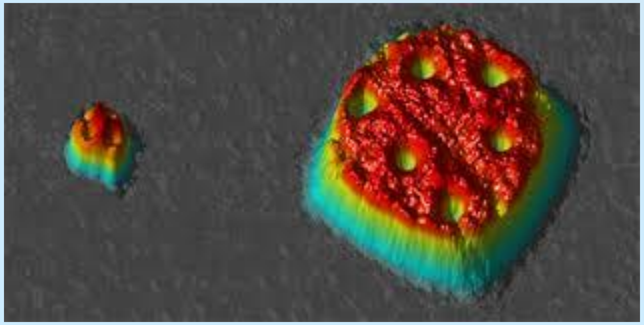
David Thouless, Duncan Haldane and Michael Kosterlitz

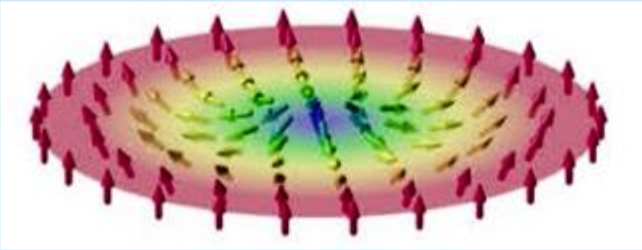


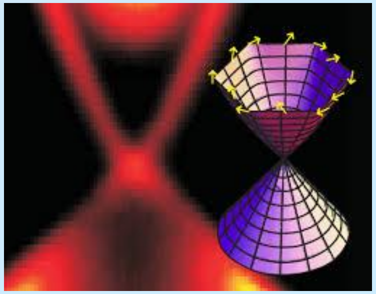










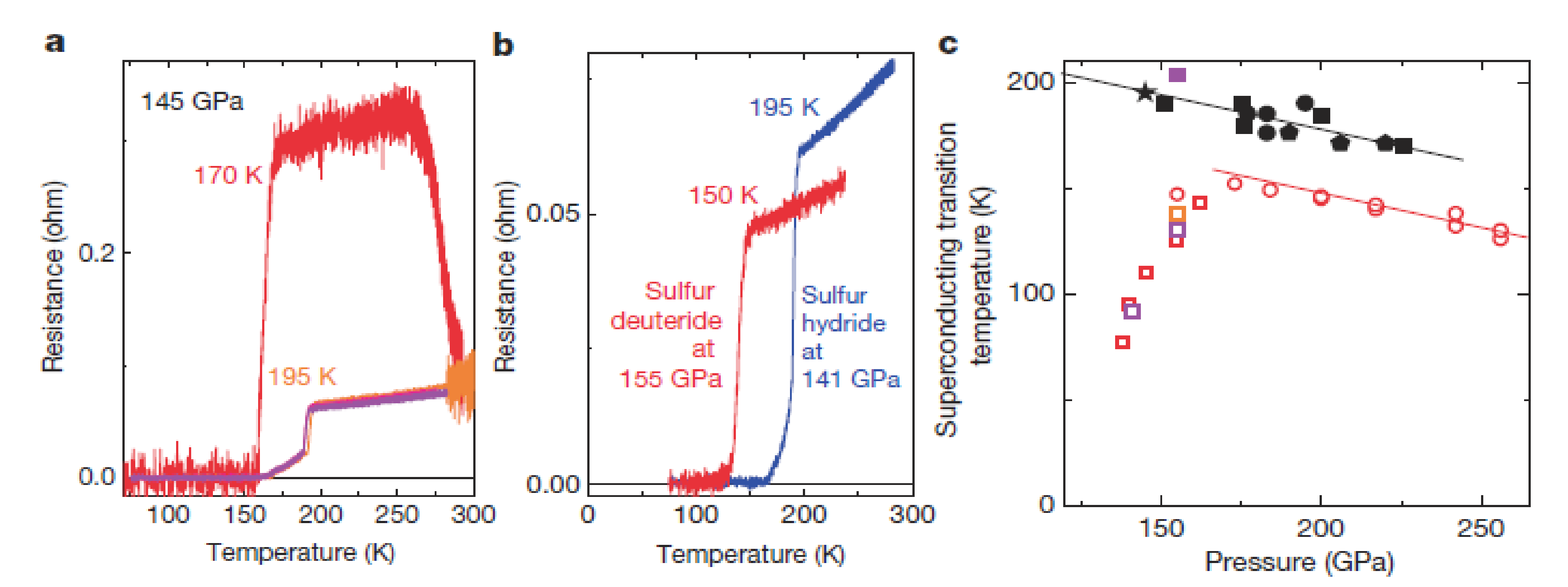


Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

doi:10.1038/nature14964
2015

A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

[1]Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128 Mainz, Germany. [2]Institut für Anorganische Chemie und Analytische Chemie, Johannes Gutenberg-Universität Mainz, Staudingerweg 9, 55099 Mainz, Germany.



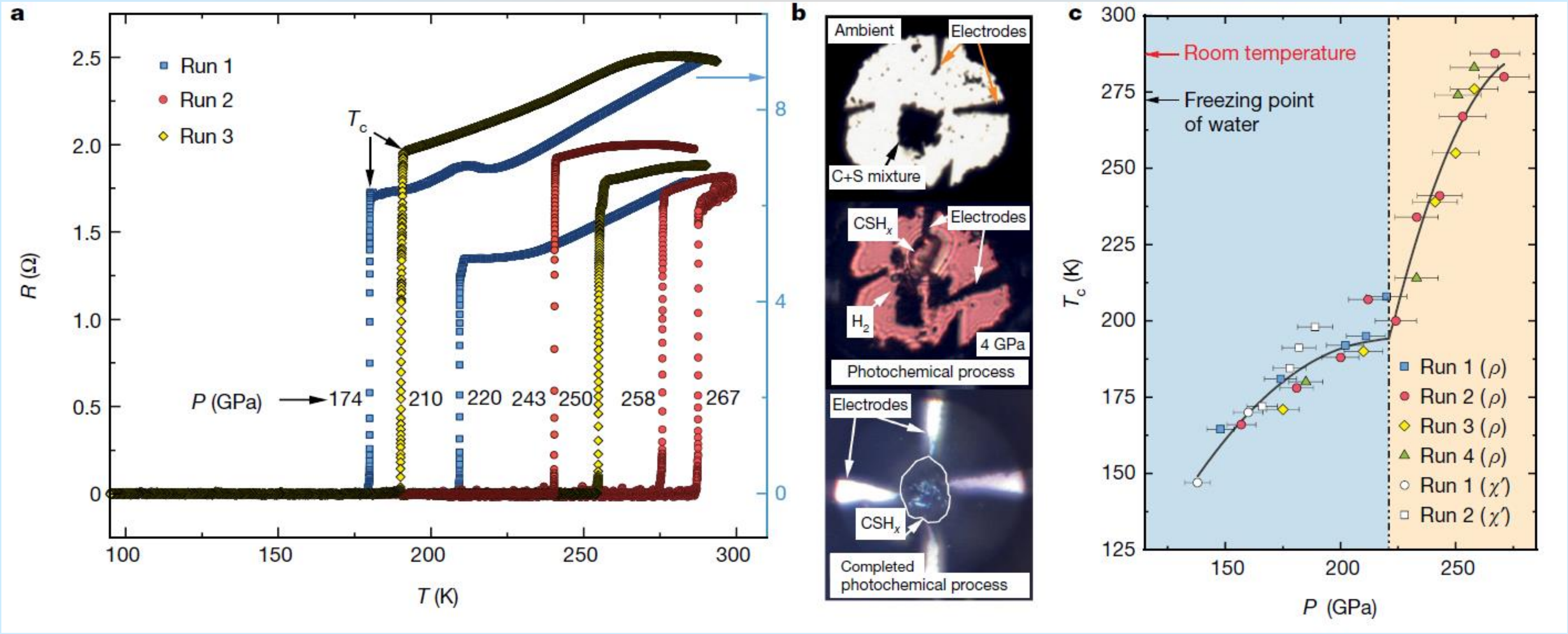
Room-temperature superconductivity in a carbonaceous sulfur hydride

Nature | Vol 586 | 15 October 2020 | **373**

Elliot Snider, Nathan Dasenbrock-Gammon, Raymond McBride, Mathew Debessai, Hiranya Vindana, Kevin Vencatasamy, Keith V. Lawler, Ashkan Salamat & Ranga P. Dias

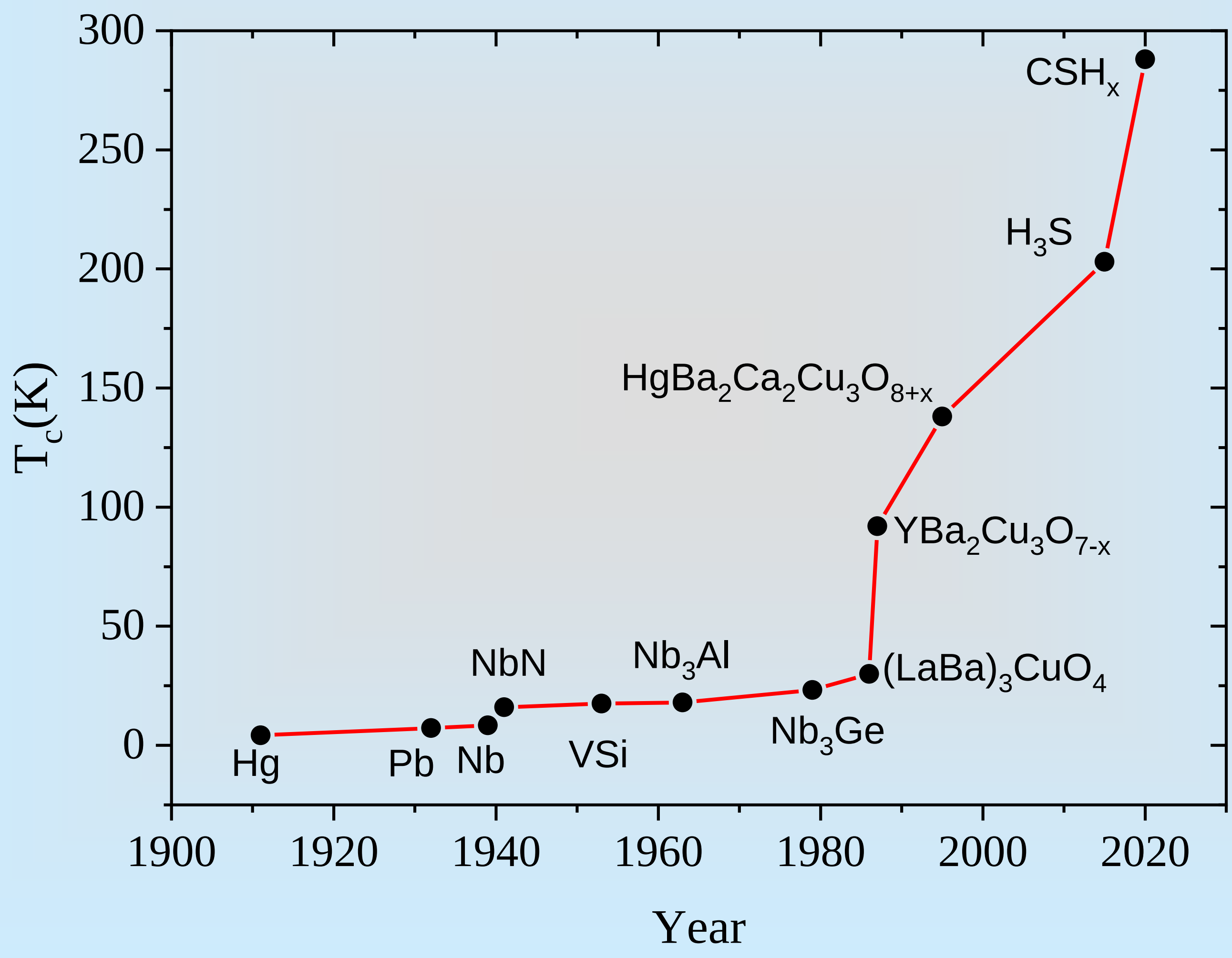
University of Rochester, Intel Corporation, University of Nevada, USA

Here we report superconductivity in a photochemically transformed carbonaceous sulfur hydride system, starting from elemental precursors, with a maximum superconducting transition temperature of 287.7 ± 1.2 kelvin (about 15 degrees Celsius) achieved at 267 ± 10 gigapascals. The superconducting state is observed over a broad pressure range in the diamond anvil cell, from 140 to 275 gigapascals, with a sharp upturn in transition temperature above 220 gigapascals.

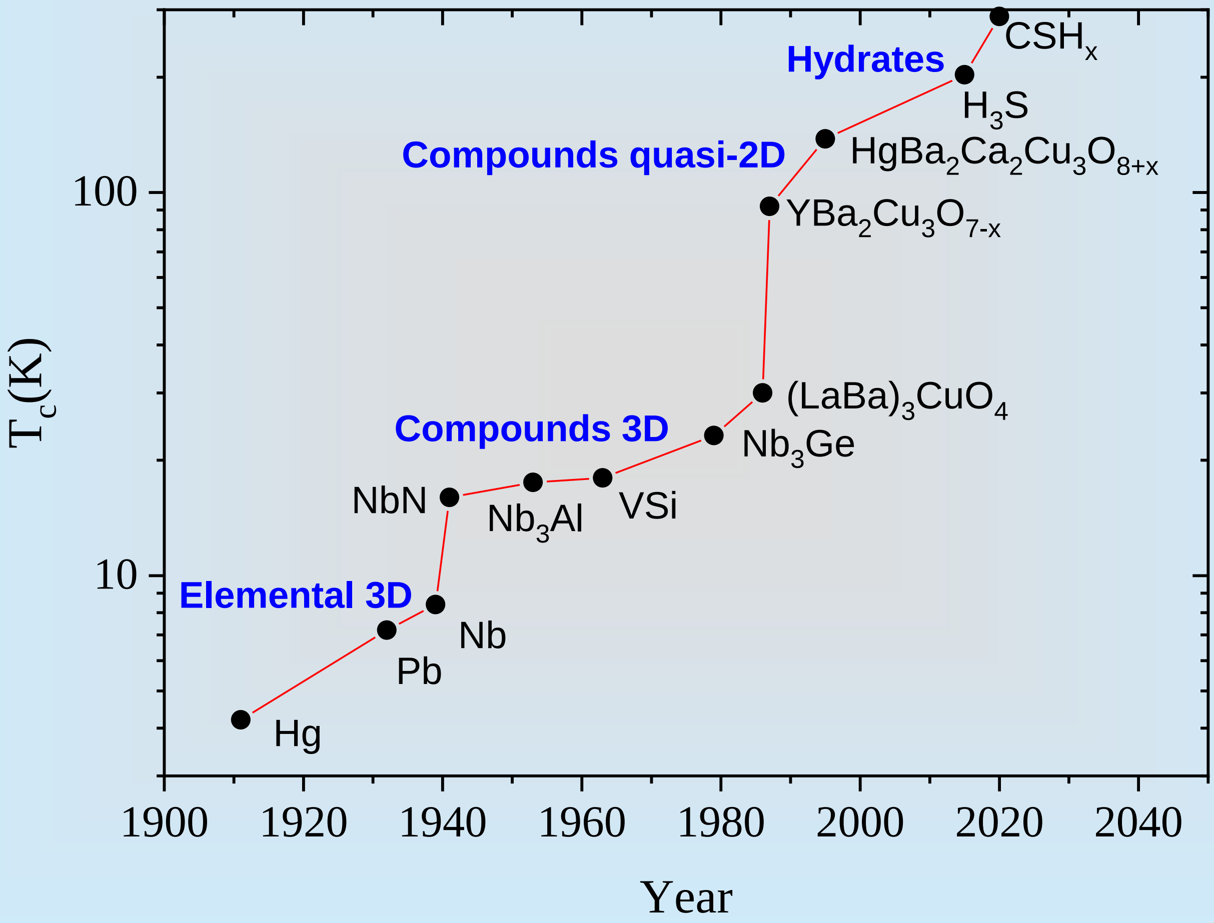


UiO : University of Oslo

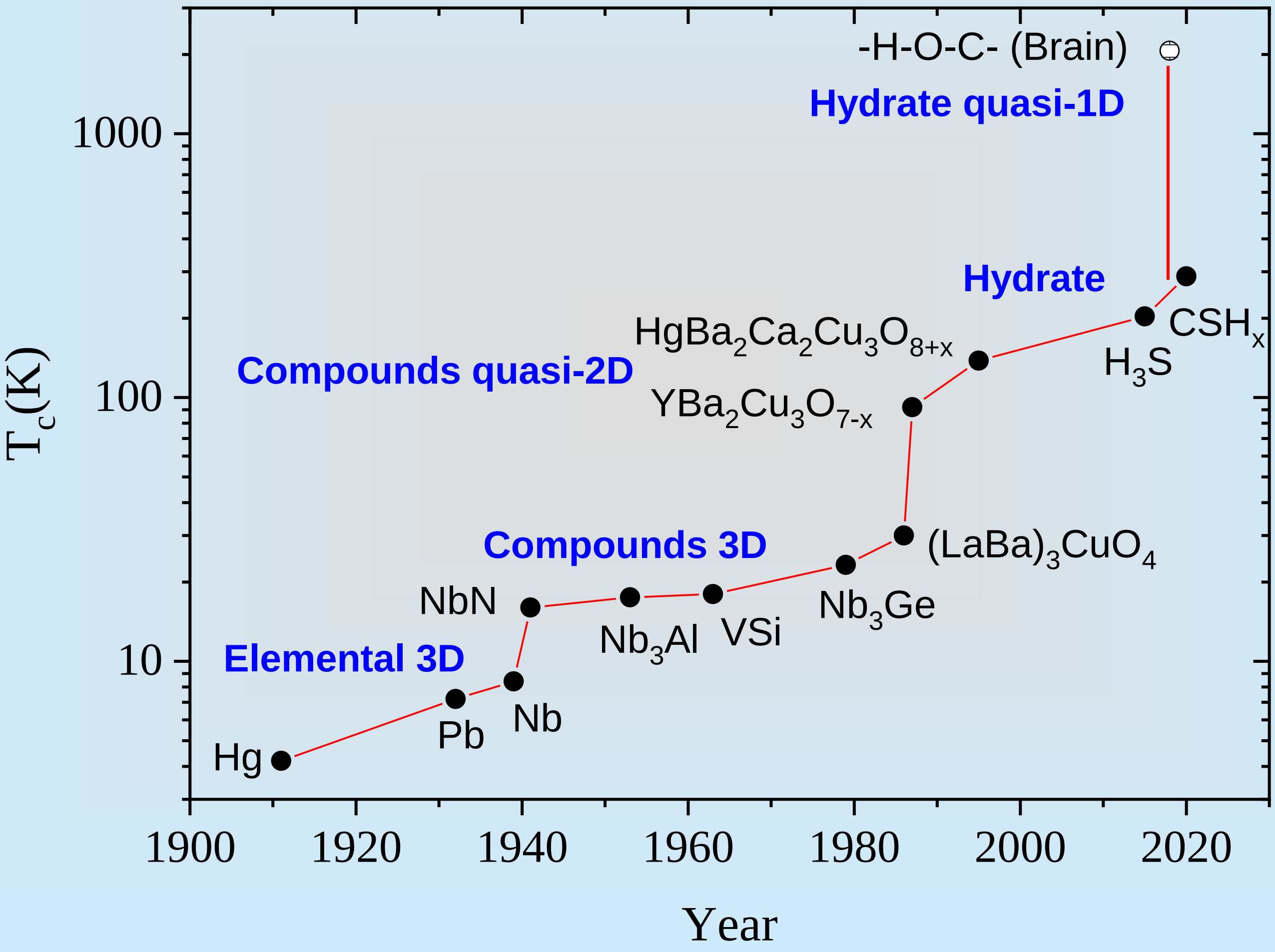
Critical temperature of superconductors



Critical temperature of superconductors



Critical temperature of superconductors



UiO : University of Oslo

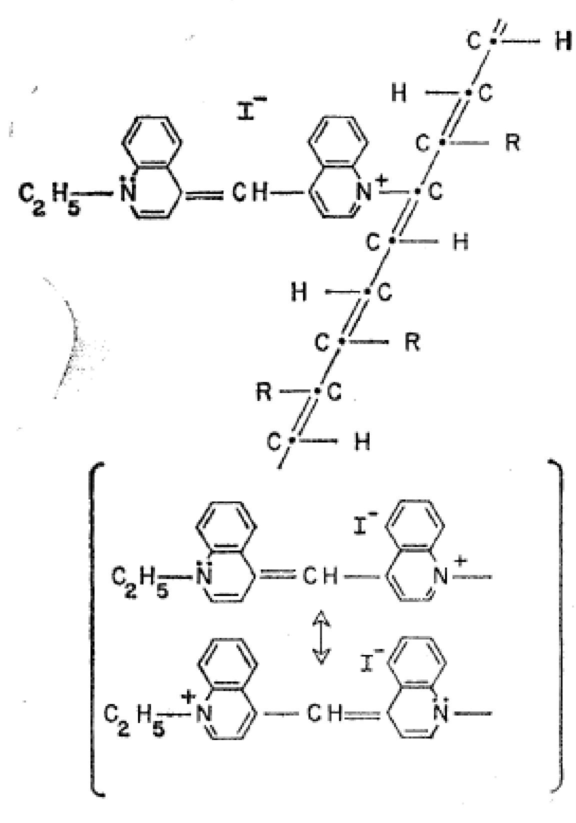
Quasi-1D superconductivity

PHYSICAL REVIEW VOLUME 134, NUMBER 6A 15 JUNE 1964

Possibility of Synthesizing an Organic Superconductor*

W. A. LITTLE
Department of Physics, Stanford University, Stanford, California

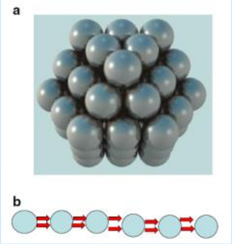
(Received 13 November 1963; revised manuscript received 27 January 1964)



If there was no bond localization in the spine, then we could use Eq. (2.9) to estimate the superconducting transition temperature using (4.3) and the above density of states. One obtains a temperature $\approx 2200°$K in this case! This extremely high transition temperature can be understood when it is realized that in the chosen structure it is an electronic oscillation which provides the coupling between the electrons rather than the oscillation of the nuclei as in a conventional superconductor. The simple argument of the isotope effect that the transition temperature for a phonon-coupled superconductor is proportional to $1/M^{1/2}$, where M is the isotopic mass of the nuclei indicates that for an electron-coupled superconductor the transition temperature should be a factor of $(M/m)^{1/2}$ (i.e., ≈ 300) times larger. This is, perhaps, too glib an answer for it is necessary to choose the over-all structure so as to obtain a sufficiently strong coupling matrix element (2.6). Our particular model illustrates this in detail.

J Supercond Nov Magn (2018) 31:611–617

Paths to Room-Temperature Superconductivity, Vladimir Z. Kresin



Nanosystems

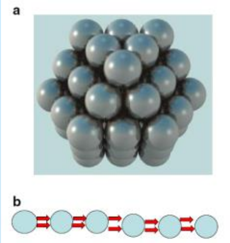
'The first experimental observation of the high-T_c superconducting state in metallic nanoclusters was described in [31, 32]. With the use of photoionization measurements, the authors [31, 32] have observed the spectral manifestation of the pair correlation… One should stress that the effect is not universal and has been observed in some selected clusters only. Especially interesting is that the phenomenon was observed for Al_{66} clusters, in agreement with theoretical prediction (see above). The value of the critical temperature, $T_c \approx 120$ K (!), greatly exceeds that for usual bulk Al ($T_c \approx 1.2$ K). Such a large increase is caused by the shell effect.'

'One should note that the shell effect is a special case of the size quantization of the electronic energy spectrum, which is manifested in thin films and nanoparticles. This effect leads to an increase in the density of states and, subsequently, to an increase in T_c.'

31. Halder, A., et al.: Nano Lett. **15**, 1410 (2015)
32. Halder, A., Kresin, V.V.: Phys. Rev. B **92**, 214506 (2015)

J Supercond Nov Magn (2018) 31:611–617

Paths to Room-Temperature Superconductivity, Vladimir Z. Kresin



Interface Superconductivity

‘The phenomenon of interface superconductivity (see [43–47]) usually describes the superconducting state occurring at the interface of two materials, which are not superconducting and even not metallic (see reviews [45–47]). As a result, we are dealing with 2D superconductivity;.. As for the mechanism of the pairing, one can expect that it is provided by phonons or by electronic excitations (see above). **It is interesting that the behavior of the gap as a function of the charge carrier depletion turns out to be similar to that in the high-T_c cuprates.**

A special case is the interface formed by the insulating and normal metallic La-based cuprates [43]. This interface displays the superconducting state with values of Tc, which can reach 50 K.’

Conclusion

‘**One can state only that the phenomenon of room-temperature superconductivity is perfectly realistic and it will be observed in the near future.**’

43. Gozar, A., et al.: Nature 455, 782 (2008)

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

SPRINGER SCIENCE+
BUSINESS MEDIA, LLC 1972

SPECULATIONS OF SUPERCONDUCTIVITY IN BIOLOGICAL AND ORGANIC SYSTEMS*†

E. H. Halpern and A. A. Wolf

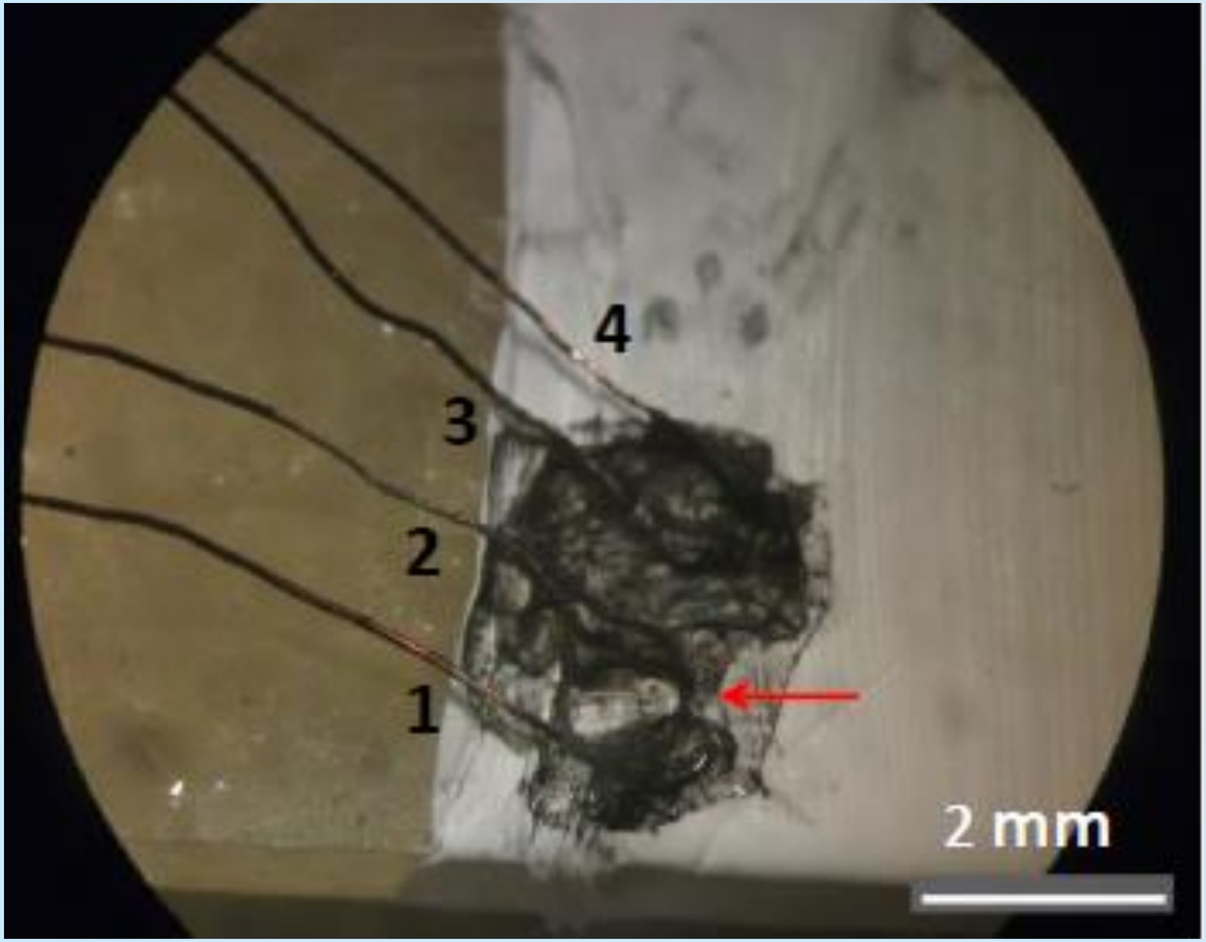
Naval Ship Research and Development Center
Annapolis, Maryland

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.

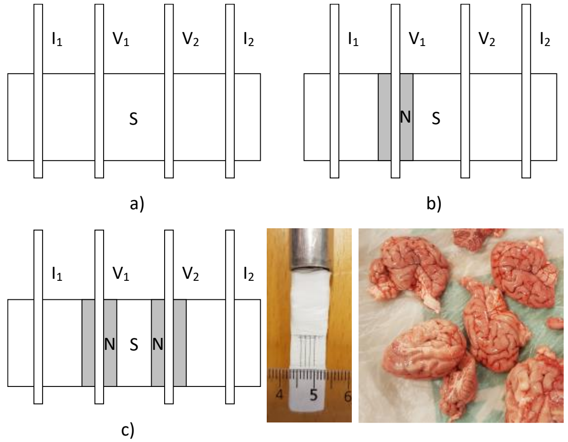
It is certainly conceivable to explain long-term memory (70 to 100 years lifetime of a person) in terms of persistent currents. That persistent currents exist seems to have been established by the response of living systems to strong magnetic fields. No theories of memory today seek to explain this phenomenon 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.

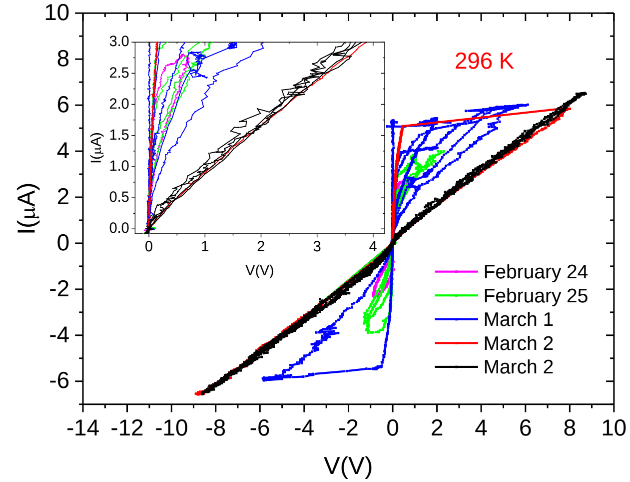
Four-electrodes transport measurements

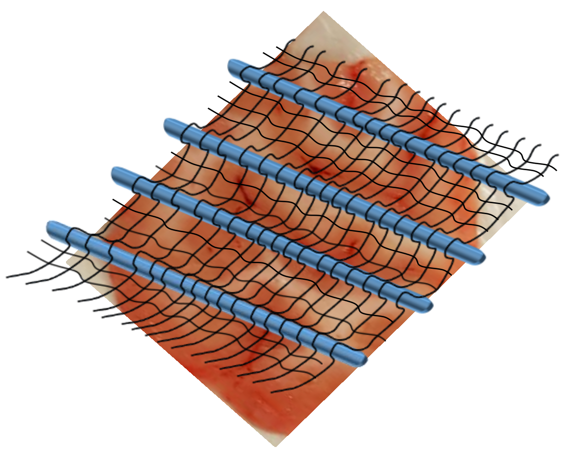


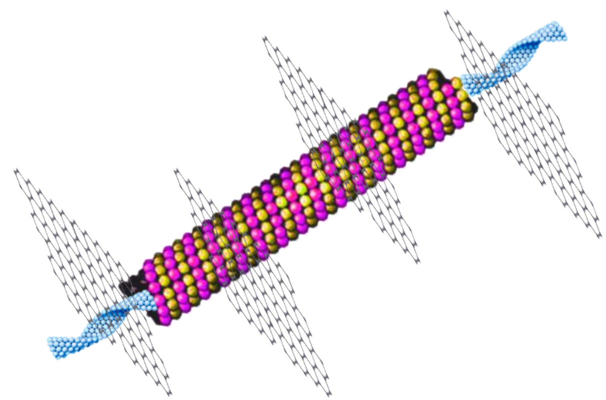
Optical image of a slice of brain exposed to water solution of graphene flakes and connected to the wires. The electrical current was passed between leads 1 and 4 and potential was measured between 2 and 3. The red arrow marks narrow constriction between the leads 1 and 2. A dark spot close to the sample contains remnants of graphene leaked from the slice. White area is an insulating polytetrafluoroethylene (PTFE) tape

Room-temperature superconductivity in neural network



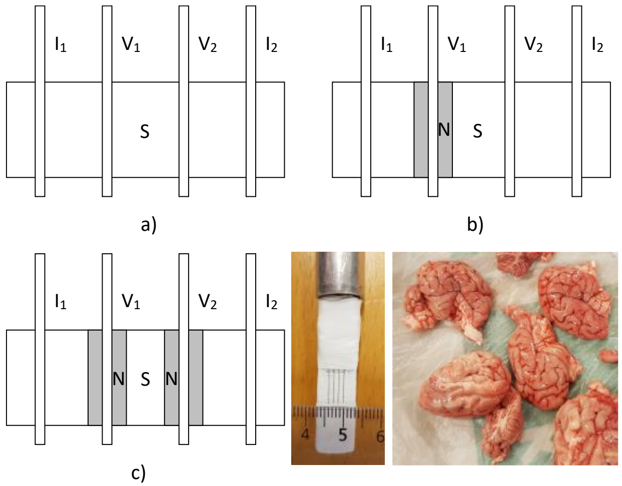


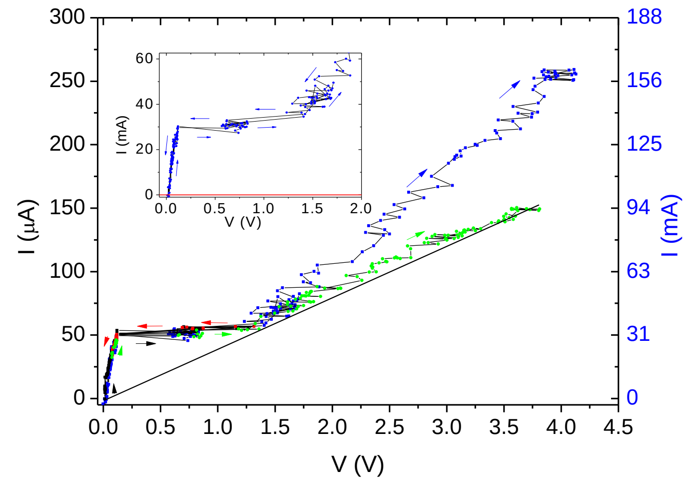


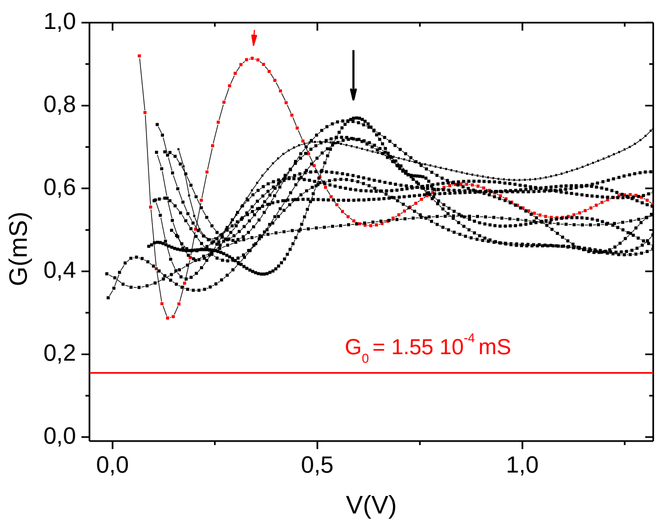


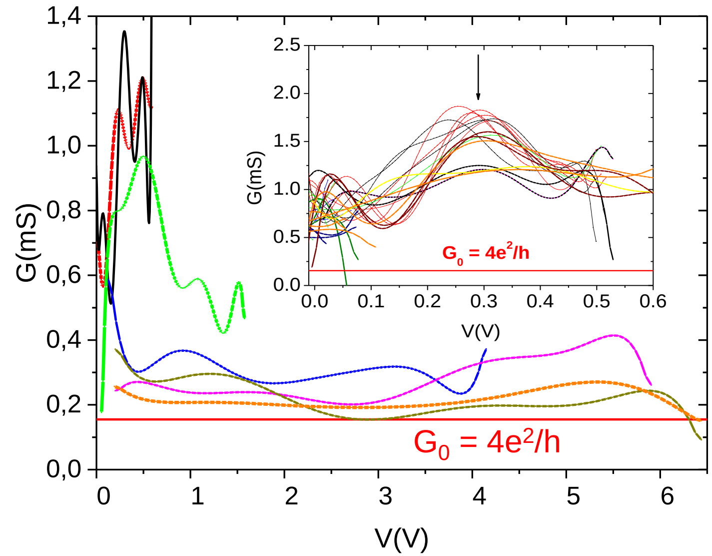
P. Mikheenko, "Graphene-assisted Transport Measurements of Biological Samples", 2016 International Conference on Nanomaterials: Application & Properties (NAP), Lviv, 2016, pp. 02CBNM04-1-02CBNM04-4, IEEE Xplore Digital Library 7757272, 2016.

Room-temperature superconductivity in neural network

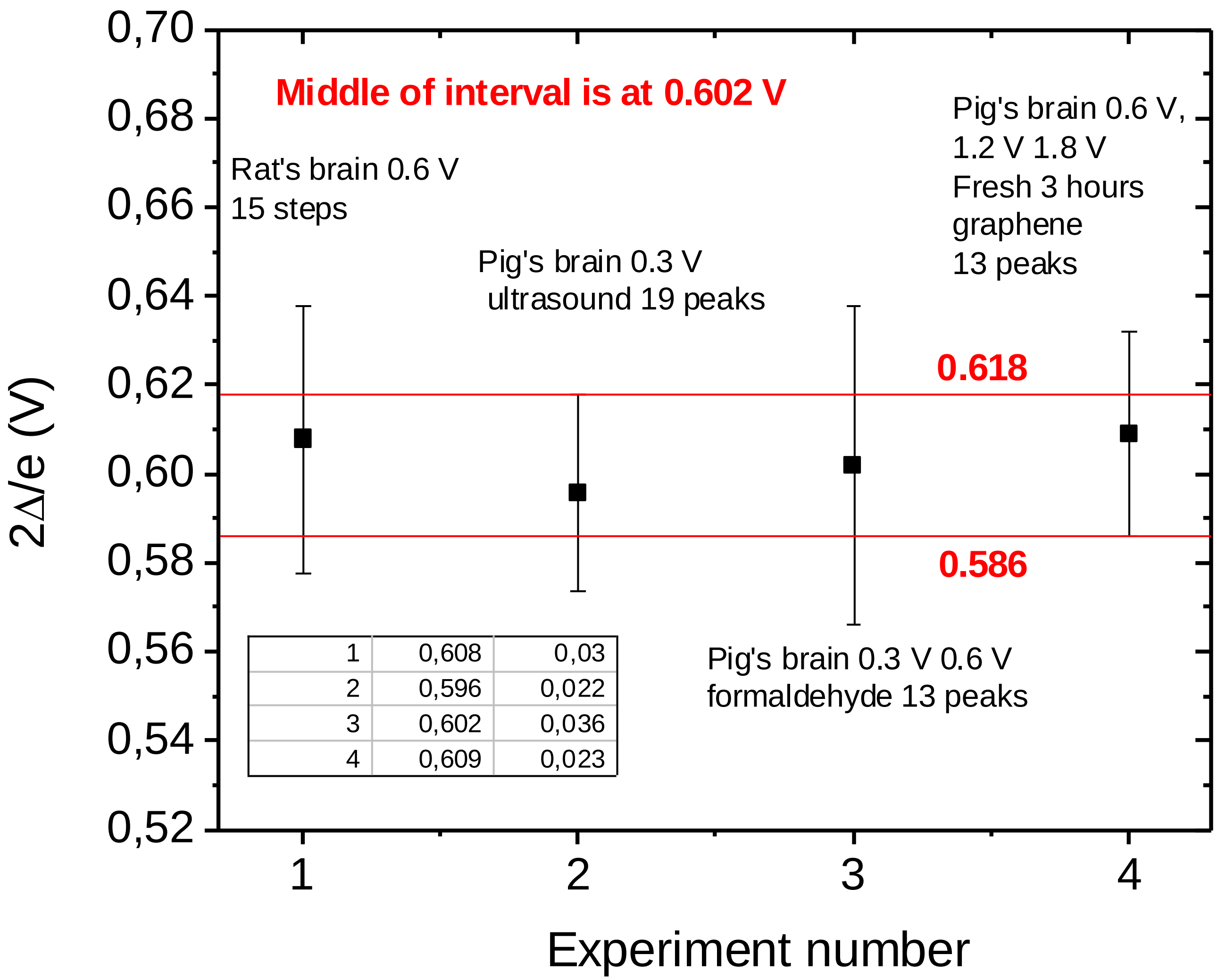








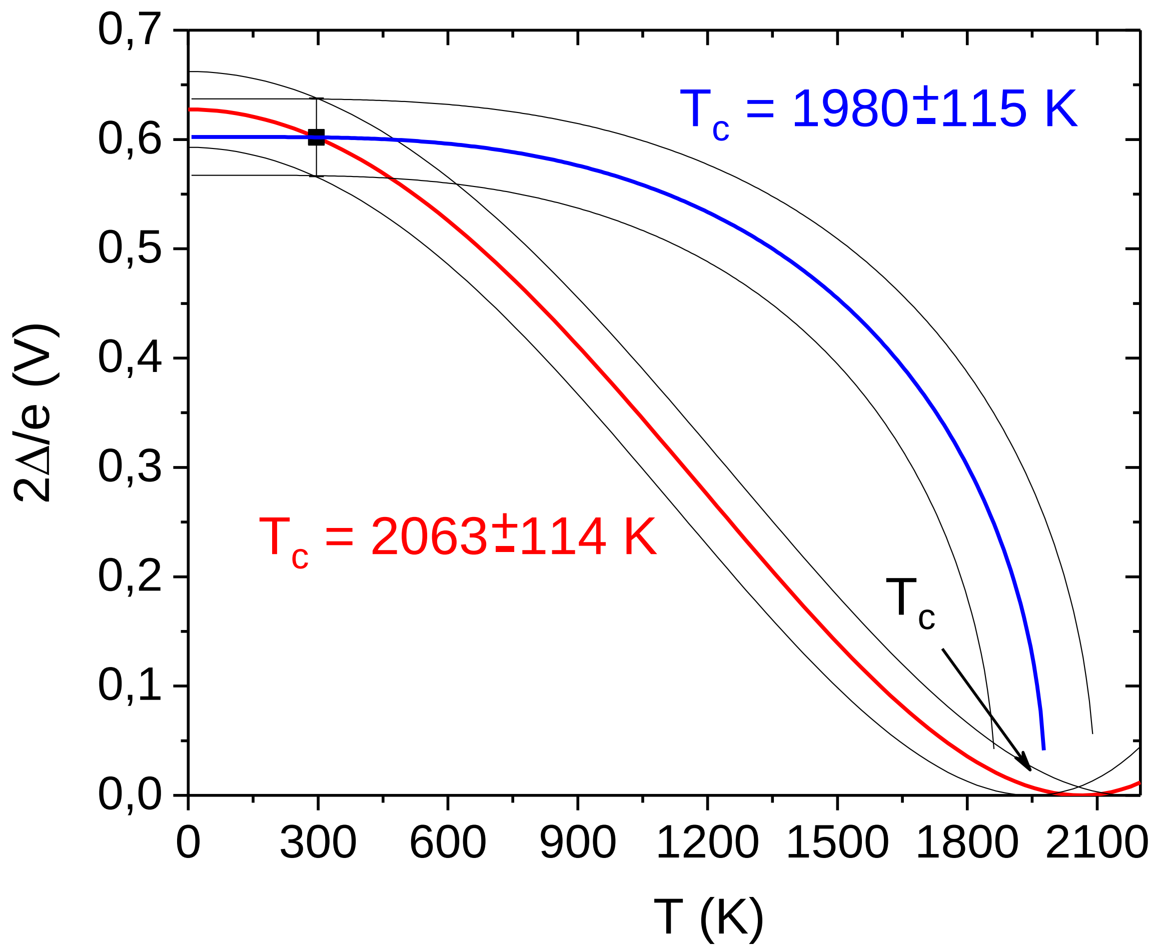
Statistical treatment of data



1	0,608	0,03
2	0,596	0,022
3	0,602	0,036
4	0,609	0,023

Estimation of T_c

$2\Delta(0)/e = 3.53\ k_B T_c$ $\Delta(T) = \Delta(0)\cdot(1-(T/T_c)^2)^2$ $\Delta(T) = \Delta(0)\cdot\tanh[1.74\cdot(T_c/T-1)^{0.5}]$



T_c = 2022 ± 157 K

Possible superconductivity in the brain

https://link.springer.com/article/10.1007/s10948-018-4965-4

Springer Link

Journal of Superconductivity and Novel Magnetism
pp 1–14 | Cite as

Possible Superconductivity in the Brain

Authors | Authors and affiliations

P. Mikheenko

Review Paper
First Online: 18 December 2018

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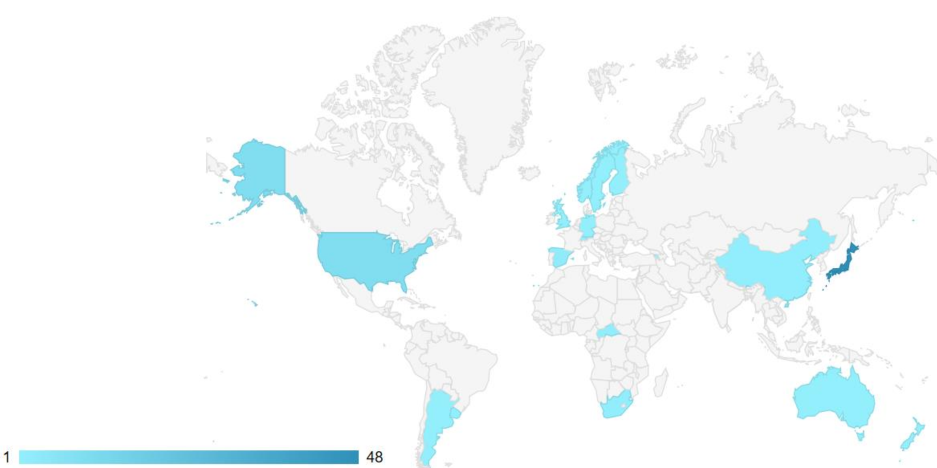
of 12,833,273 outputs	of 149 outputs

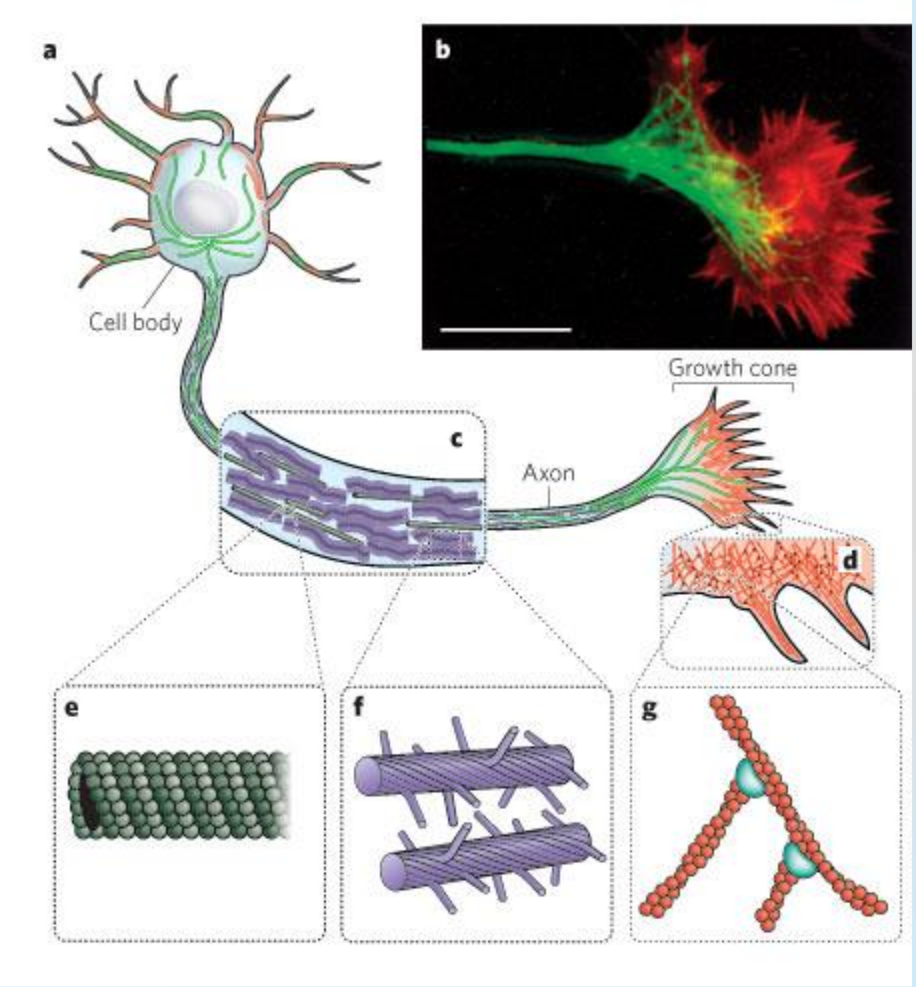


Altmetric has tracked 12,833,273 research outputs across all sources so far. Compared to these this one has done particularly well and is in the 99th percentile: it's **in the top 5% of all research outputs ever tracked** by Altmetric.

https://www.altmetric.com/details/52746868#score

Microtubules

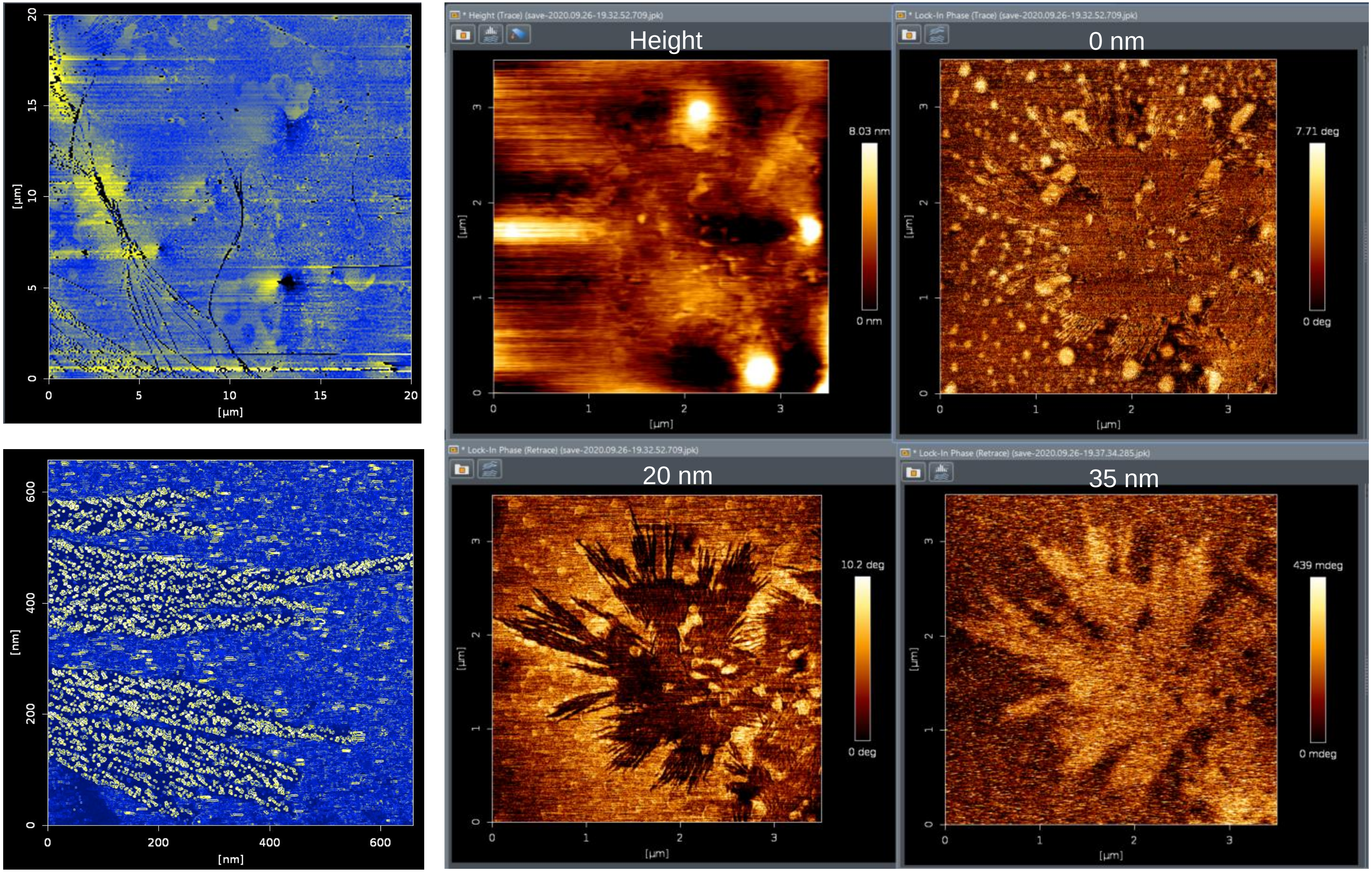
NATURE|Vol 463|28 January 2010|doi:10.1038/nature08908



Neurons have elaborate cytoskeletal structures. (A, B) Neurons have a cytoskeleton that consists of three main polymers: microtubules (green), intermediate filaments (purple) and actin filaments (red). Scale bar, 20 μm. (C) The neuronal axon is a long membrane-bounded extension, in which neurofilaments form a structural matrix that embeds microtubules (E) Microtubules consist of 13 protofilaments of tubulin dimers arranged in a hollow tube. (F) Neurofilaments have flexible polymer arms that repel neighboring neurofilaments and determine the radius of the axon. (G) Actin filaments are arranged into networks. Typical length: microtubules - 5,000 μm, actin filaments - 13.5 μm and intermediate filaments - 0.5 μm.

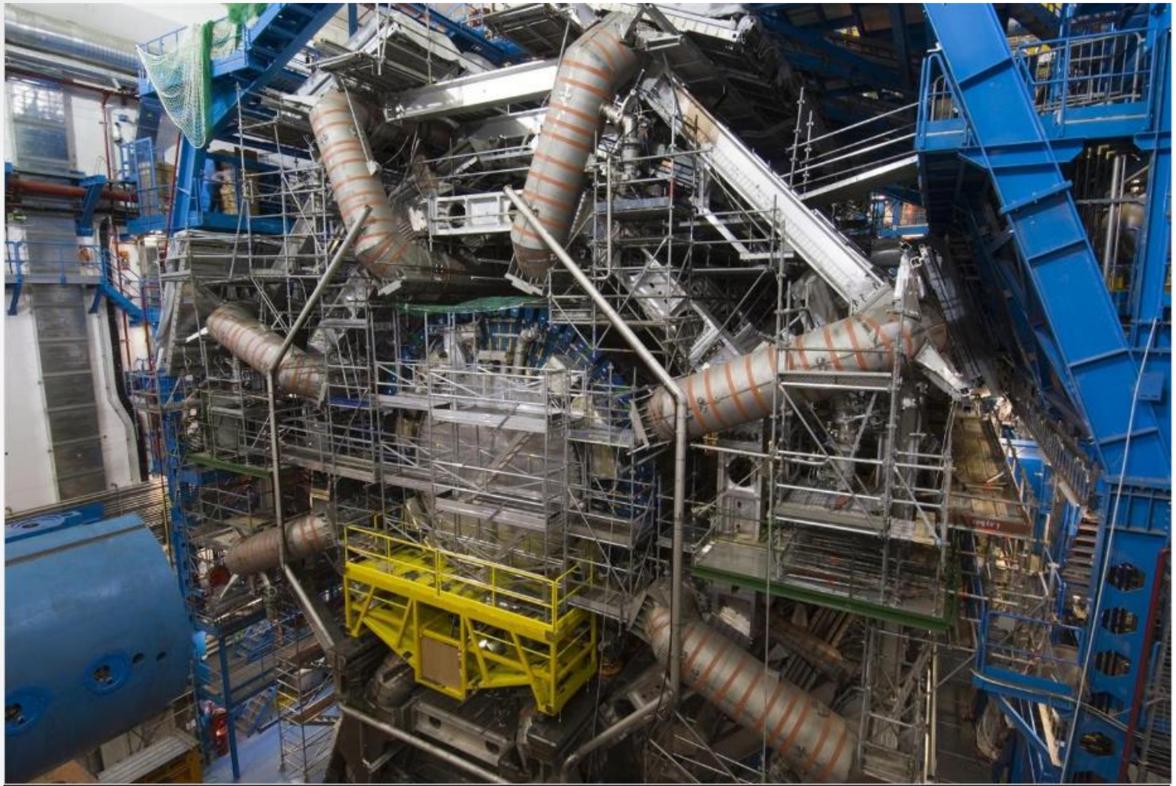
https://www.nature.com/scitable/topicpage/microtubules-and-filaments-14052932

Diamagnetism in microtubules



Phase shift in individual microtubules and fragments of nerve cells of the brain

Superconductivity in relativistic heavy ion collisions



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)

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.

14. What are practical applications of superconductors?

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,”

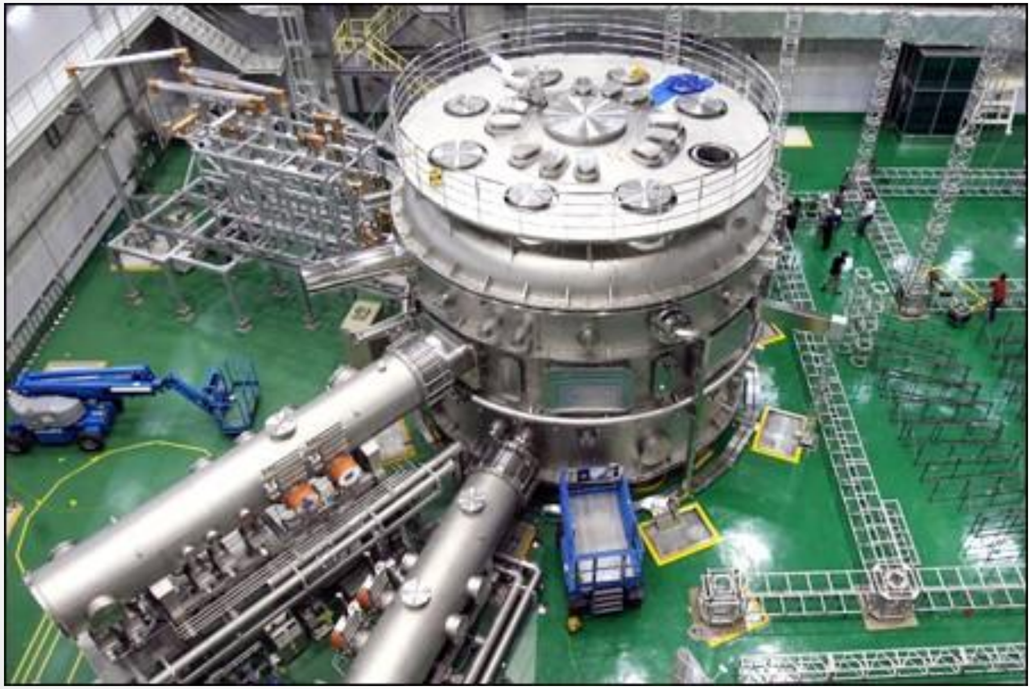
http://thesilicongraybeard.blogspot.no/2015/07/techy-tuesday-using-superconductors-to.html
http://news.mit.edu/2015/making-cancer-treatment-more-accessible-0604

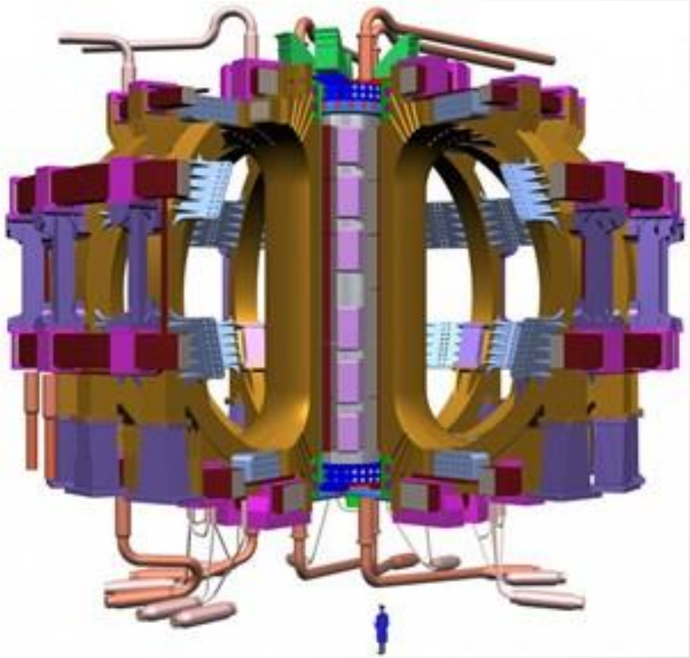
14. What are practical applications of superconductors?

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



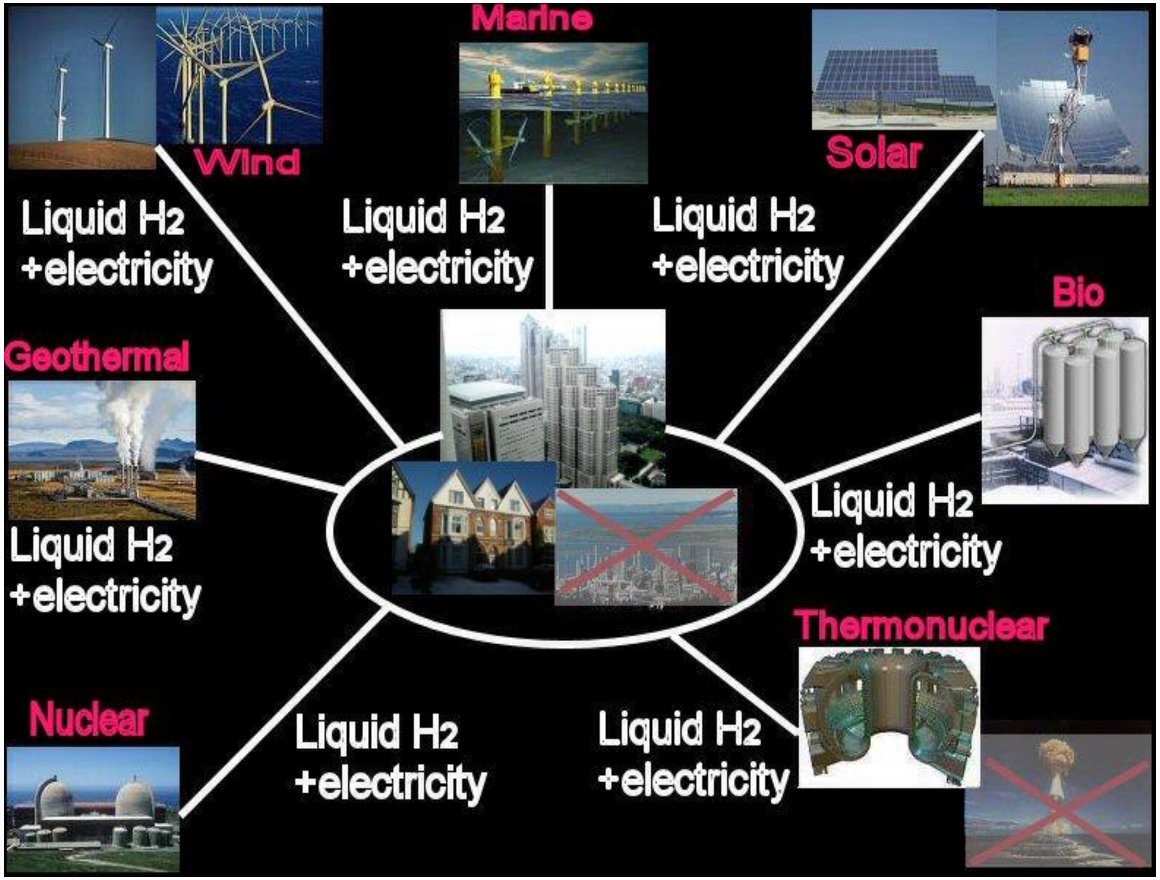


'Without superconductivity, ITER would go from being a "net energy positive" machine to a "net energy negative" machine.'

https://www.iter.org/newsline/146/408

14. What are practical applications of superconductors?

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.

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

21. How could superconductivity be important for renewable energy economy?

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Superconductivity for hydrogen economy

P.Mikheenko, A hope for superconductivity (2011)
http://proeco.visti.net/naturalist/oracle/orc_037.pdf

P. Mikheenko, Superconductivity for hydrogen economy, *Journal of Physics: Conference Series* **286** 012014 (2011).

P. Mikheenko, T. H. Johansen, Smart superconducting grid, *Energy Procedia*, v. **58**, pp. 73 – 78 (2014).

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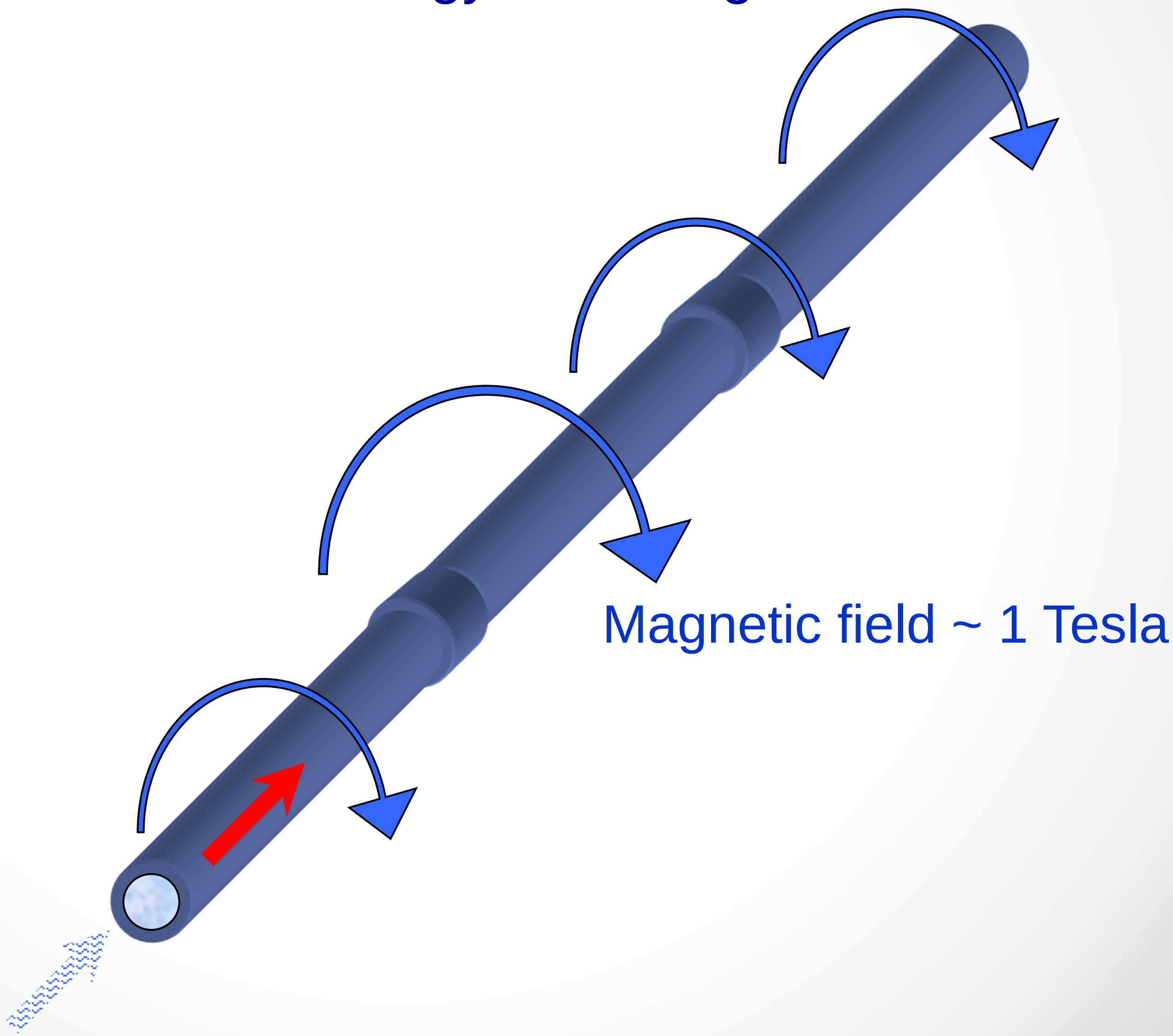
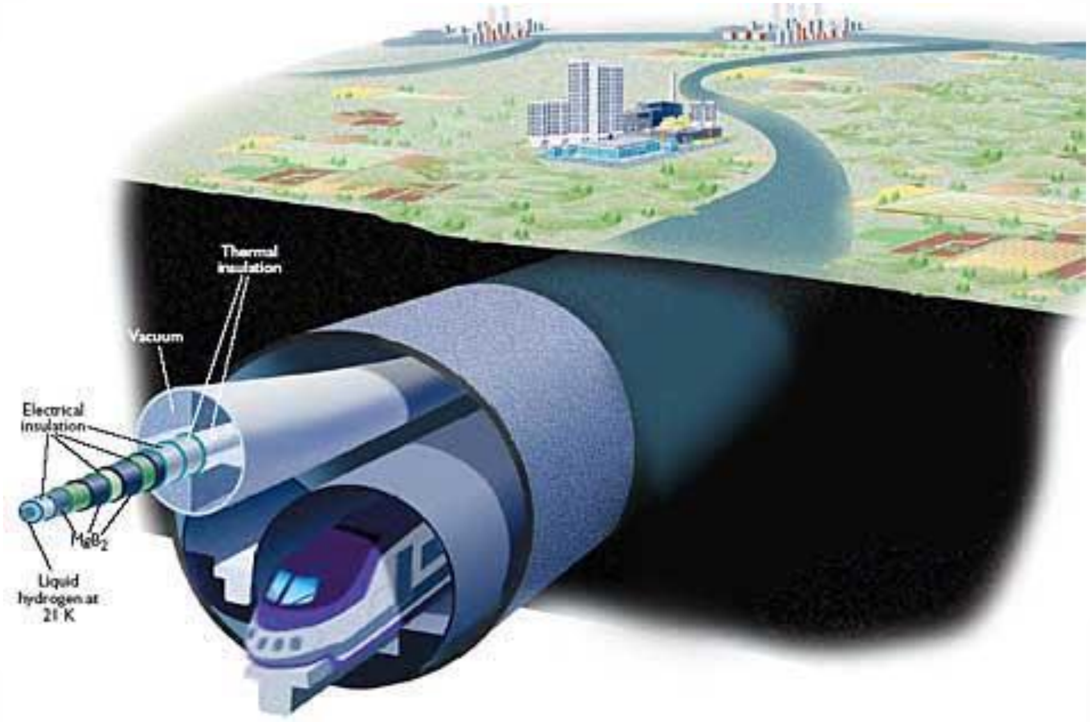
UNIVERSITY OF BIRMINGHAM

Superconducting pipelines: transport of liquid hydrogen and electrical energy, levitating train



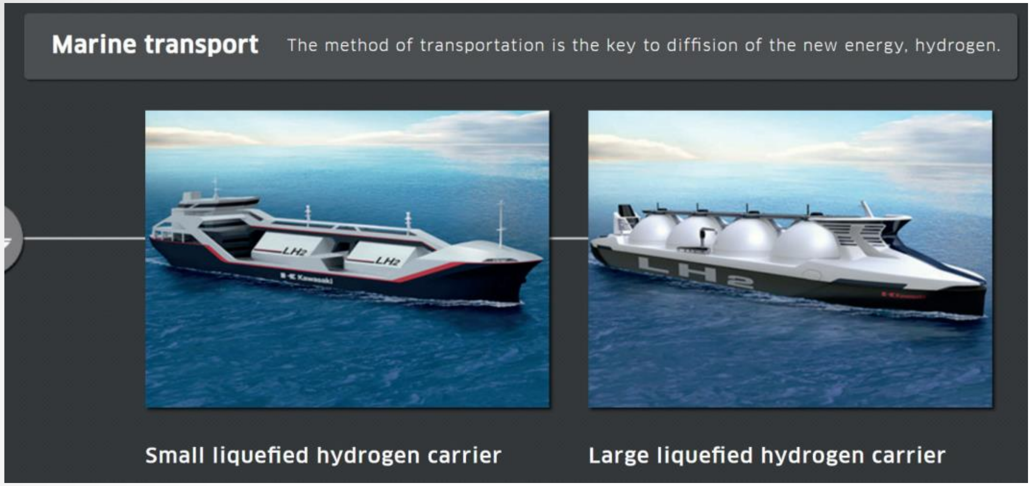
The Liquid Hydrogen "Supergrid"

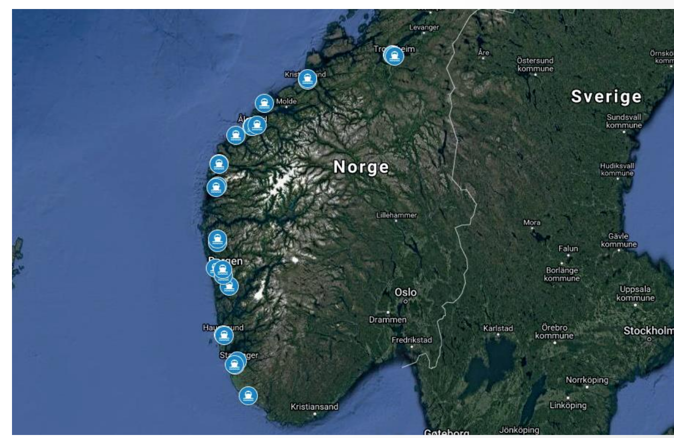


The above image was generated by the Electric Power Research Institute (EPRI)

http://www.phoenixprojectfoundation.us/

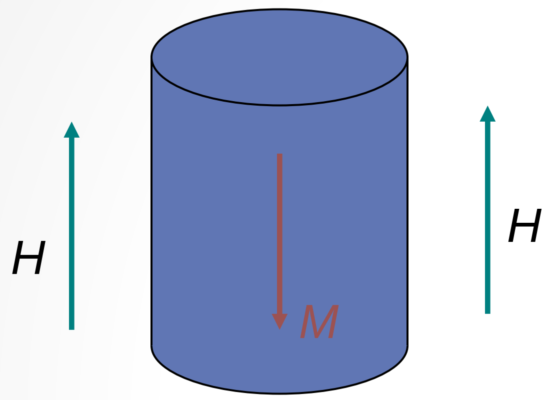
Norwegian Liquid Hydrogen Value Chain





https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf

Type I superconductors: Magnetization curve

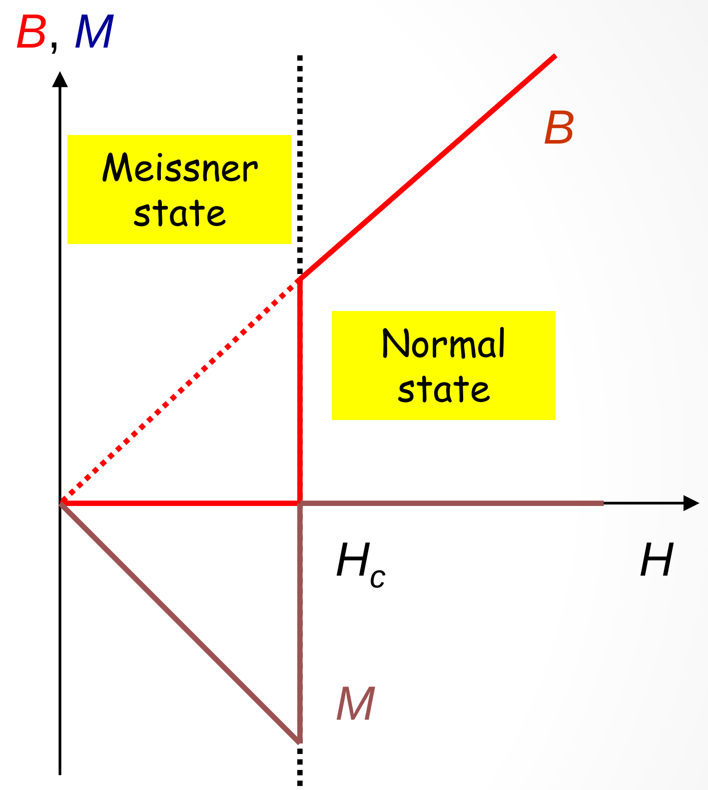


$$B = H + 4\pi M$$

H – magnetic field strength

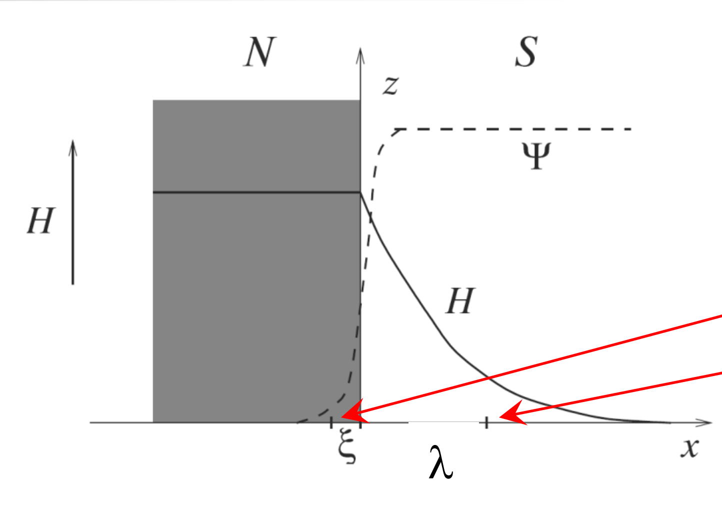
M – magnetization

B – magnetic induction



5. What is the difference between type-I and type-II superconductors?

N-S interface



$$\Psi = \tanh \frac{x}{\xi\sqrt{2}}$$

ξ ⟶ *the coherence length.*

λ is just the London penetration depth near T_c.

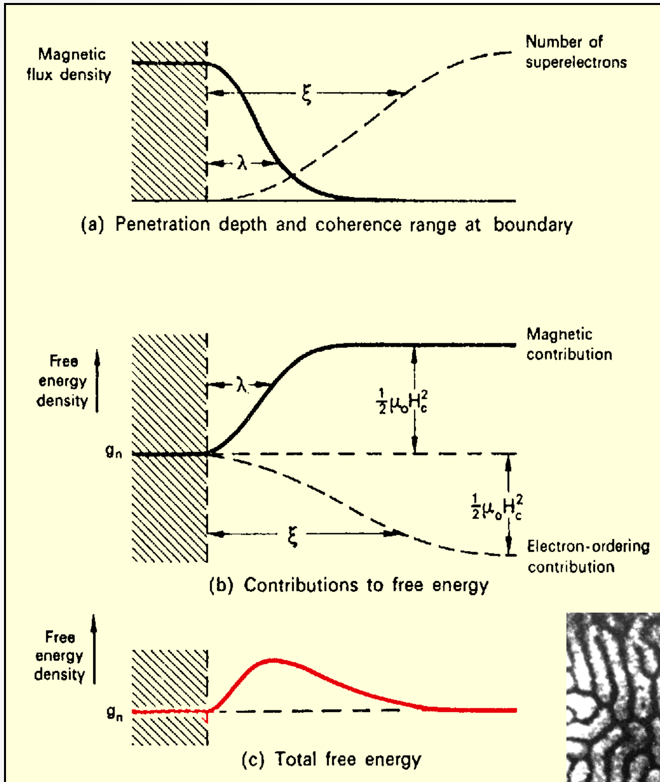
Surface energy:

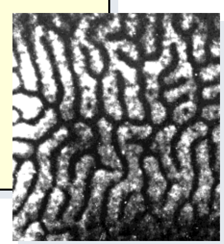
$$\sigma_{ns} = \begin{cases} > 0, & \kappa < 1/\sqrt{2} \\ = 0, & \kappa = 1/\sqrt{2} \\ < 0, & \kappa > 1/\sqrt{2}, \end{cases} \qquad \kappa = \frac{\lambda}{\xi}$$

Depending on GL parameter there is a tendency either to create, or not to create new surfaces

6. Does positive energy of the interface between normal and superconducting state lead to quantization of magnetic flux?

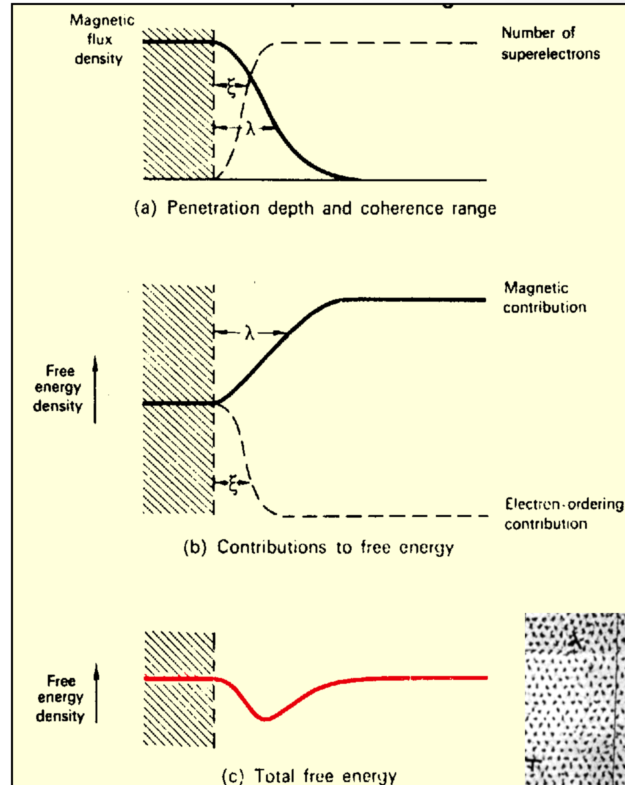
Summary: Two types of superconductors

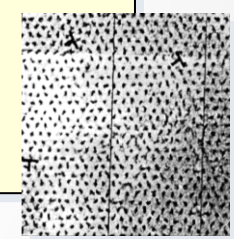




Surface energy is positive:

Type I superconductivity





Surface energy is negative:

Type II superconductivity

(Abrikosov lattice, 1952)

Nobel Prize 2003, V. Ginzburg, A. Abrikosov

Modification for alloys:

$$\lambda(T) = \lambda(0)\sqrt{\frac{\xi(T)}{\ell}}$$

$$\xi_{\text{eff}} \approx \sqrt{\xi\ell}$$

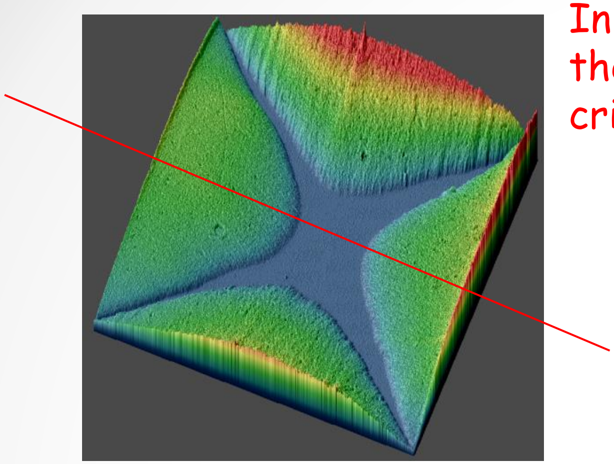
$$\kappa = \frac{\lambda}{\xi_{\text{eff}}} = 0.72\frac{\lambda(0)}{\ell}$$

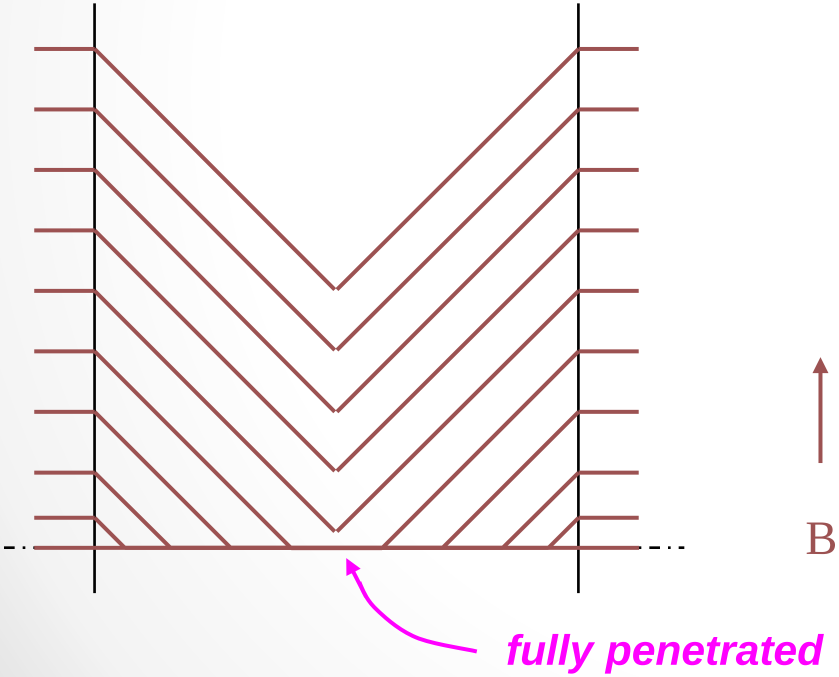
$\xi \approx \hbar v_F/\Delta$ - coherence length in a clean material,
$\lambda(0)$ – London penetration depth at $T = 0$,
ℓ - electron mean free path.

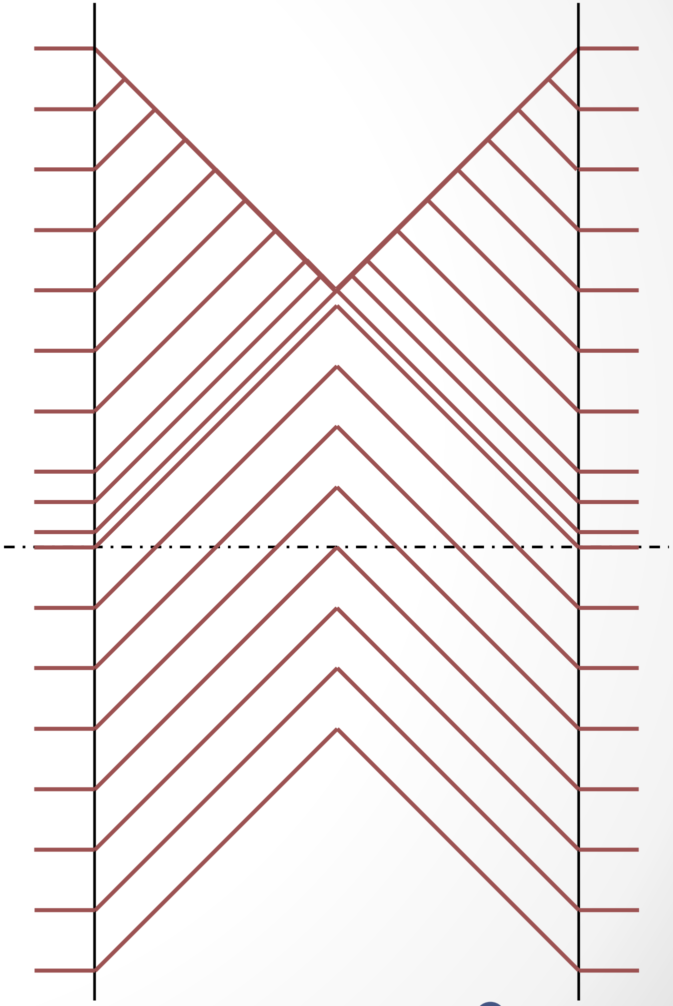
Alloys are usually type II superconductors

Bean critical state model

In bulk materials, 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.

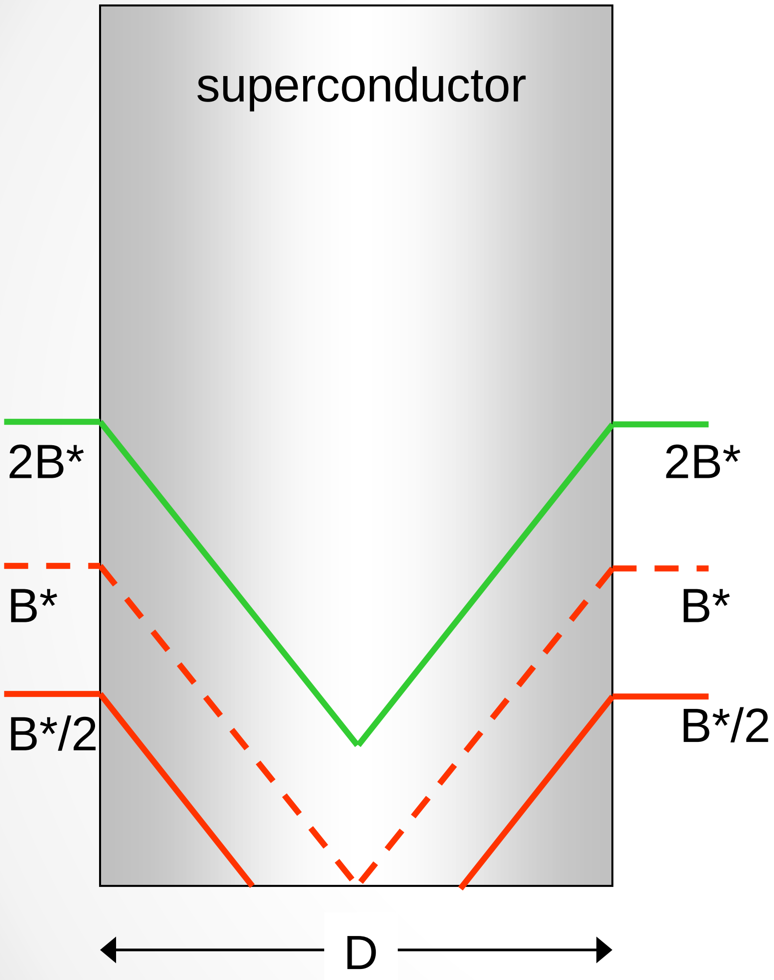


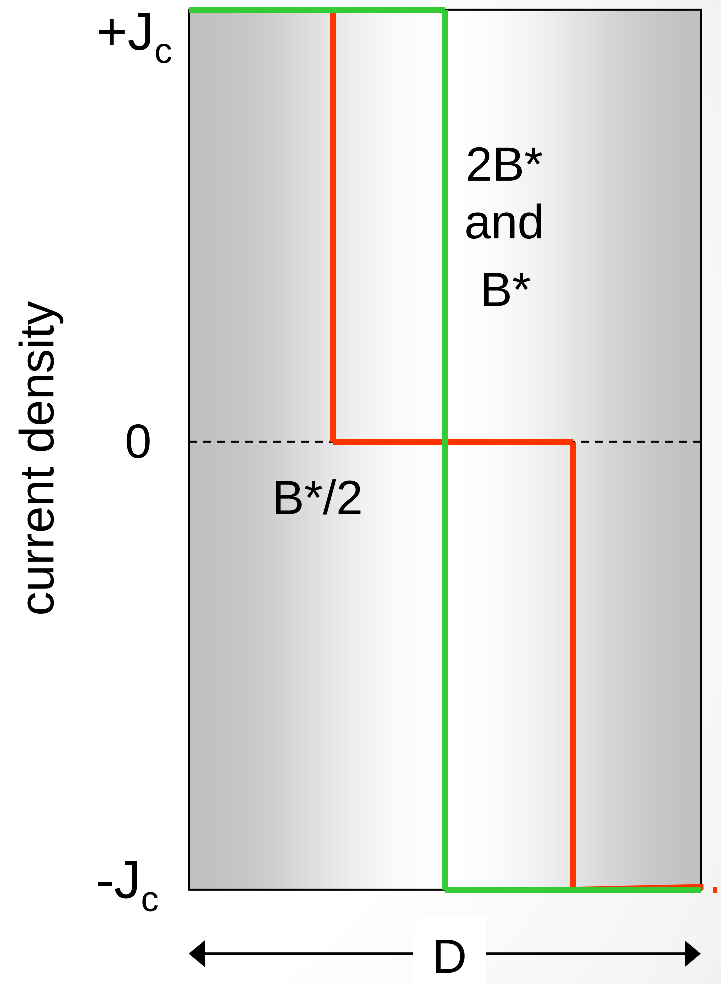




8. Do flux quanta move free in superconductor? What is the pinning? Is pinning important for practical applications?

Meissner effect: current distribution



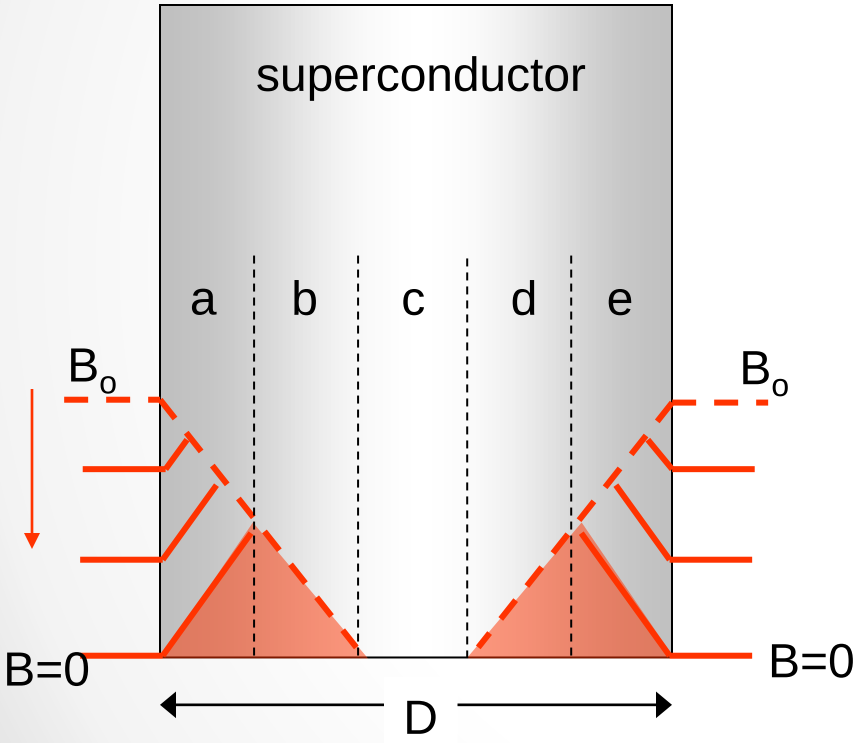


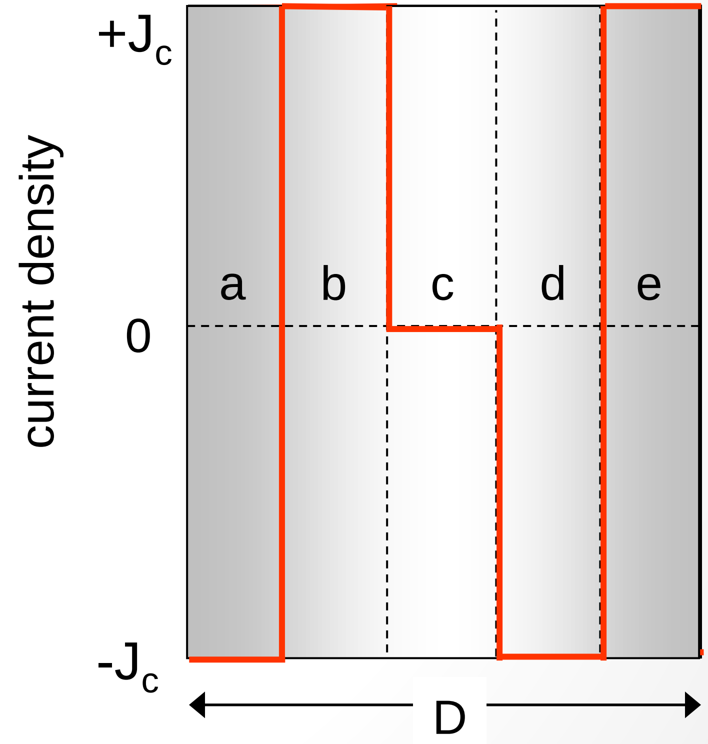
10. Can you say anything about critical current flowing in the sample if gradient of magnetic flux is known in bulk superconductor?

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





9. What is critical state of superconductor? Have Bean's model for superconductors anything common with sand-pile model?

Bean critical state: thin films

Inductance measurements of HTSC films with high critical currents

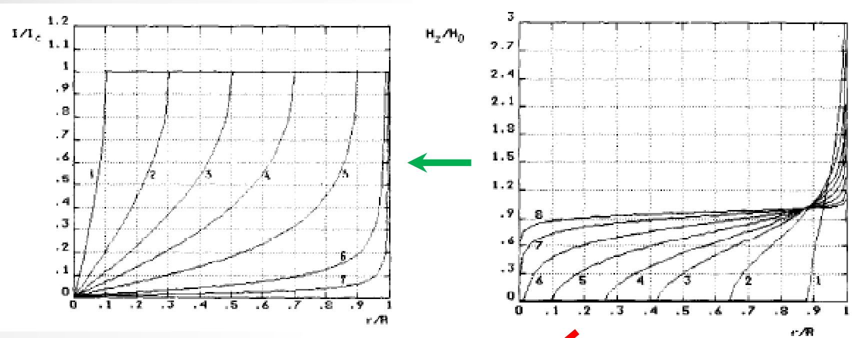
P.N. Mikheenko and Yu.E. Kuzovlev

Physica C 204 (1993) 229–236
North-Holland

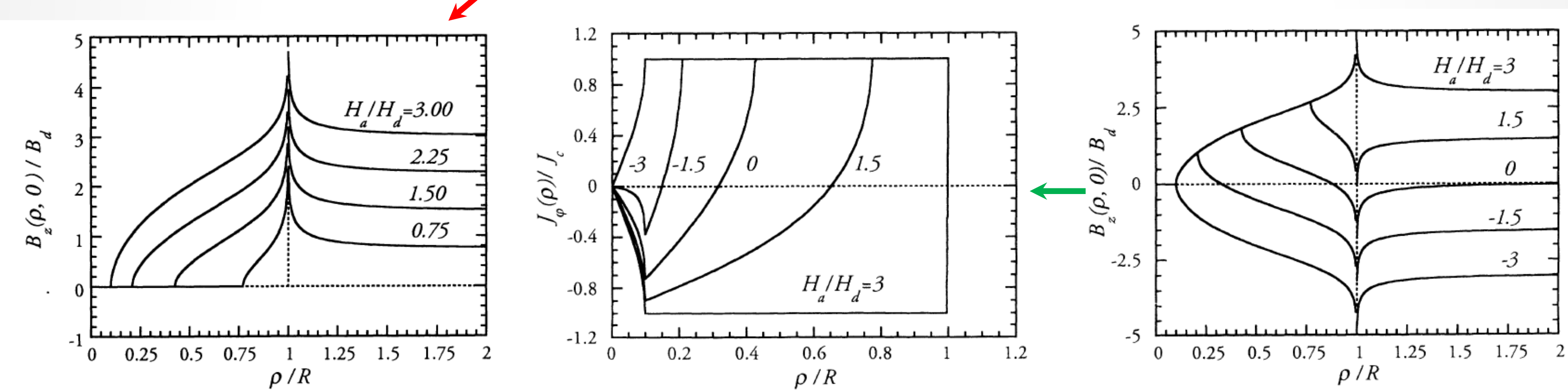
PHYSICAL REVIEW B VOLUME 50, NUMBER 13 1 OCTOBER 1994-I

Hysteretic ac losses and susceptibility of thin superconducting disks

John R. Clem and Alvaro Sanchez

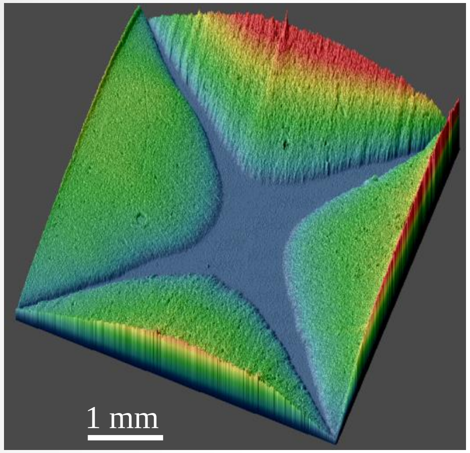


An important theoretical advance recently has been made by Mikheenko and Kuzovlev,[4] who showed how to apply the critical-state theory to thin superconducting disks. This work has been extended (and corrected) by Zhu *et al.*[5] The latter paper contains the basic information that is needed to calculate the hysteretic ac losses in a thin superconducting disk, as well as related properties such as the complex ac susceptibility.

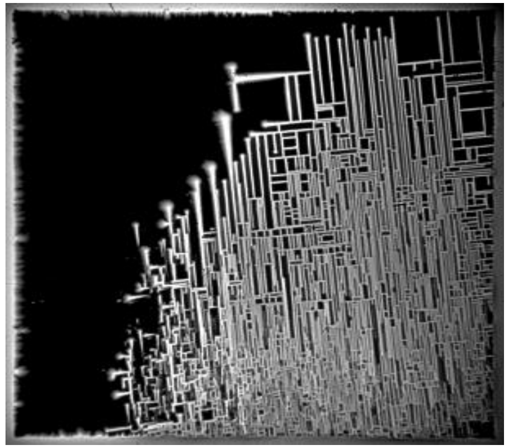


Magnetic field penetrates to or 'exit' from the sample with a varying gradient. Current is equal to critical current in region with magnetic flux. There is current in flux-free region.

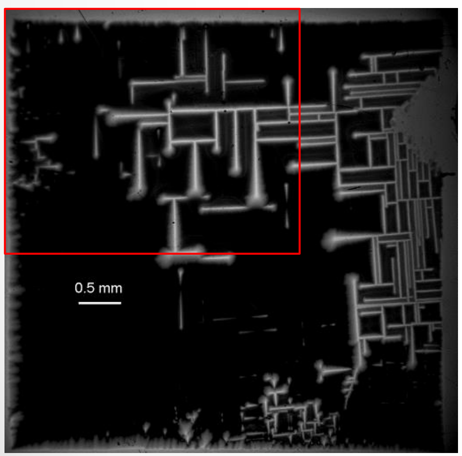
Magnetic flux penetration in superconducting films



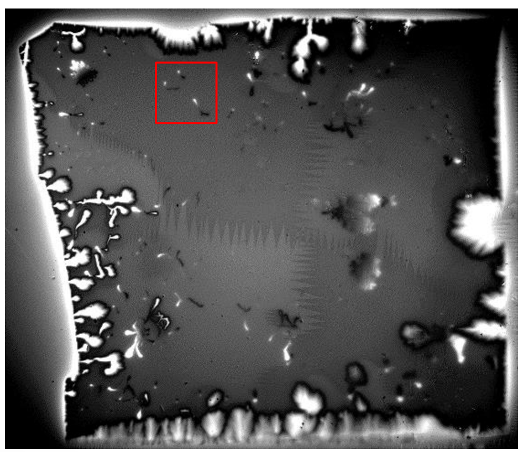
T = 70 K, ideal YBCO



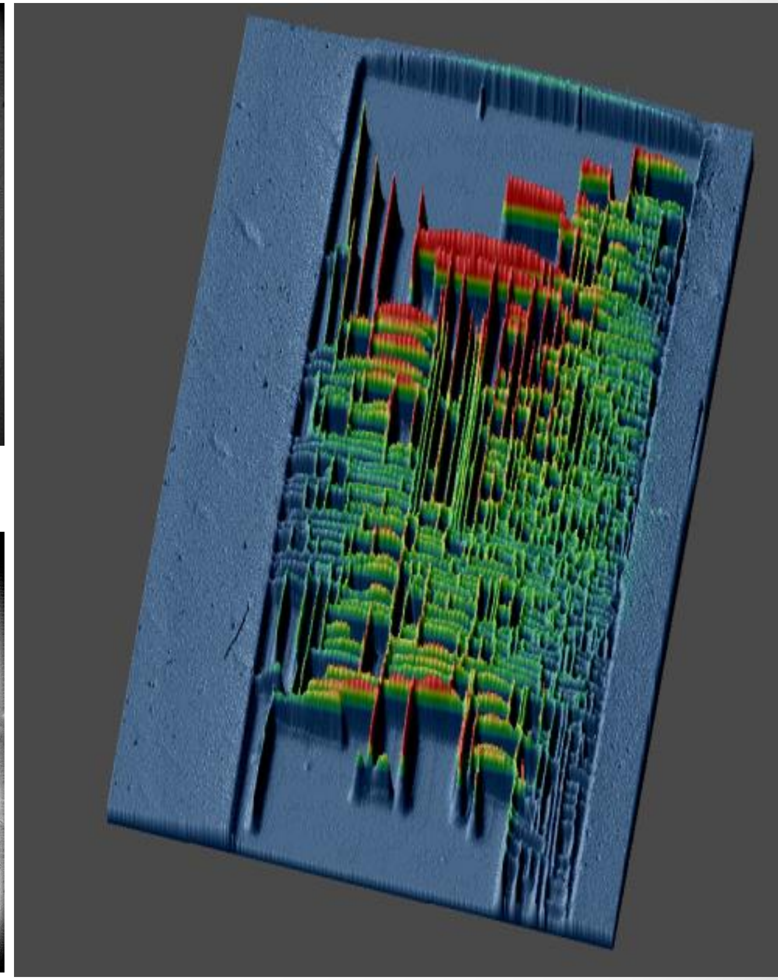
T = 4 K, YBCO



T = 4 K , YBCO



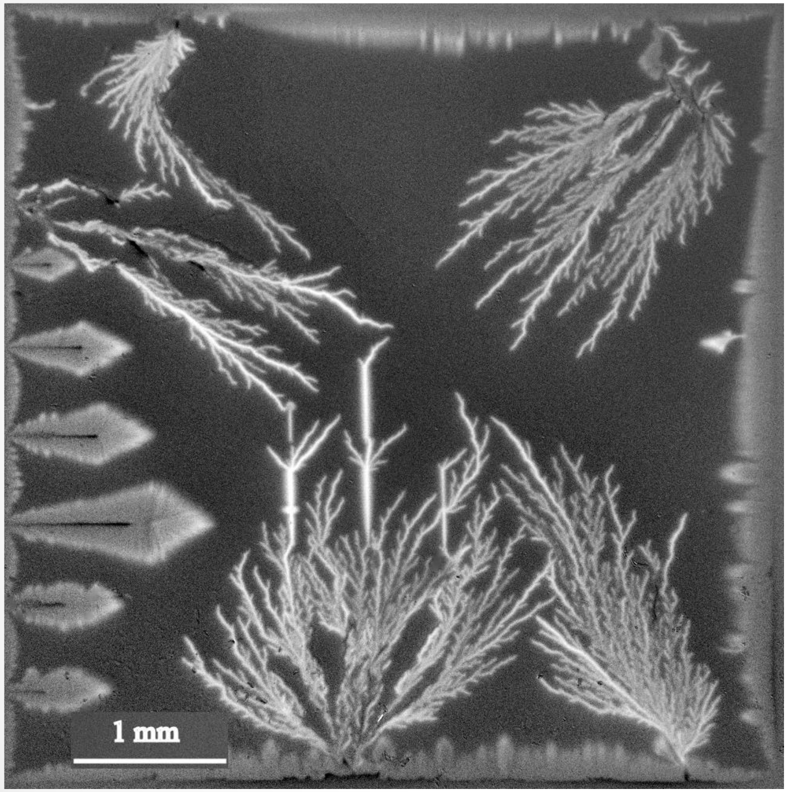
T = 4 K , MgB_2

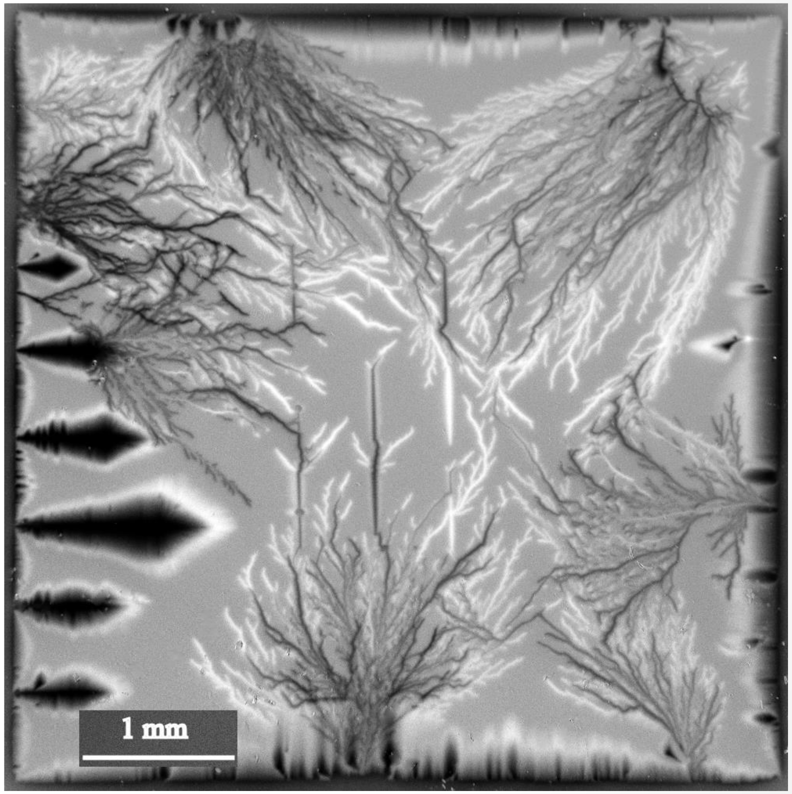


T = 20 K , YBCO

UiO : University of Oslo | UNIVERSITY OF CAMBRIDGE | UNIVERSITY OF BIRMINGHAM | JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

Dendritic flux penetration in NbN films

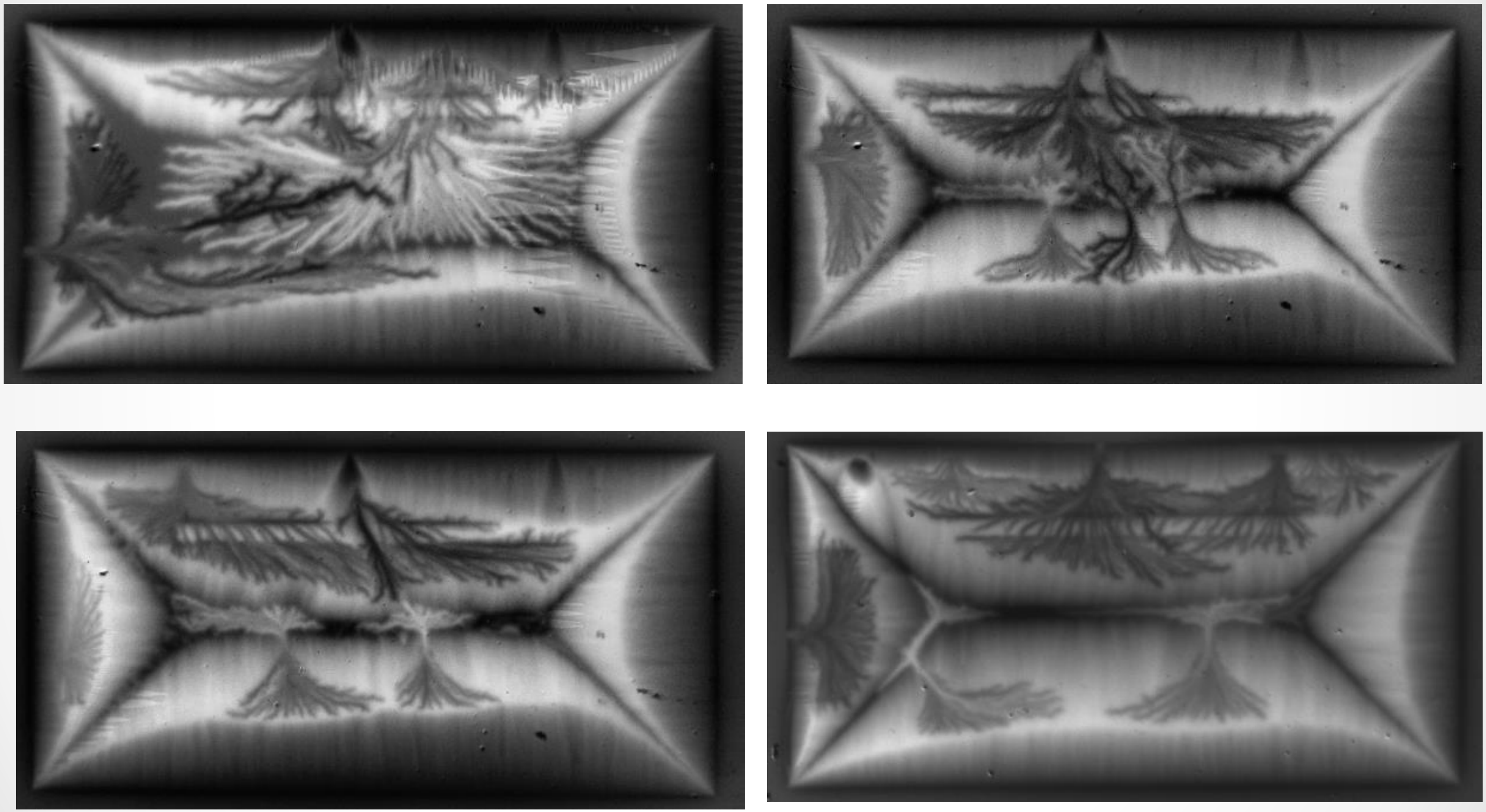




Dendrites and antidendrites in superconducting NbN films at T = 4 K.

17. How does magnetic flux penetrate in superconducting thin films? Is abrupt penetration possible?

Vortex-antivortex avalanches in NbN films

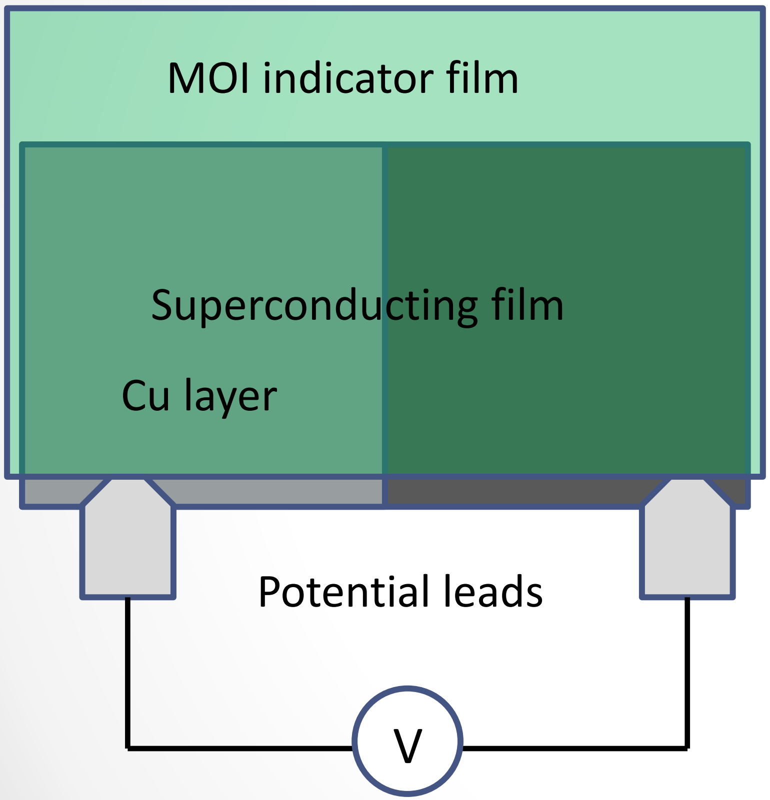


Simultaneous excitation of dendrites and antidendrites in superconducting NbN films at T = 4 K.

18. What is thermo-magnetic instability? What are dendritic flux avalanches? Are these effects linked?

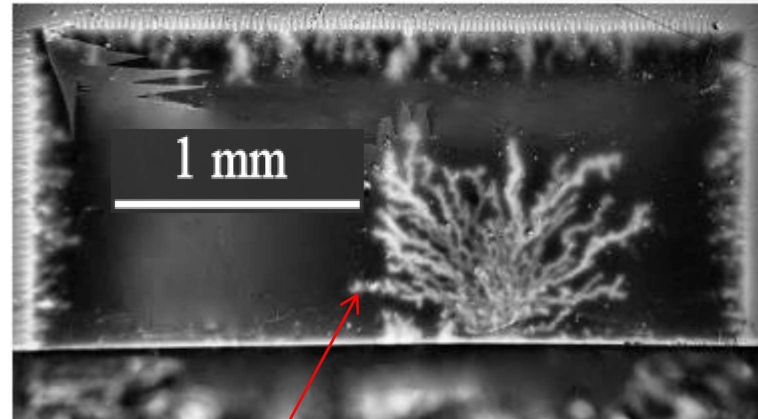
Pulse measurements of dendritic avalanches

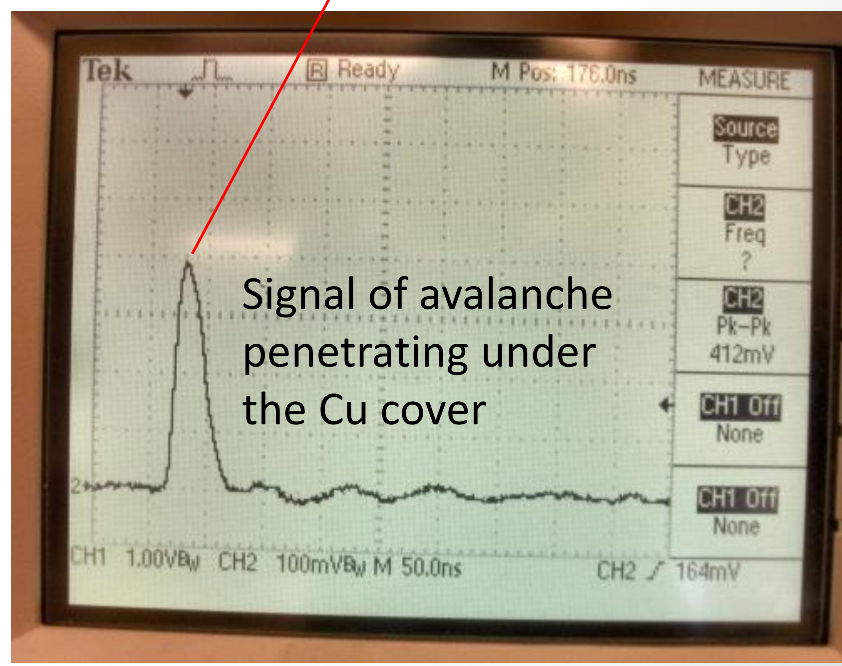
The voltage peak appears when avalanche strikes under Cu pad.



Voltmeter with nanoseconds resolution

P. Mikheenko et al., Appl. Phys. Lett. **102**, 022601 (2013).

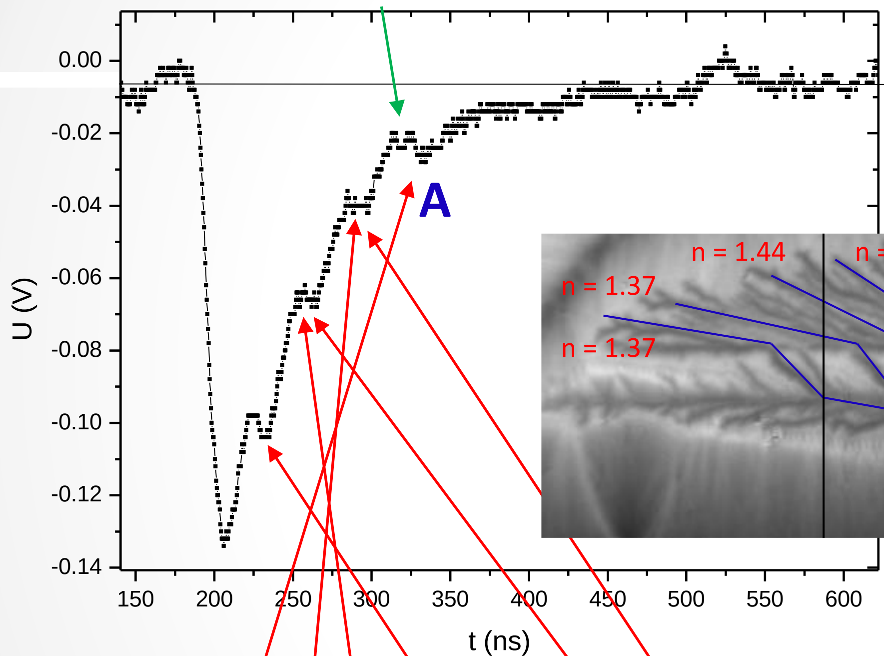


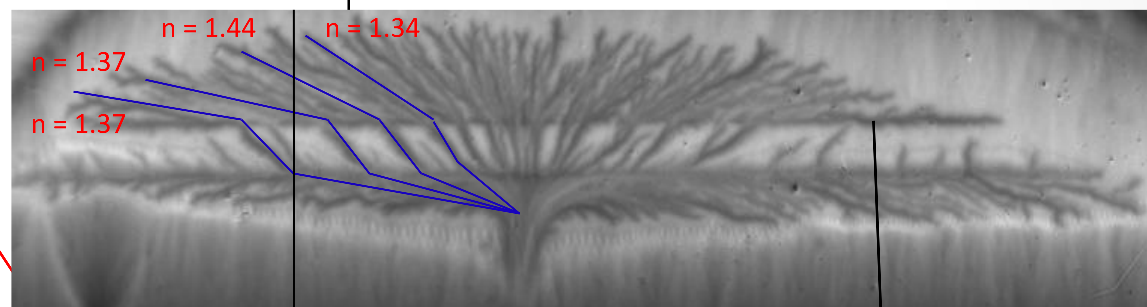


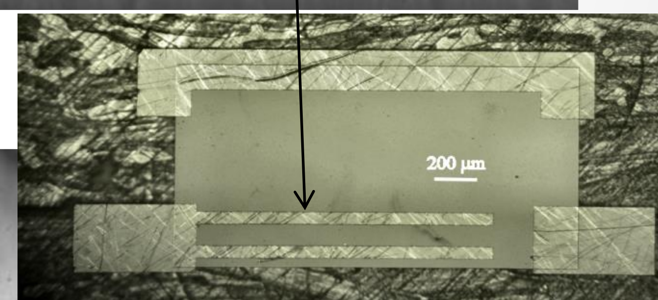
Geometrical optics of dendritic flux avalanches

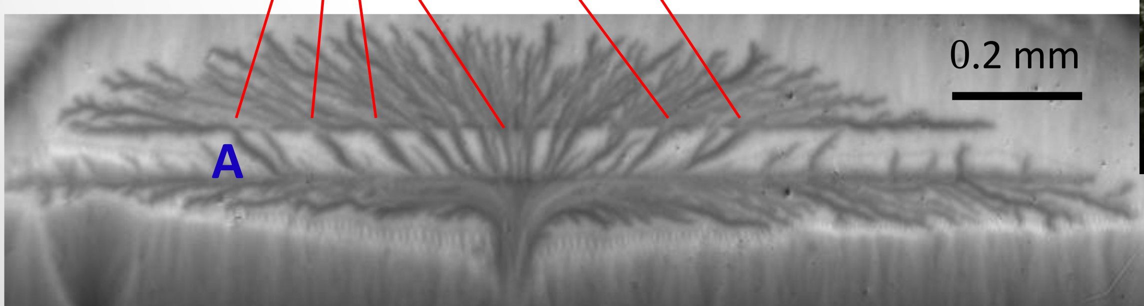
Snells law $$\frac{\sin(\Theta_1)}{\sin(\Theta_2)} = \frac{n_2}{n_1}$$

v_{CuNbN} = 8.2 km/s and v_{NbN} = 11.5 km/s



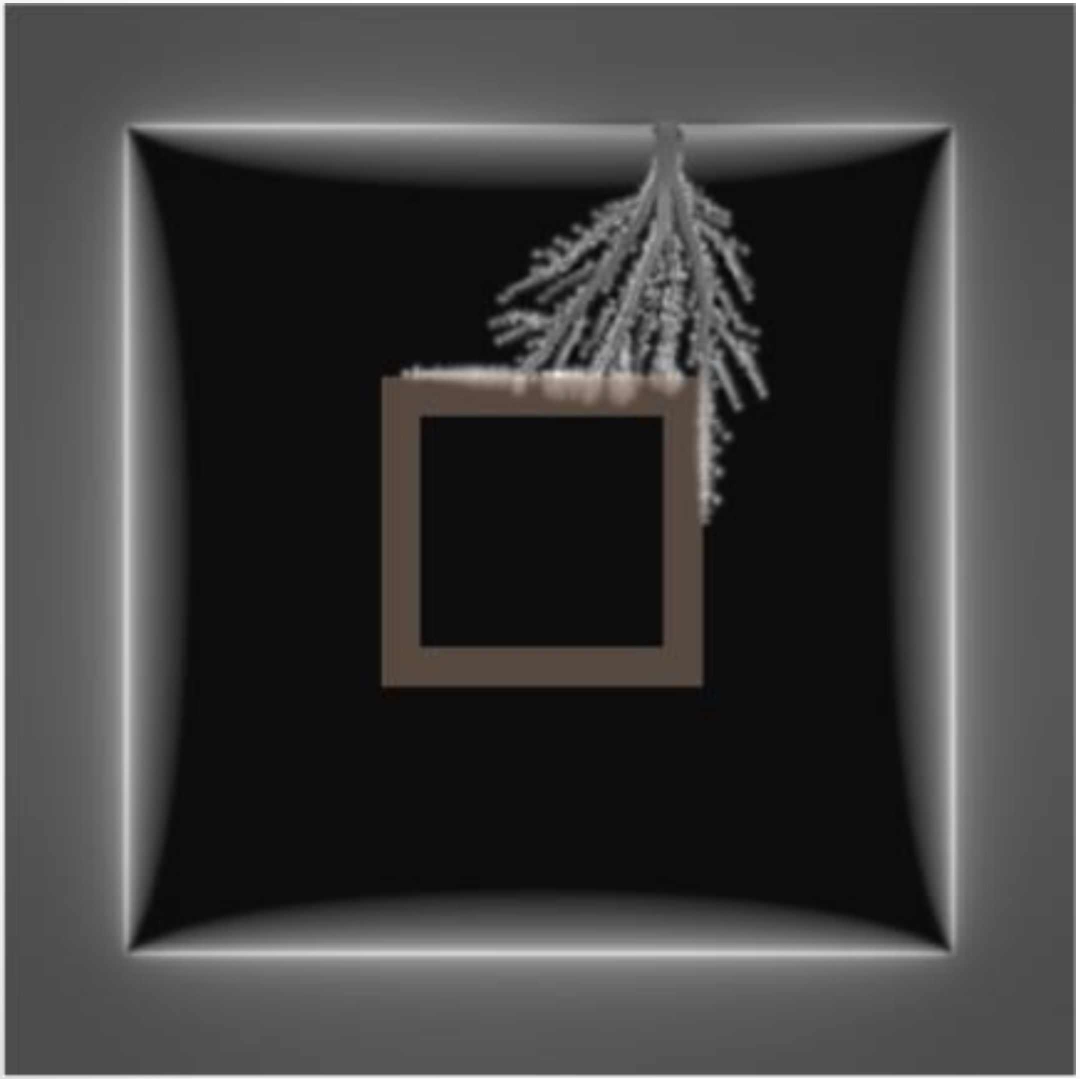






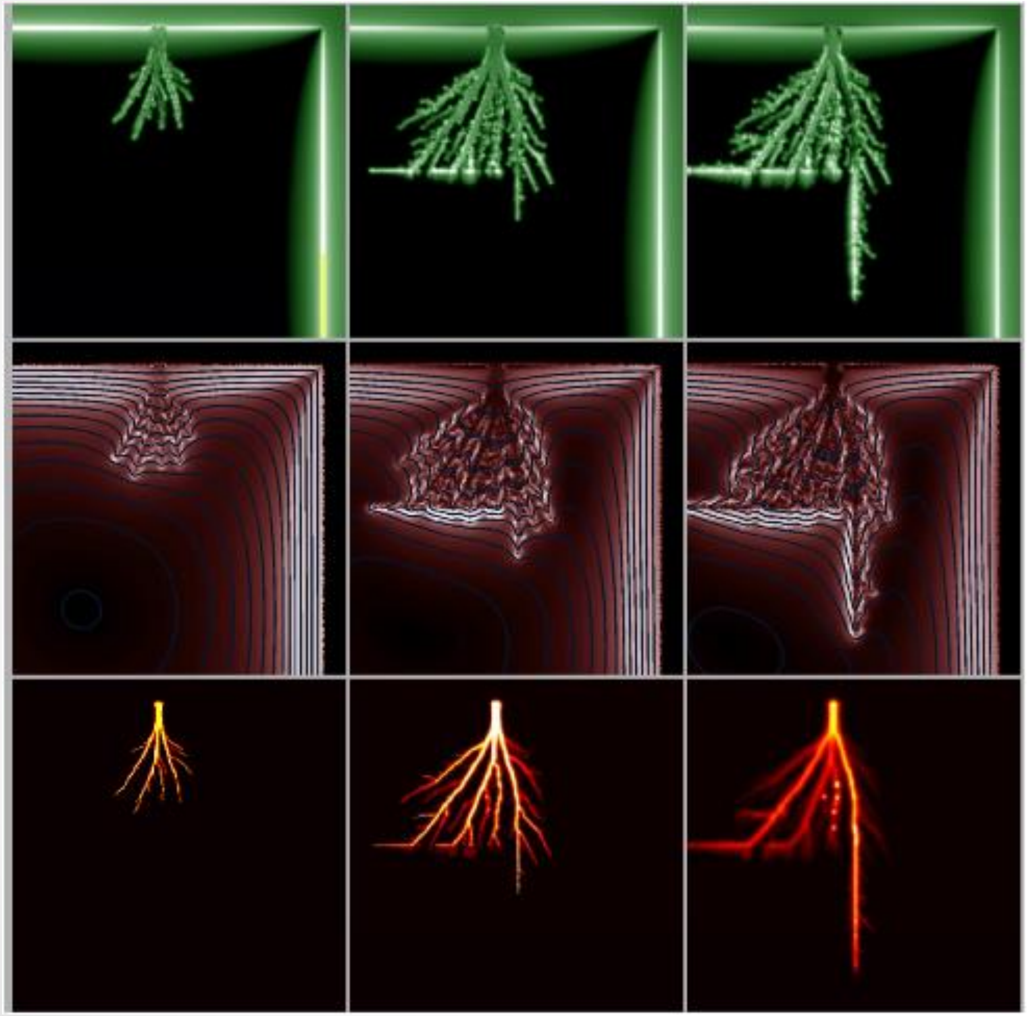
P. Mikheenko et al., **Phys. Rev. B 91,** 060507(R) (**2015**).

Screening of dendritic flux avalanches: numerical simulations



A conductive layer deposited on or applied to superconductor can be used to protect a particular area from the invasion of avalanches.

Distribution of magnetic flux, current and temperature



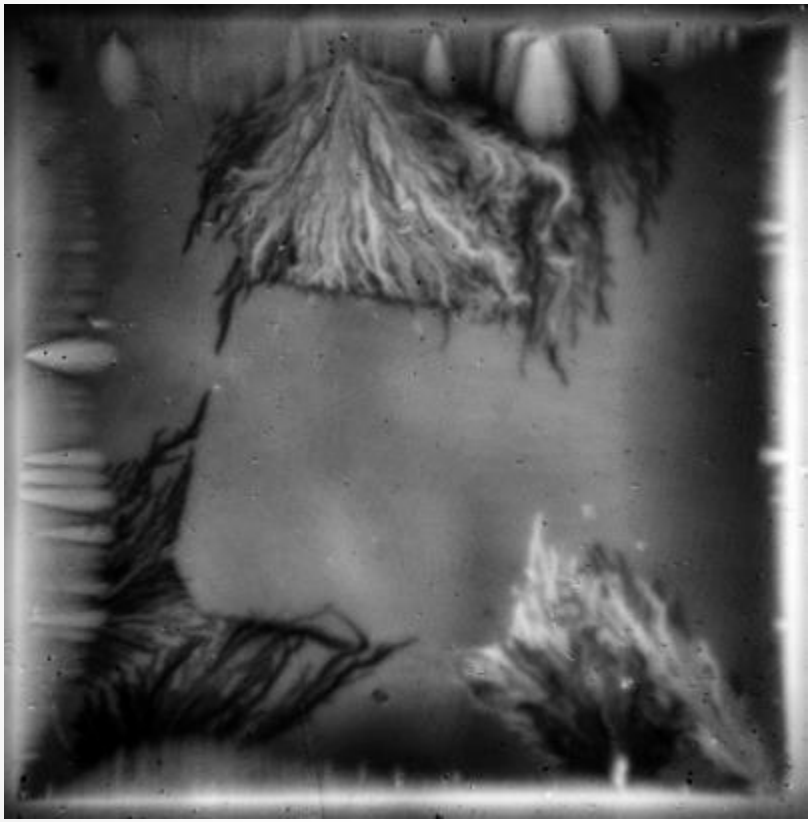
Flux density map on different stages of dendrite penetration into superconducting sample.

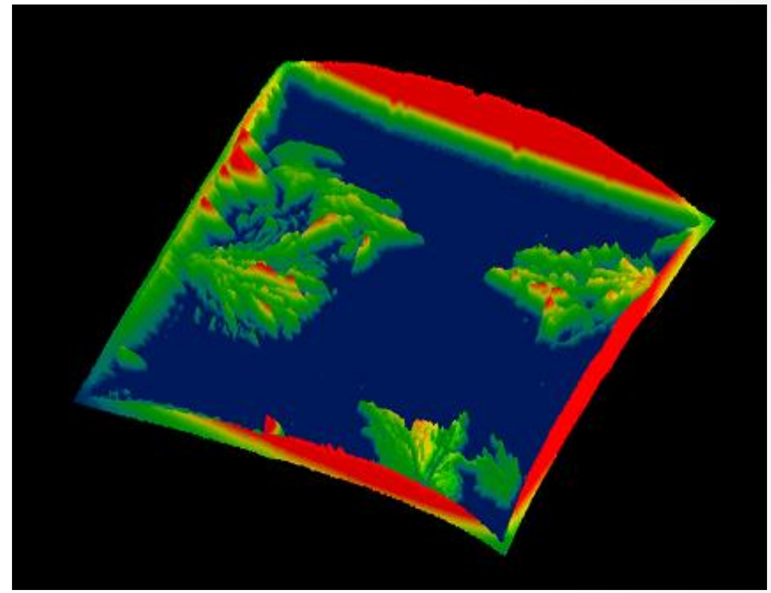
Distribution of electrical current on different stages of dendrite penetration into the sample.

Distribution of temperature during dendrite penetration into the sample. The sample can be overheated above critical temperature.

19. What is the physics behind the formation of dendritic flux avalanches? Does it need positive or negative feedback?

Protection of electronic equipment from dendritic avalanches



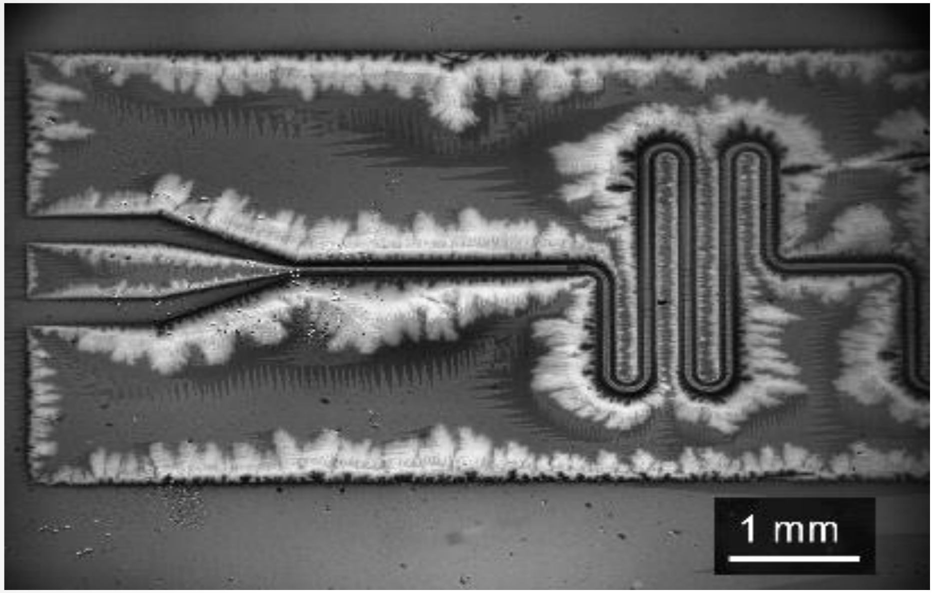


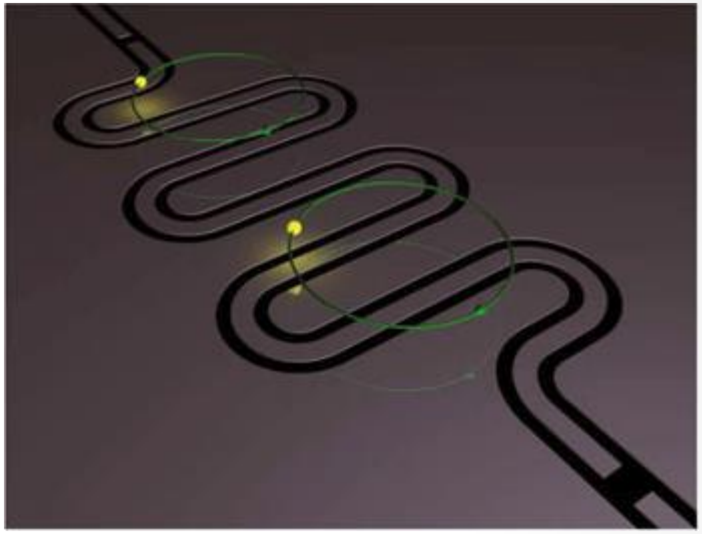
Distribution of magnetic flux in NbN superconducting film at 4 K.

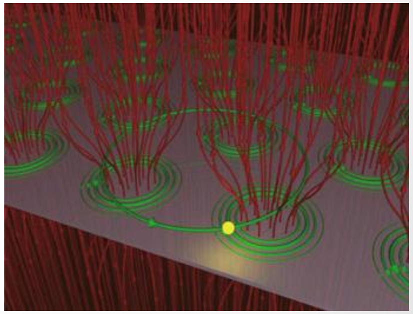
A conductive layer effectively protects an area of the film from the avalanche. Only the fast motion of flux could be screened.

20. What are main techniques for investigating dendritic flux avalanches?

Superconducting trap for single electrons.







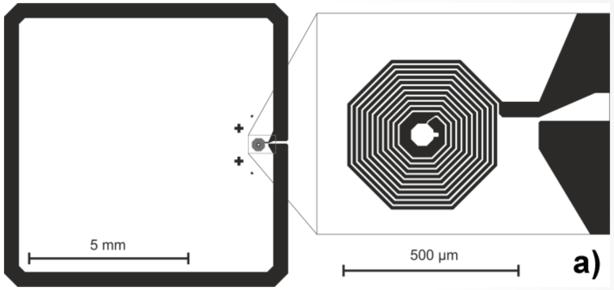
Eur. Phys. J. D 63, 9–16 (2011) DOI: 10.1140/epjd/e2011-10517-6

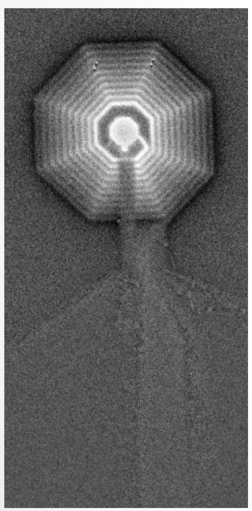
UiO University of Oslo

UNIVERSITY OF BIRMINGHAM

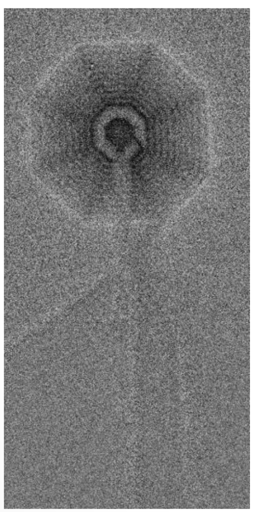
Detector of electromagnetic waves for magnetoencephalography

Magneto-optical imaging is crucial for checking quality of superconducting transformer

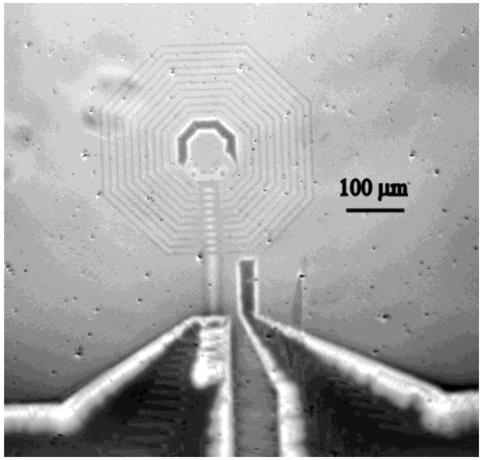


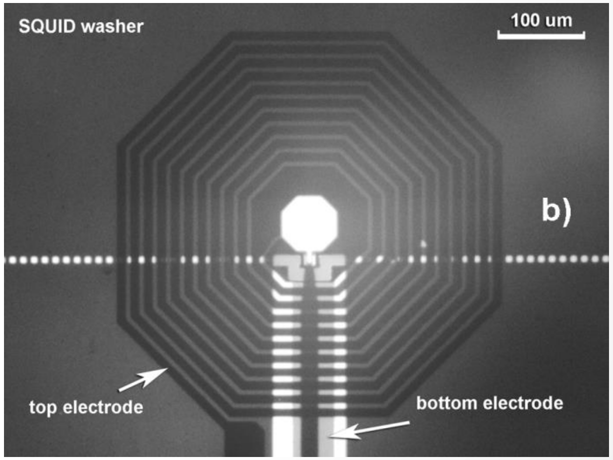


t = 0 s

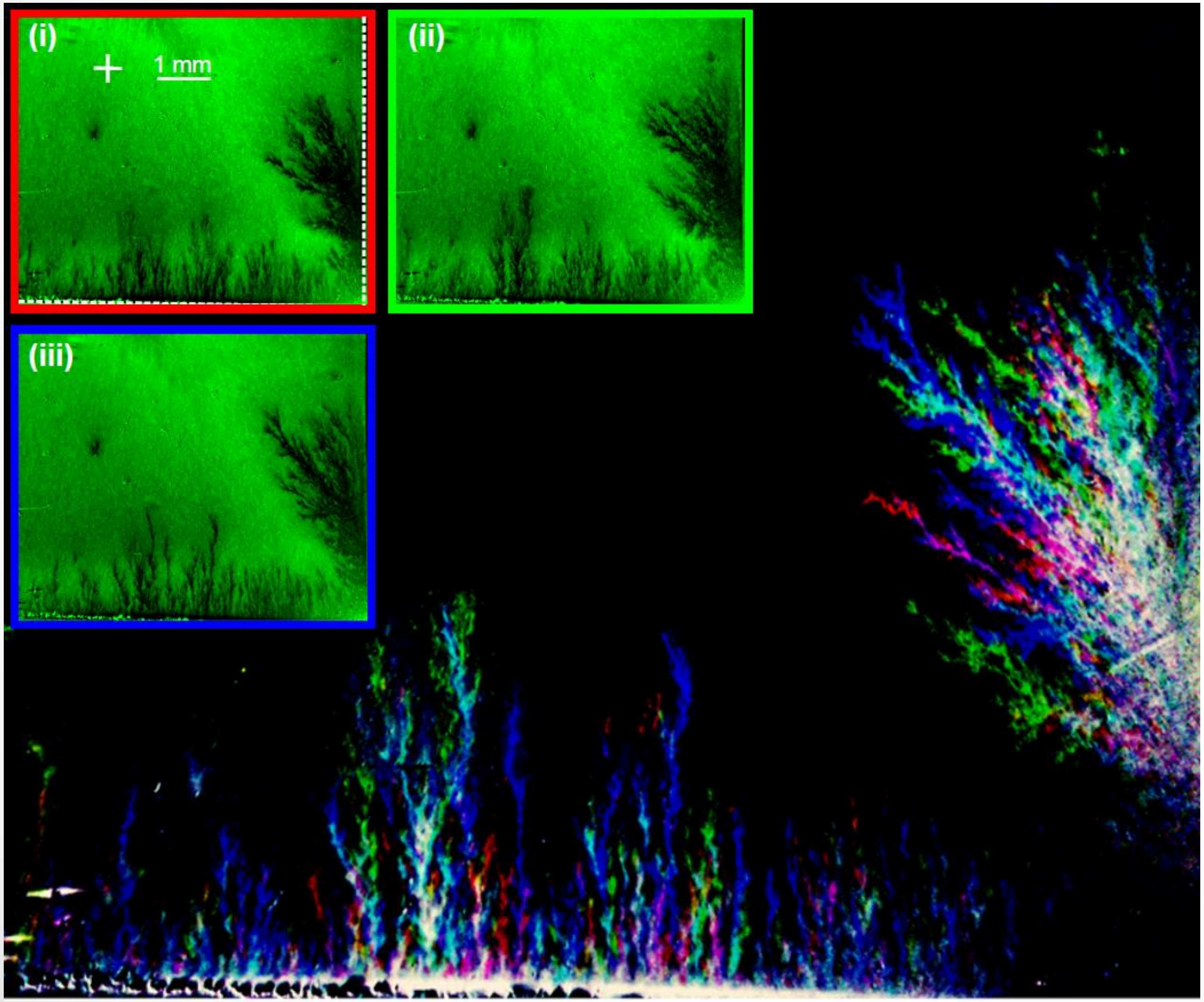


t = 0.6 s



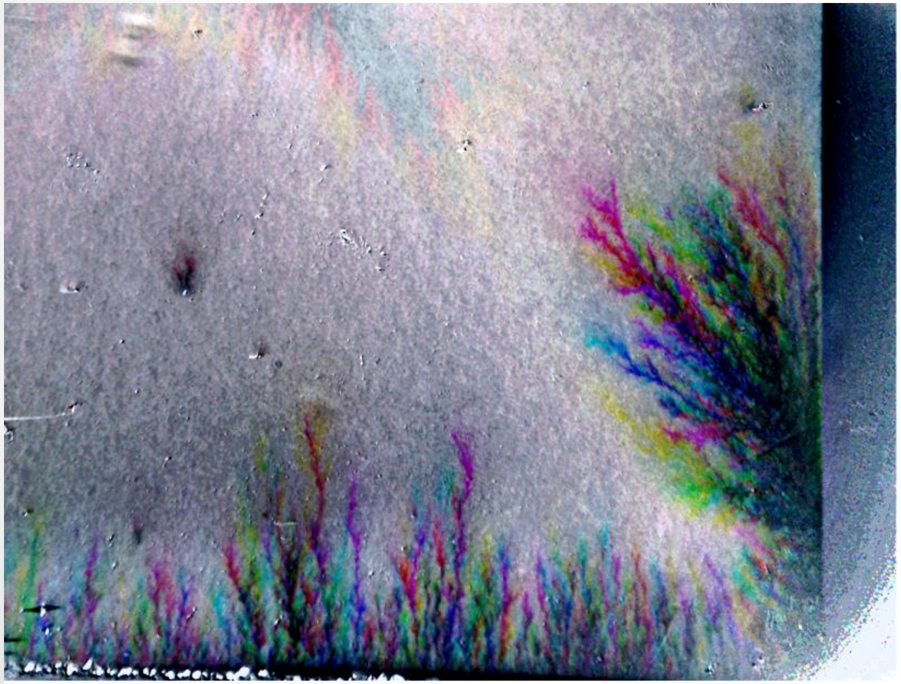


Magnetic flux penetration in Nb single crystal



Visualization of super-conducting surface state

Dendritic flux avalanches in superconducting Nb single crystal



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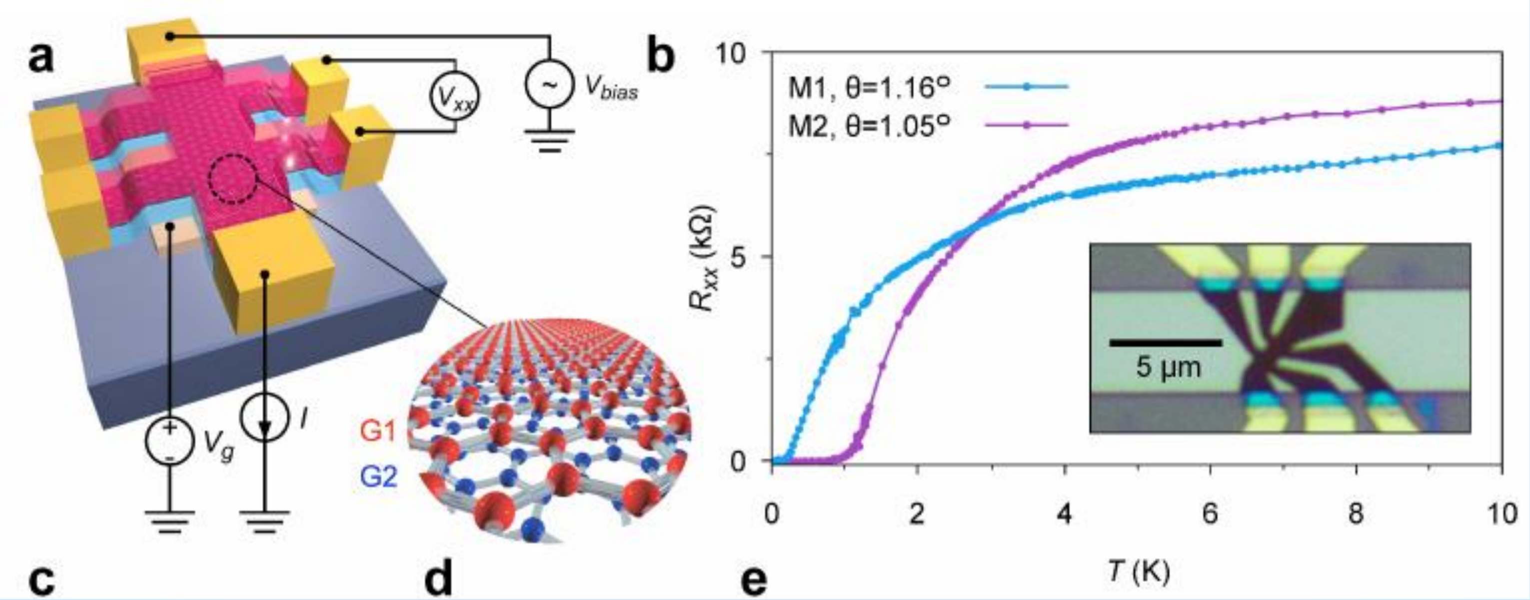
nature Accelerated Article Preview

ARTICLE
doi:10.1038/nature26160

Unconventional superconductivity in magic-angle graphene superlattices

Yuan Cao, Valla Fatemi, Shiang Fang, Kenji Watanabe, Takashi Taniguchi, Efthimios Kaxiras & Pablo Jarillo-Herrero



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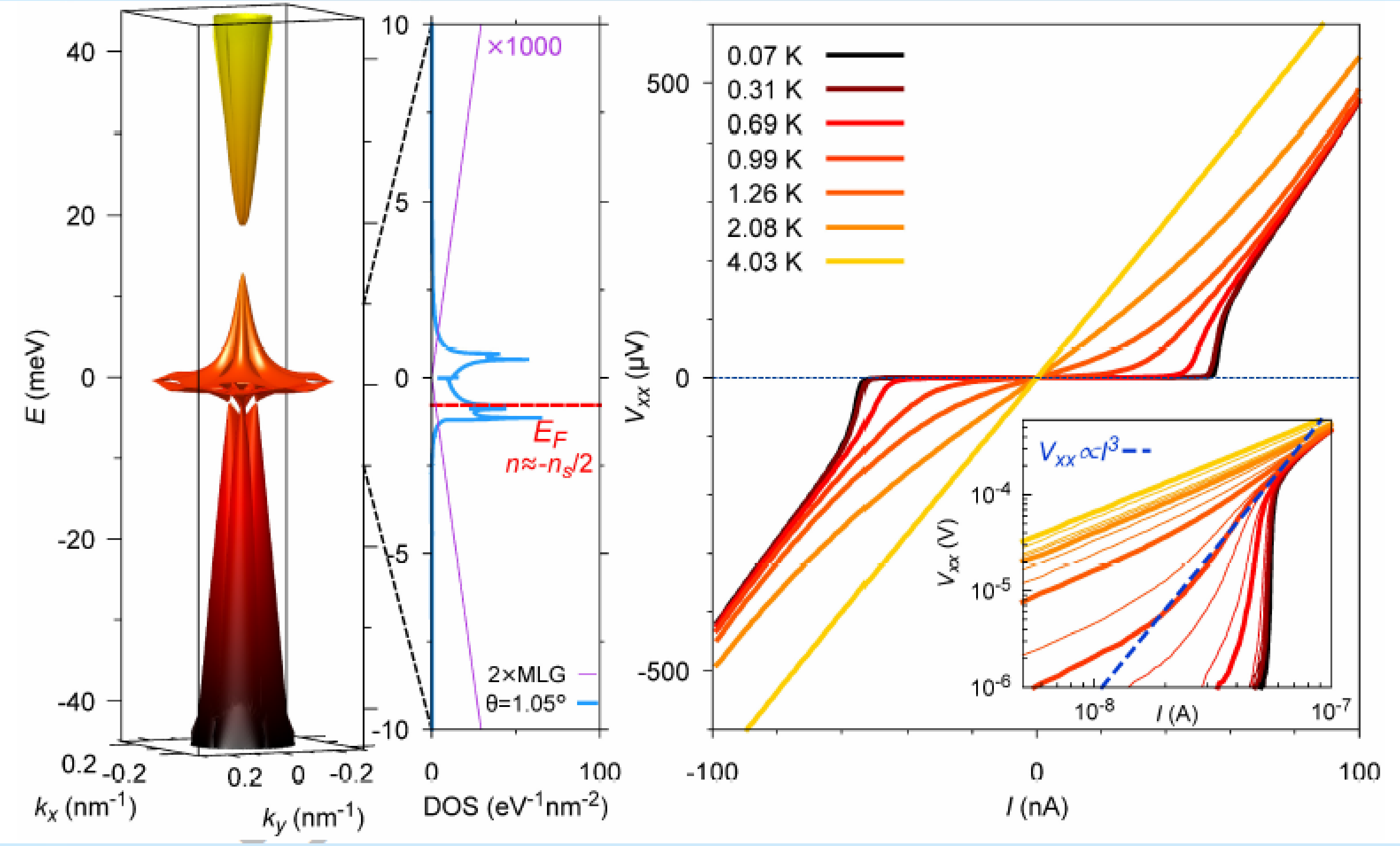

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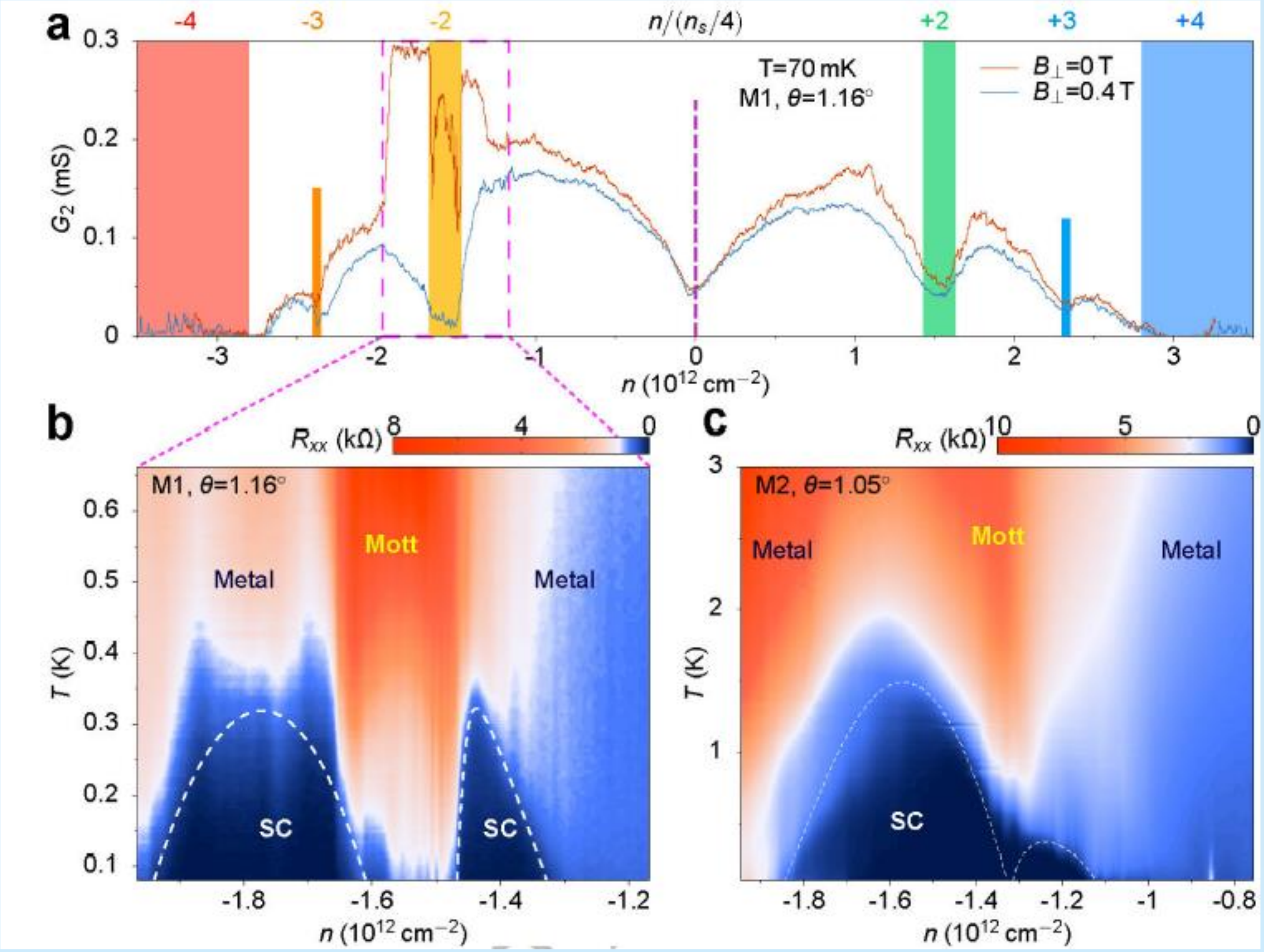


2021 highlight

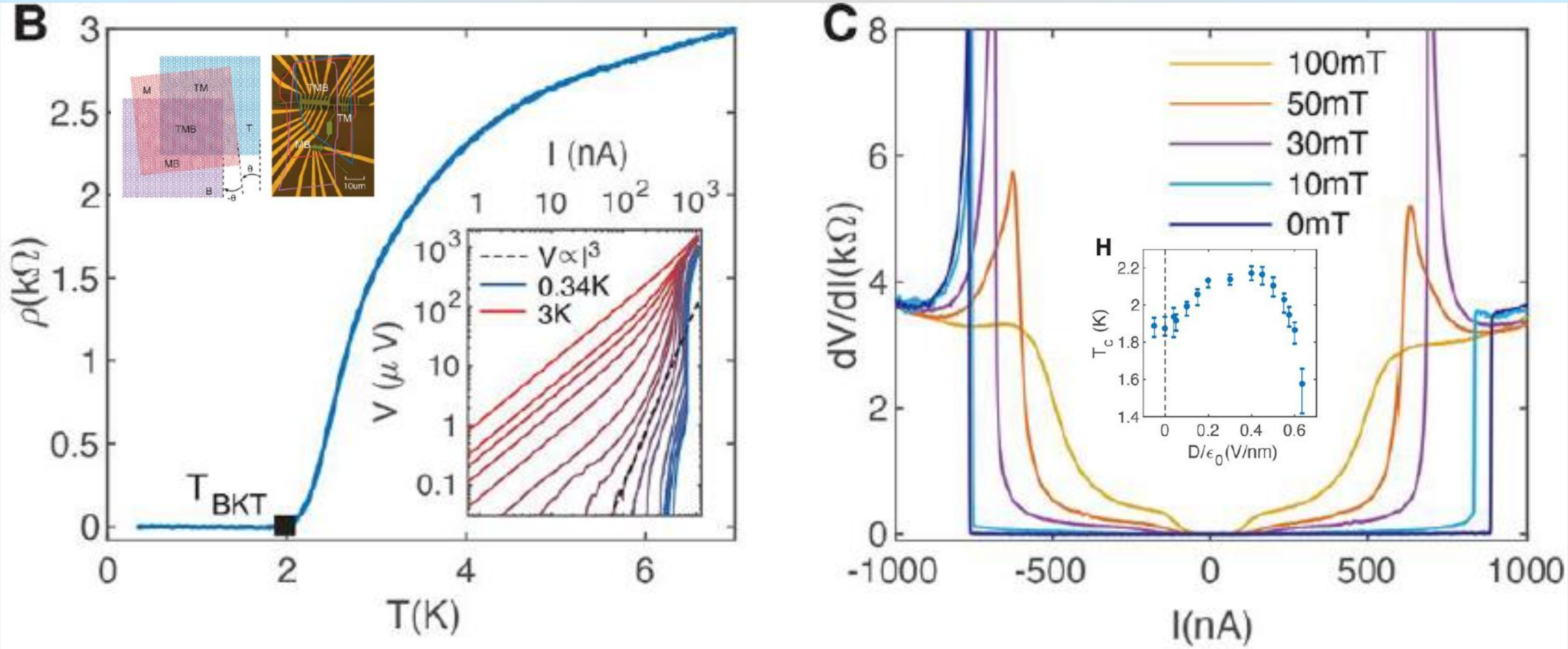
Cite as: Z. Hao *et al.*, *Science* 10.1126/science.abg0399 (2021).

Electric field tunable superconductivity in alternating twist magic-angle trilayer graphene

Zeyu Hao[1]*, A. M. Zimmerman[1]*, Patrick Ledwith[1], Eslam Khalaf[1], Danial Haie Najafabadi[1], Kenji Watanabe[2], Takashi Taniguchi[3], Ashvin Vishwanath[1], Philip Kim[1]†

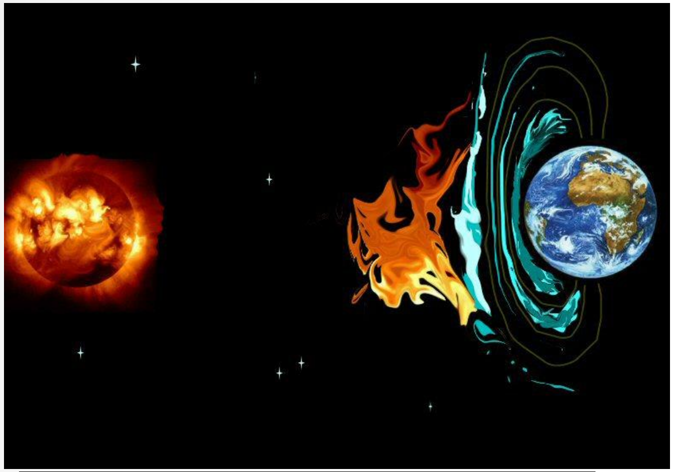
[1]Department of Physics, Harvard University, Cambridge, MA 02138, USA. [2]Research Center for Functional Materials, National Institute for Material Science, 1-1 Namiki, Tsukuba 305-0044, Japan. [3]International Center for Materials Nanoarchitectonics, National Institute for Material Science, 1-1 Namiki, Tsukuba 305-0044 Japan.

Engineering moiré superlattices by twisting layers in van der Waals (vdW) heterostructures has uncovered a wide array of quantum phenomena. Here, we construct a vdW heterostructure consisting of three graphene layers stacked with alternating twist angles ±θ. At the average twist angle θ ~ 1.56°, a theoretically predicted magic angle for the formation of flat electron bands, we observed displacement field tunable superconductivity with a maximum critical temperature of 2.1 K.



Global applications of superconductivity

Magnetic field protection of Earth during poles reversal

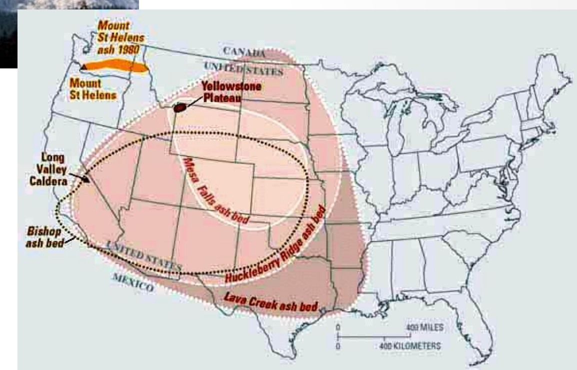


The liquid hydrogen-cooled superconducting pipeline encircling planet could be built

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

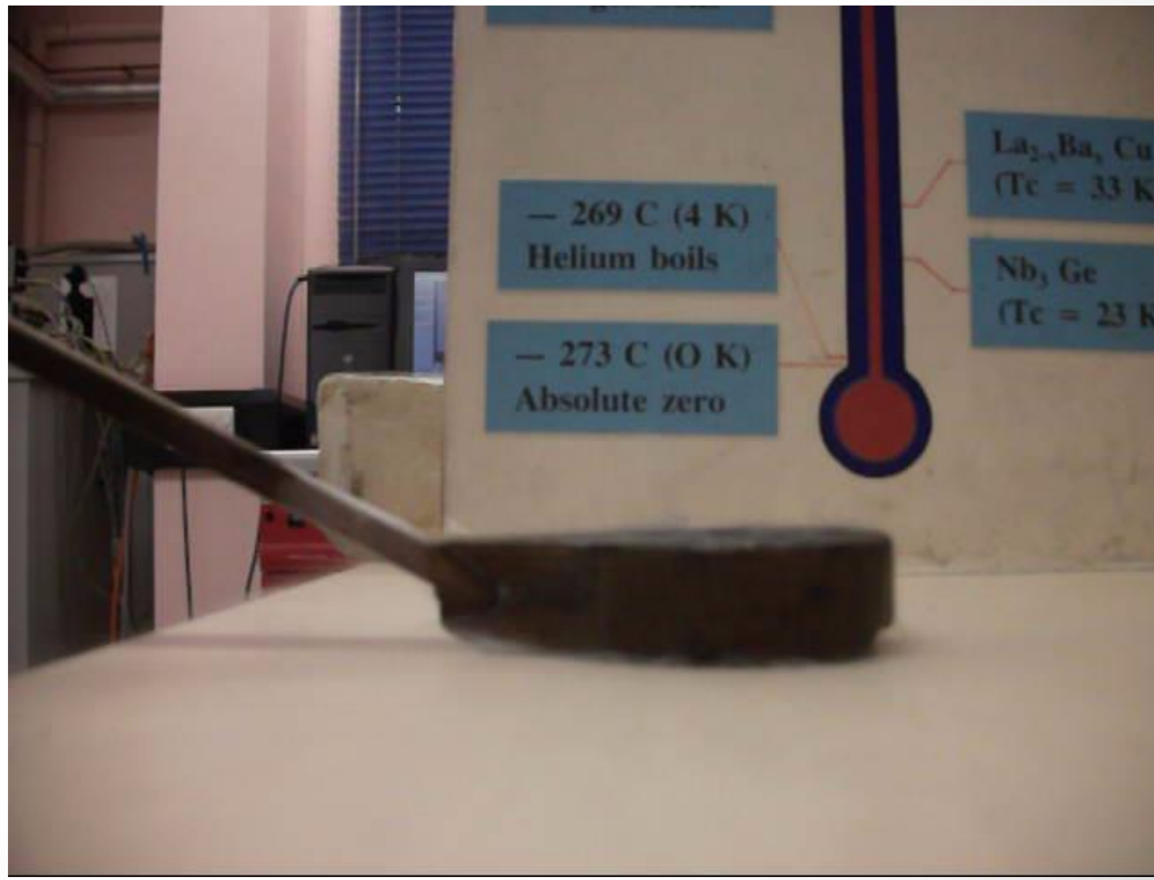
Prevention of super-volcano eruption

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



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



Conclusions

- Superconductivity is unique phenomenon that is very important for practical applications.
- Transition to hydrogen economy gives unique opportunity for superconductivity. Combination of superconductivity and hydrogen economy promises efficient solution of current energy and ecology problems
- Development of superconducting materials and techniques for hydrogen economy is well under way
- Magneto-optical imaging (MOI) is an efficient technique that allows direct optical observation of magnetic flux distribution in superconducting and magnetic samples.