Superconductivity

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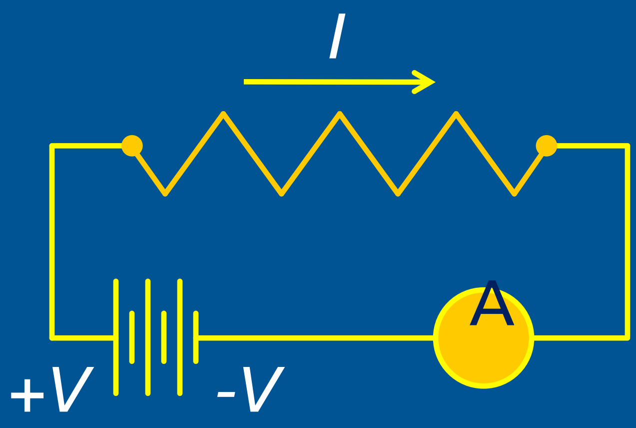
This talk:

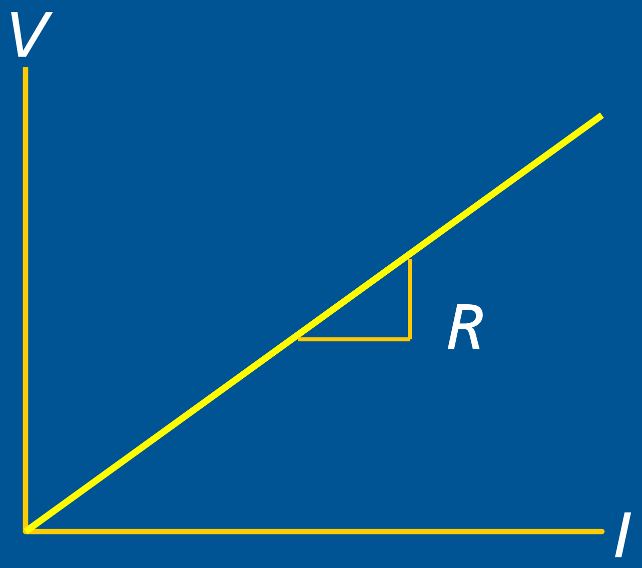
- Metallic conductors , Ohm’s law, and the effect of temperature
- Semiconductors and departures from Ohm’s law
- The need for low temperatures and liquid He
- Superconductivity in Hg
- The superconducting elements
- The Meissner effect and superconducting levitation
- Type I and type II superconductors
- Superconducting magnets and MRI
- The rudiments of Bardeen-Cooper-Schrieffer theory
- High T_C
- Newer systems

Metallic conductors and Ohm’s Law

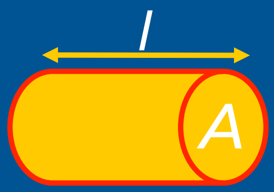
Georg Simon Ohm (1789–1854); law stated in 1827: $V = IR$

The potential difference V across a metallic conductor is proportional to the current I, and the constant of proportionality is the resistance R





The resistivity ρ incorporates sample geometry, and is an intrinsic property of all materials:
$\rho = AR / l$
Units are Ohm-meter: Ω m



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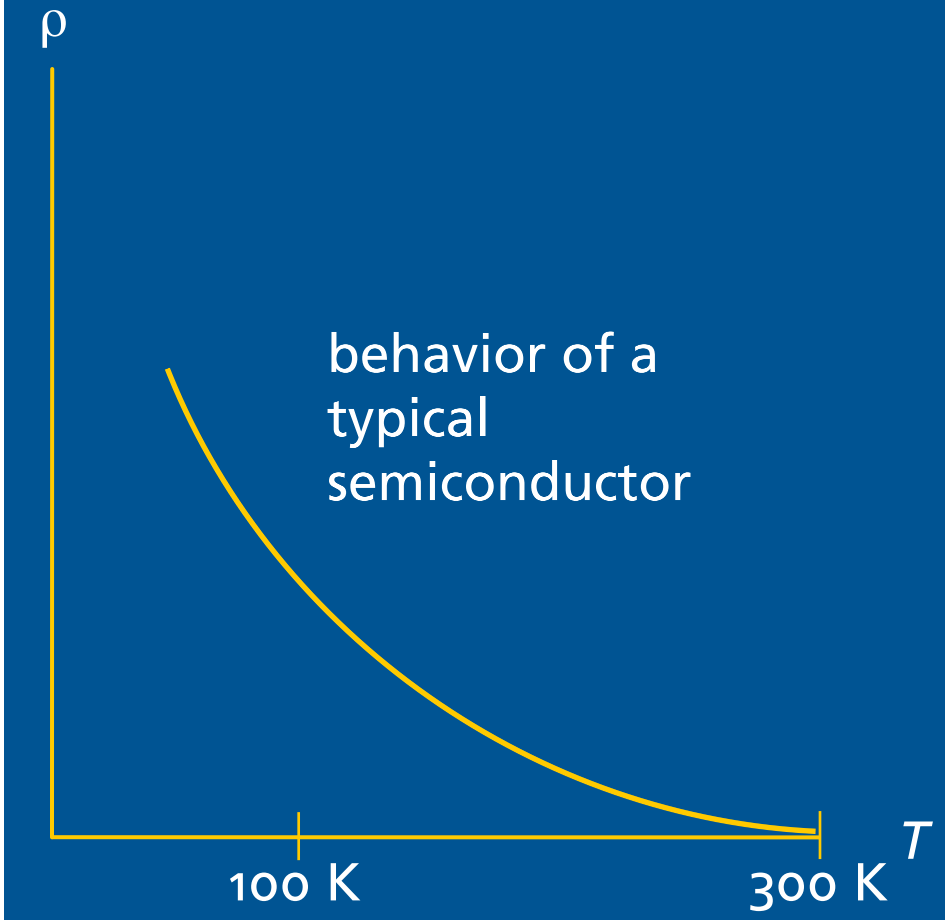
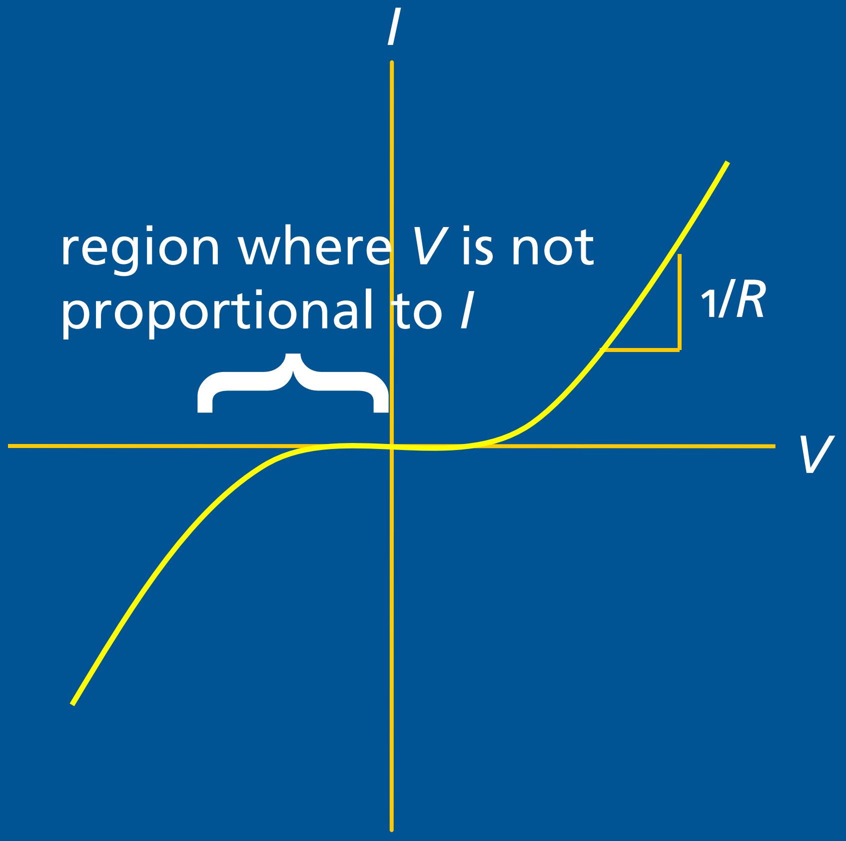
Semiconductors and departures from Ohm’s law

Semiconductors have an energy gap that prevents electrons from carrying current until a certain energy barrier is overcome. This barrier can be overcome at high temperatures, or at high voltages:





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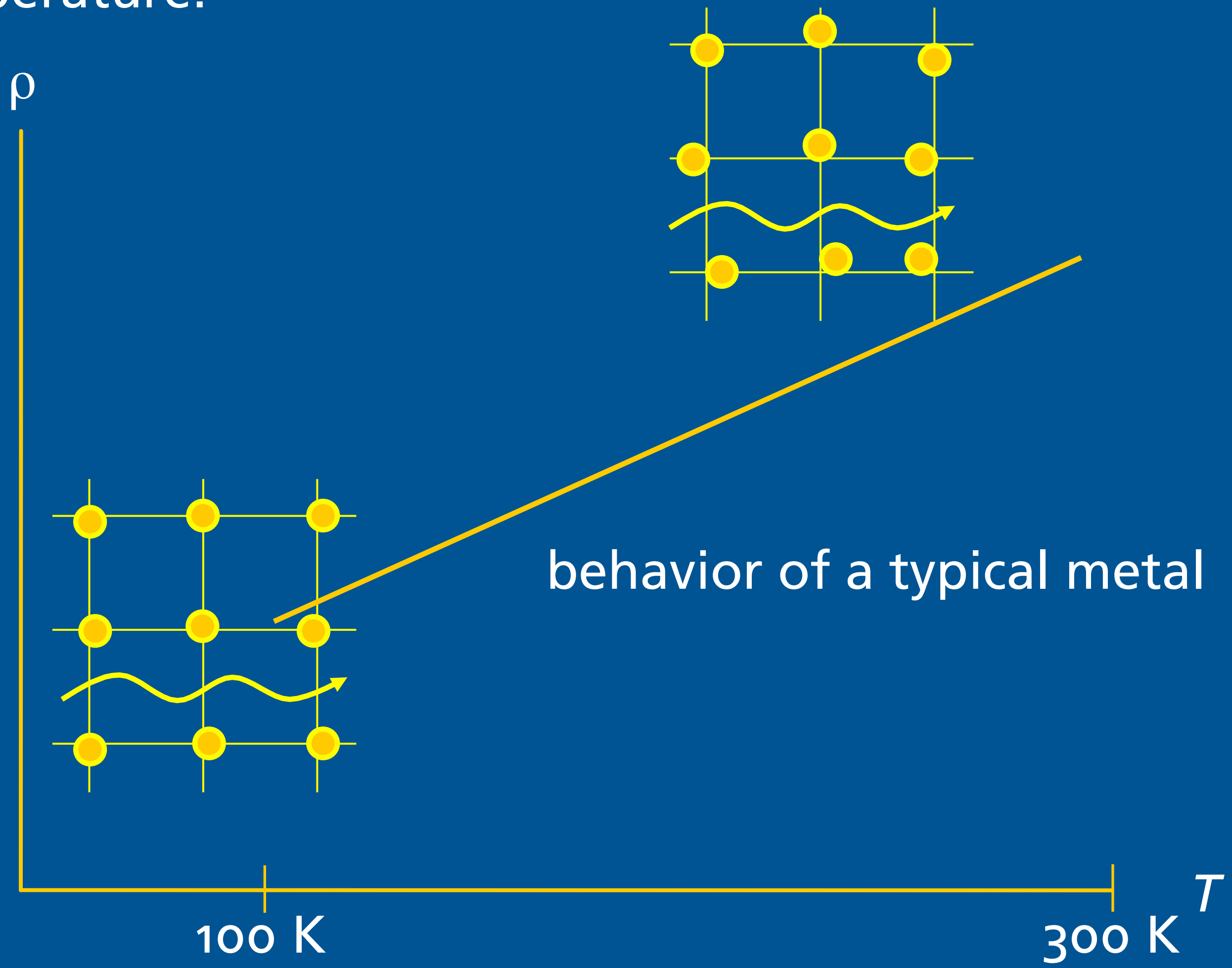
Temperature effects on metallic conductivity

Vibrations in solids (also called phonons) scatter electrons, giving rise to the resistivity, and the scattering processes increase with the temperature:



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Very low temperatures 1

How are they achieved: Cascaded refrigeration processes involving the successive compression and expansion of different gases. The order followed was: CH_3Cl (249.35 K)→ C_2H_4 (169.5 K)→ O_2 (90.20 K) → air (81.6 K) → H_2 (20.35 K)→ He (4.2 K)

Temperature scales			
Temperature	K	^oF	^oC
absolute zero	0	-459.67	273.15
Ice melting	273.15	32	0
Water boiling	373.15	212	100

Refrigeration in a nutshell: Compress a fluid *isothermally*, and then expand *adiabatically*

H. Kamerlingh Onnes, *Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium*, Nobel Lecture, December 11, 1913.

Very low temperatures 2

He (4.2 K) first achieved by Heike Kamerlingh Onnes at the University of Leiden in the Netherlands, 1908

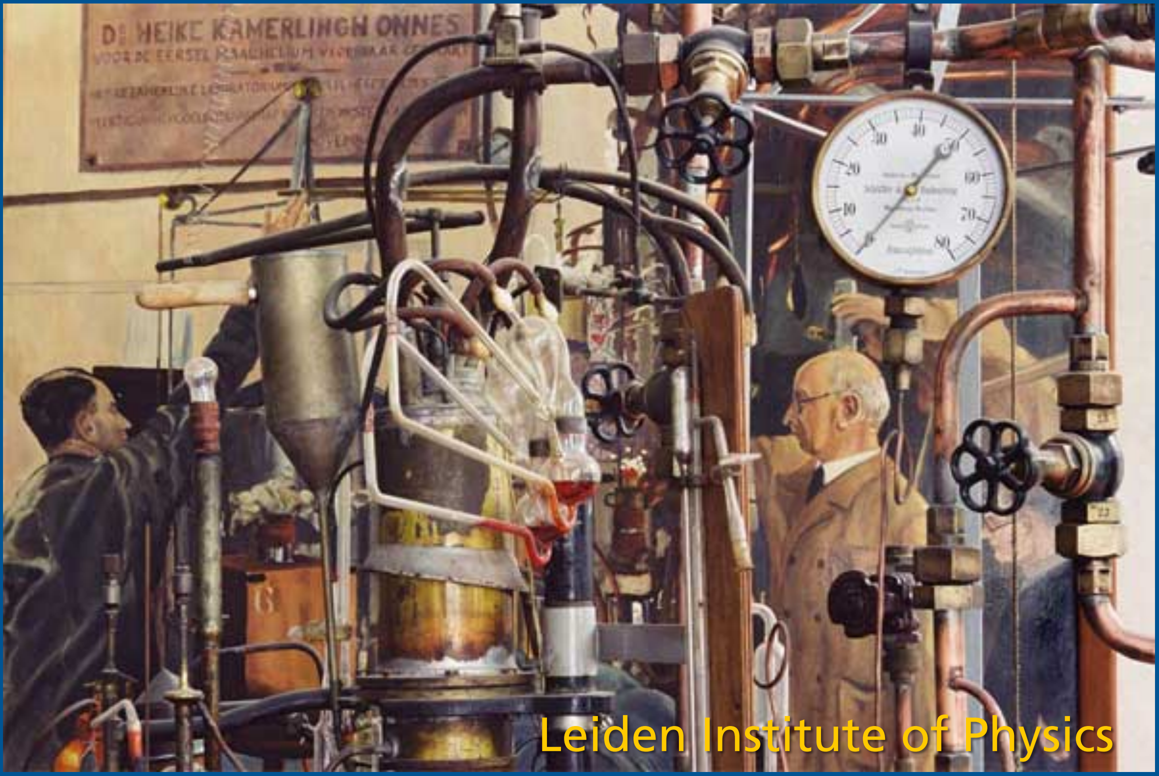
"How happy I was to be able to show condensed helium to my distinguished friend Van der Waals, whose theory had guided me to the end of my work on the liquefaction of gases"


nobel.se

H. Kamerlingh Onnes, *Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium*, Nobel Lecture, December 11, 1913.

Very low temperatures 3

He (4.2 K) first achieved by Heike Kamerlingh Onnes at the University of Leiden in the Netherlands, 1908



Leiden Institute of Physics

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H. Kamerlingh Onnes, *Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium*, Nobel Lecture, December 11, 1913.

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Very low temperatures 4

More pictures of the equipment: An abstract view (left) and the Cailletet compressor (right)


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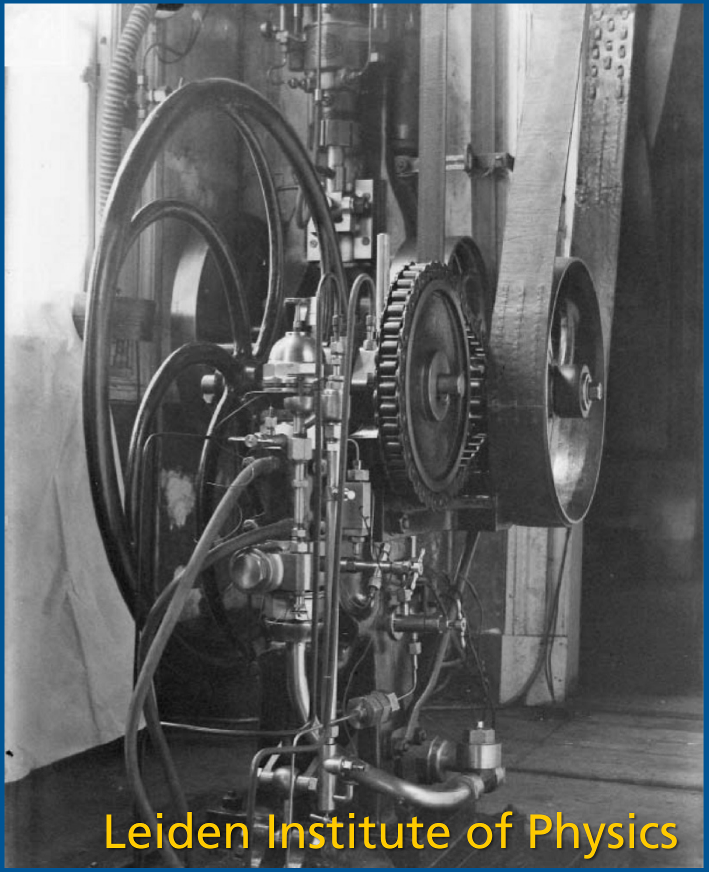
Leiden Institute of Physics

D. Van Delft, *Little cup of helium, big science, Physics Today* March 2008, page 26.

Very low temperatures 5: How it is done today

ARS Cryosystems*
closed cycle refrigerator
(4.2 K to 400 K)

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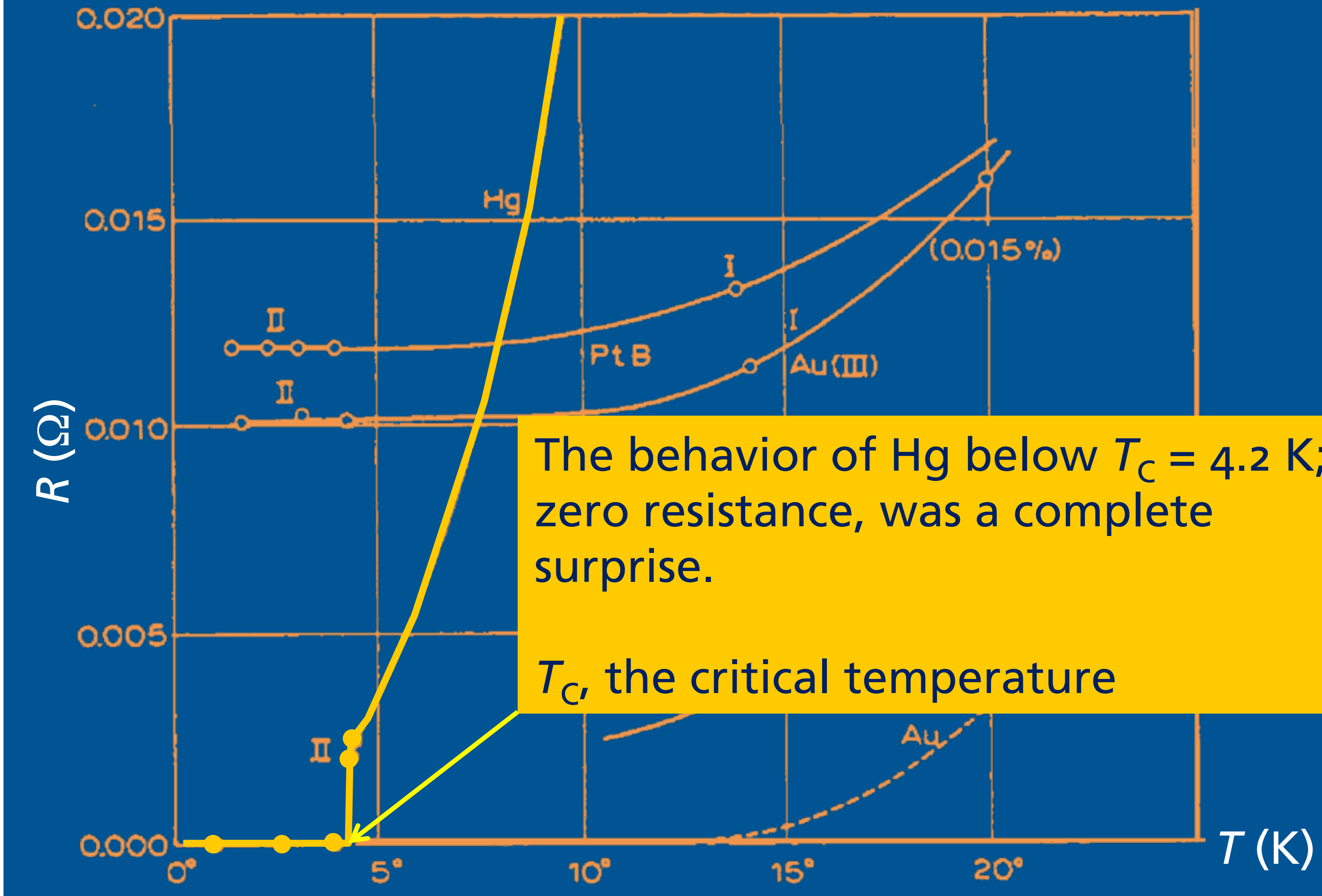
Metals at very low temperatures

Some ideas:

Augustus Mathiessen recognized that the resistivity of metal decreases as the temperature is decreased.
[Matthiessen and Vogt, *Philos. Trans. R. Soc. London*, **153** (1863) 369-383]

Lord Kelvin: Electrons would be cooled down till they came to complete halt, *ie.* metals would become completely insulating at the absolute zero.

The discovery of superconductivity in Hg (1911)



The behavior of Hg below T_C = 4.2 K; zero resistance, was a complete surprise.

T_C, the critical temperature

H. Kamerlingh Onnes, Nobel Lecture, December 11, 1913.

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What was happening ? A new quantum ground state

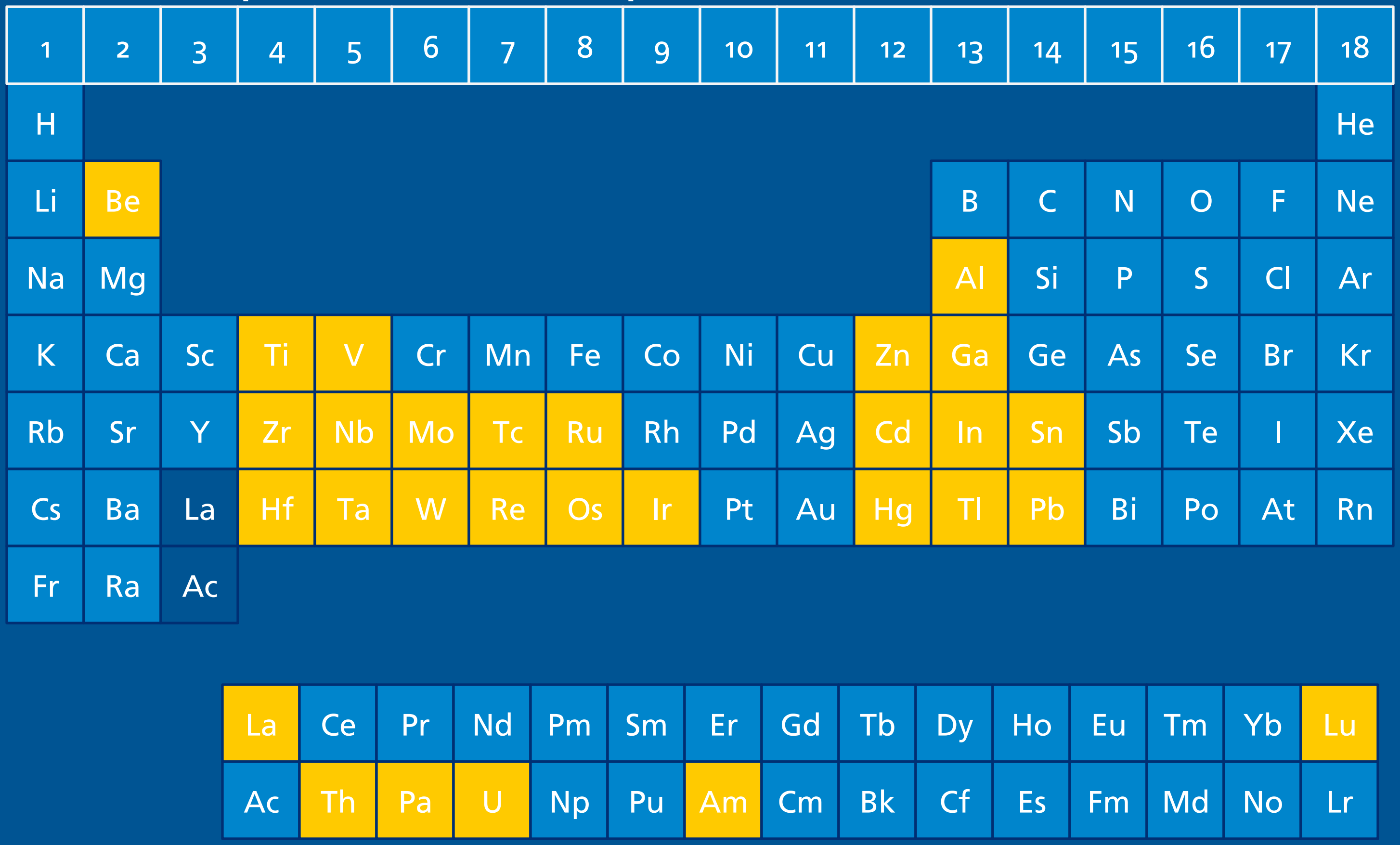
"… something unexpected occurred. The disappearance did not take place gradually but ***abruptly****. From 1/500 the resistance at 4.20 K drops to a millionth part. At the lowest temperature, 1.50 K, it could be established that the resistance had become less than a thousand-millionth part of that at normal temperature."*

Rather than immersing myself in a possible explanation based on the quantum theory, I should like to consider …

H. Kamerlingh Onnes, Nobel Lecture, December 11, 1913.

The superconducting elements 1

Bulk samples at ambient pressure:



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

La	Ce	Pr	Nd	Pm	Sm	Er	Gd	Tb	Dy	Ho	Eu	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

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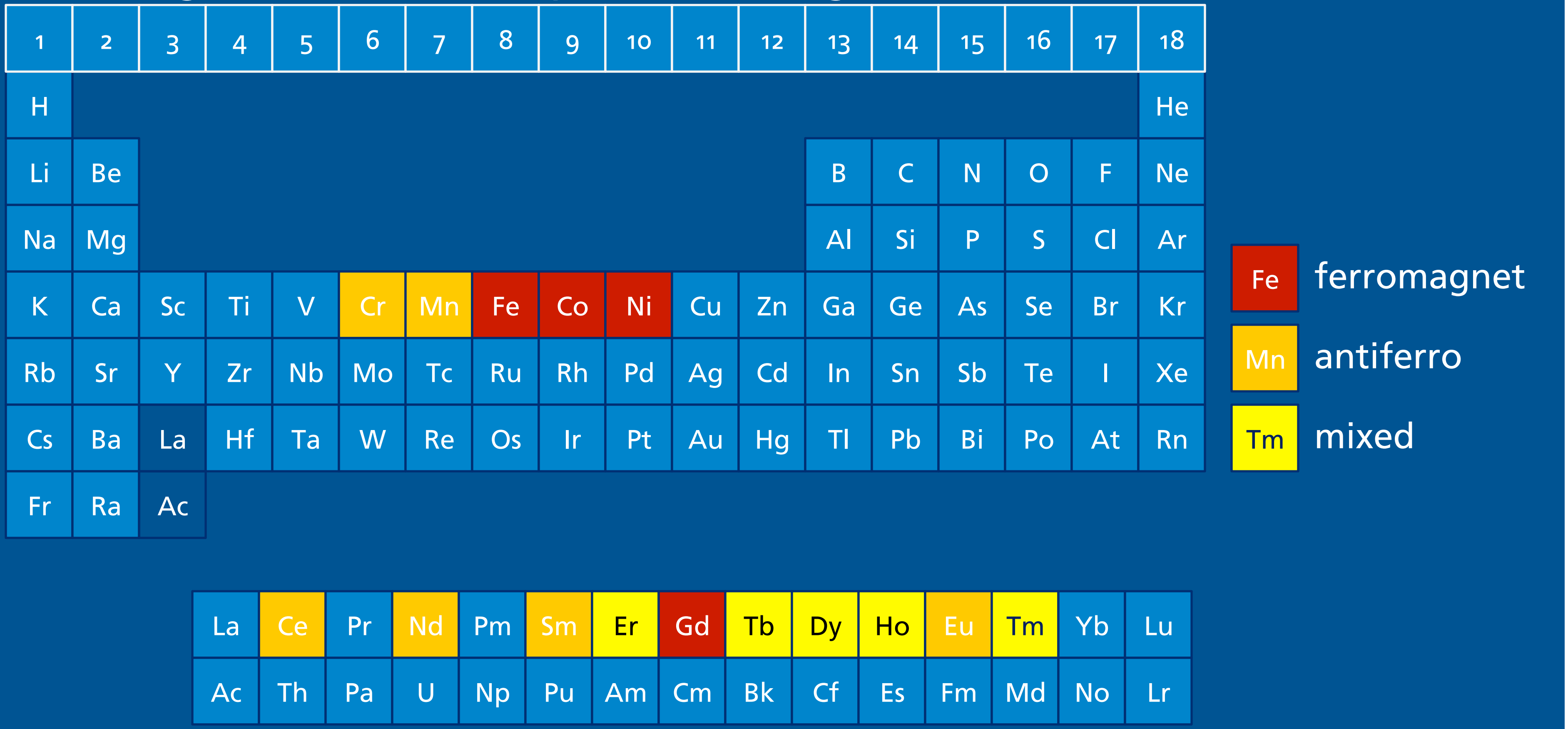
The superconducting elements 2

The magnetic (and *not* superconducting) elements:



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K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

La	Ce	Pr	Nd	Pm	Sm	Er	Gd	Tb	Dy	Ho	Eu	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

🟥 Fe	ferromagnet
🟧 Mn	antiferro
🟨 Tm	mixed

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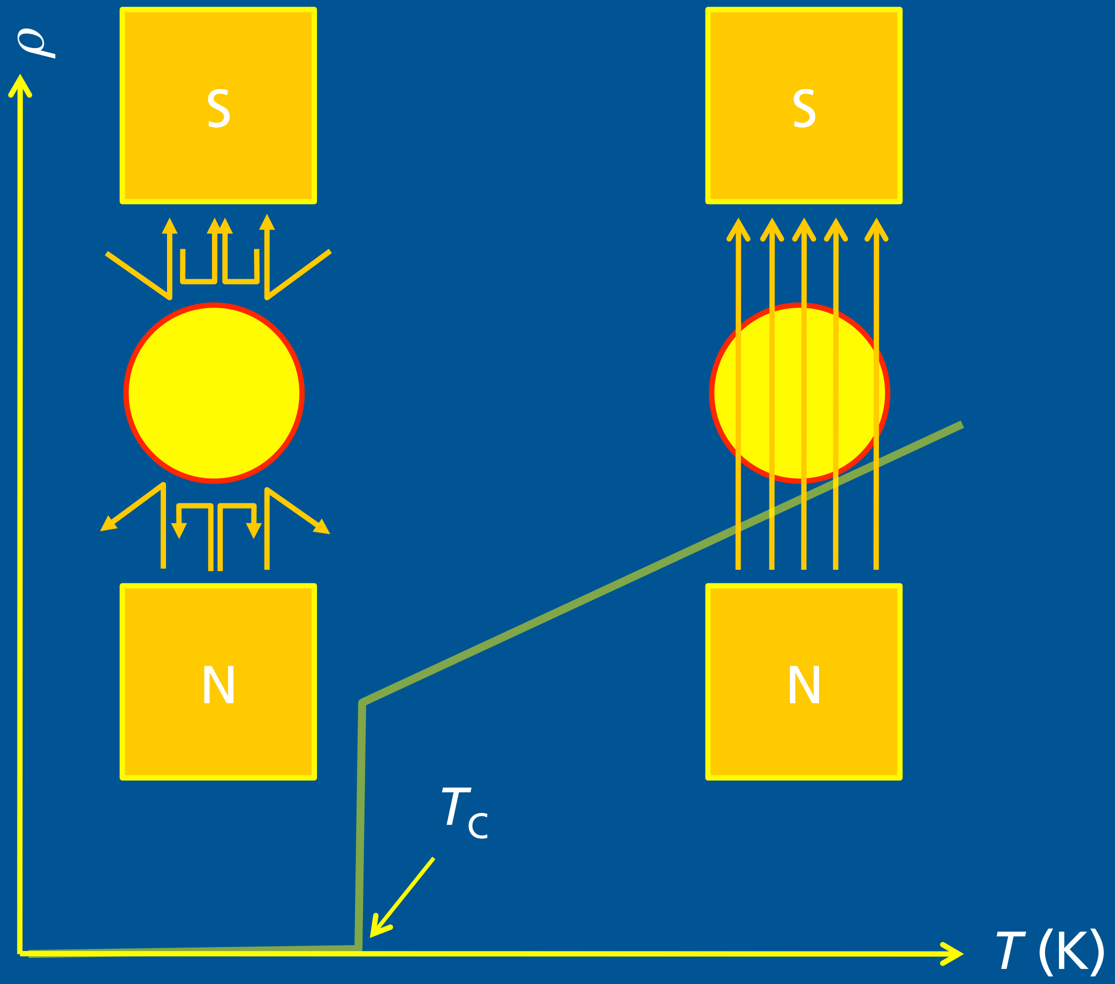
The Meissner effect (Walther Meissner 1933):



Below T_C superconductors *strongly* exclude magnetic fields; superconductors are perfect *diamagnets*

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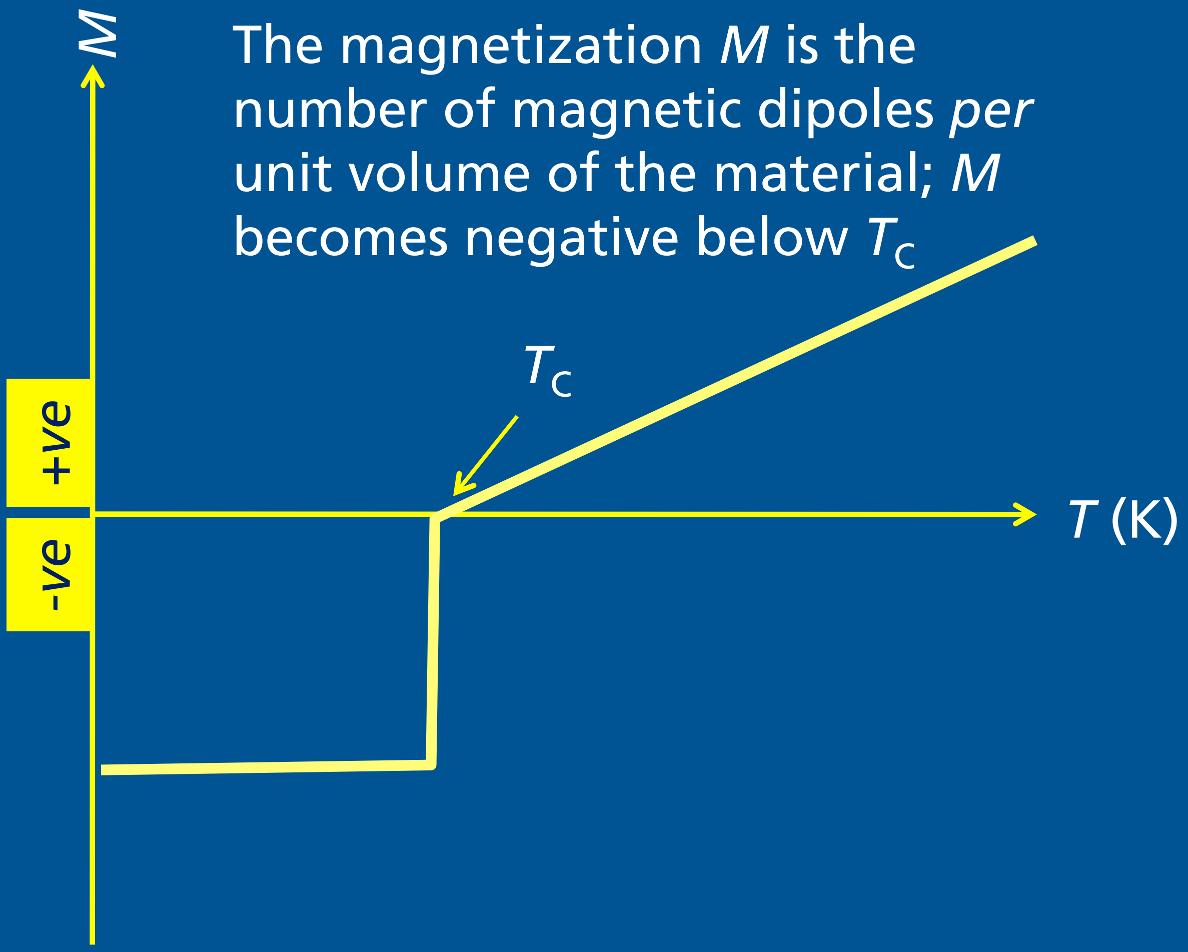
The Meissner effect (Walther Meissner 1933):



The magnetization M is the number of magnetic dipoles *per* unit volume of the material; M becomes negative below T_C

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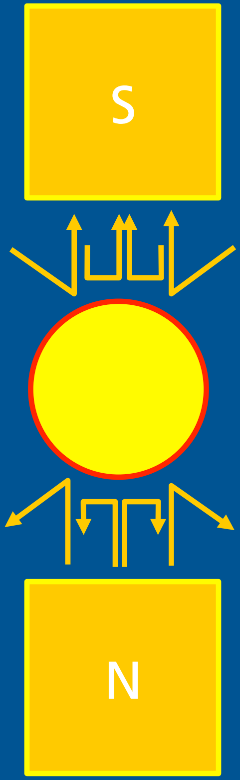
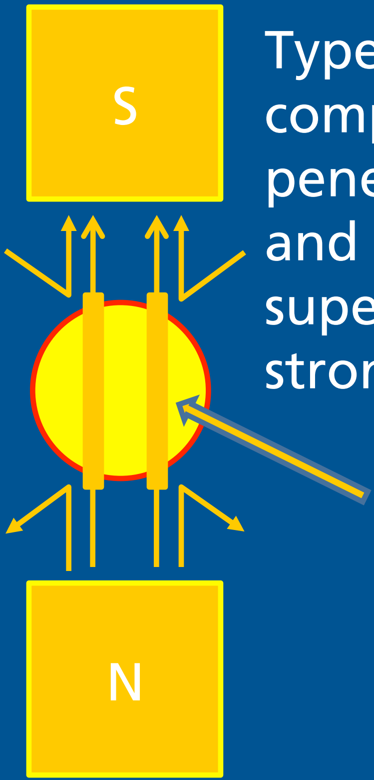
Type I and type II superconductors



Type I superconductors (usually pure metals) do not allow magnetic fields to penetrate. Above a critical field H_{C1}, they lose their superconducting properties.



Type II superconductors (usually compounds) allow magnetic fields to penetrate between critical fields H_{C1} and H_{C2}. They lose their superconducting properties at fields stronger than H_{C2}.

A flux tube; a normal non-superconducting region in a type II superconductors between H_{C1} and H_{C2}.

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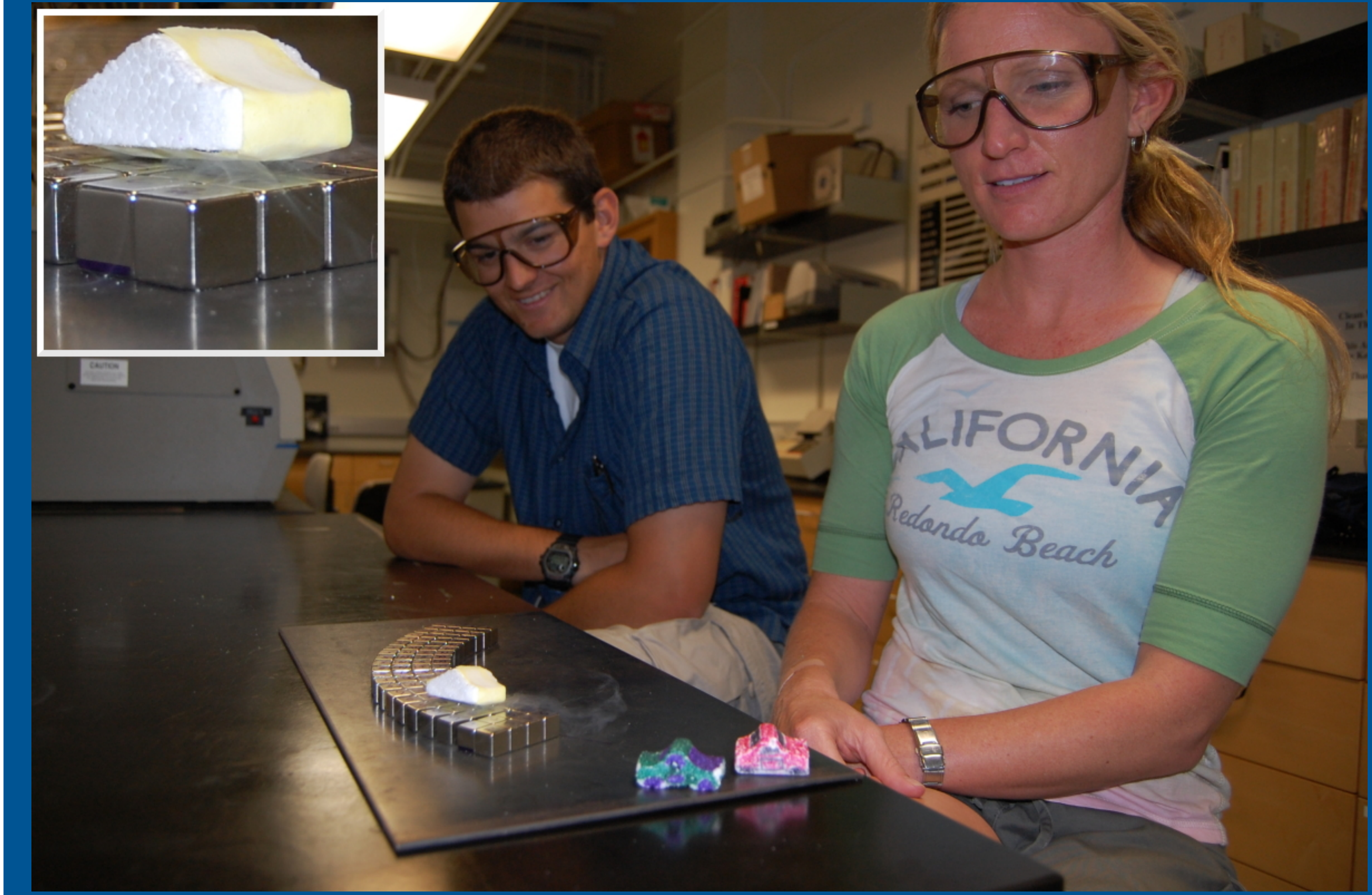
Superconducting levitation



A cooled superconductor being levitated over a track formed from many Nd-Fe-B magnets by school teachers John Gonzalez and Keri Santos: http://gonzalezret.blogspot.com/

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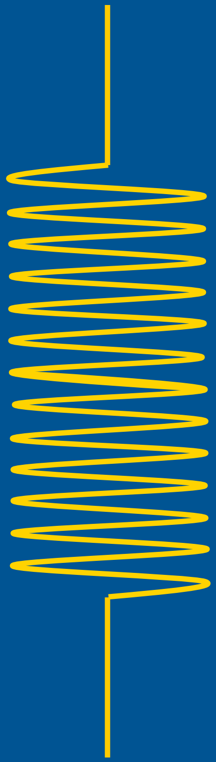
Superconducting levitation

On a larger scale, the worlds fastest train, a Japan Rail prototype uses superconducting magnets: http://en.wikipedia.org/wiki/JR—Maglev

Superconducting magnets



A solenoid is a current-carrying coil. According to the Ampère's law applied to a long coil, the magnetic field it develops is given by:

$$B = \mu_0 \frac{N}{L} I$$

The magnetic field intensity increases with the number of turns *N per* a given length *L* of the wire, and the current *I*.

For a normal (resistive) coil, high current and many turns means solenoids can melt (and they do) before high magnetic fields are reached.

The solution: Use a superconducting solenoid.

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Superconducting magnets

This whole body Magnetic Resonance Imaging (MRI) system [from Siemens in Germany*] uses a superconducting 3 T magnet.

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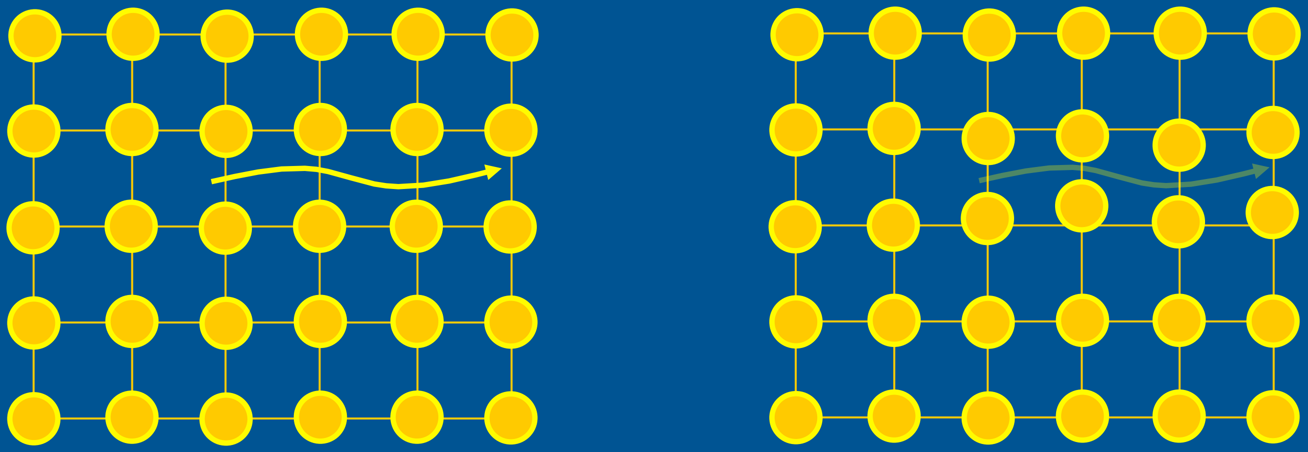
Bardeen-Cooper-Schrieffer theory

Leon Cooper (1954): At low-enough temperatures, electrons pair up to form (what are now called) Cooper pairs. These travel through crystals carrying pairs of charges ($2e^{-}$) without resistance.

John Bardeen, Leon Cooper and Robert Schrieffer (1957): The attractive pairing occurs because of crystal vibrations: As an electron travels through the crystal, it perturbs atoms near its path …



… the perturbation makes it more attractive for another electron to follow closely. This is the virtual "attraction".

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Bardeen-Cooper-Schrieffer theory: Tests

If it is about vibrations of the crystal, then perturbing the crystal should influence superconductivity. This is indeed verified by:

1. Isotope effects: Replacing atoms by heavier or lighter isotopes changes the T_C in a predictable manner.

2. Changing the nature of the vibrations by applying pressure on the crystal changes T_C in a predictable manner.

For their development of the theory, Bardeen, Cooper and Schrieffer were awarded the 1972 Nobel Prize in physics. [Pictures from nobel.se]

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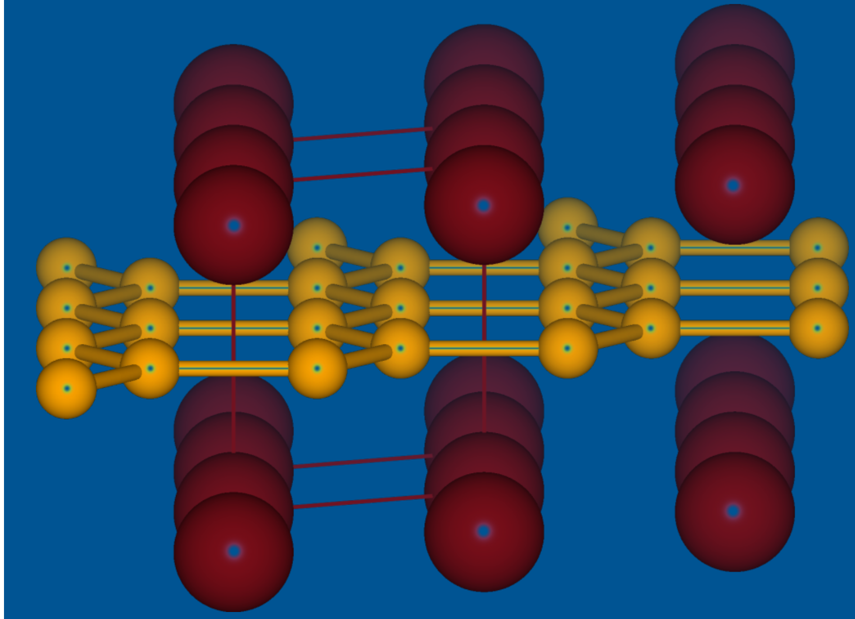
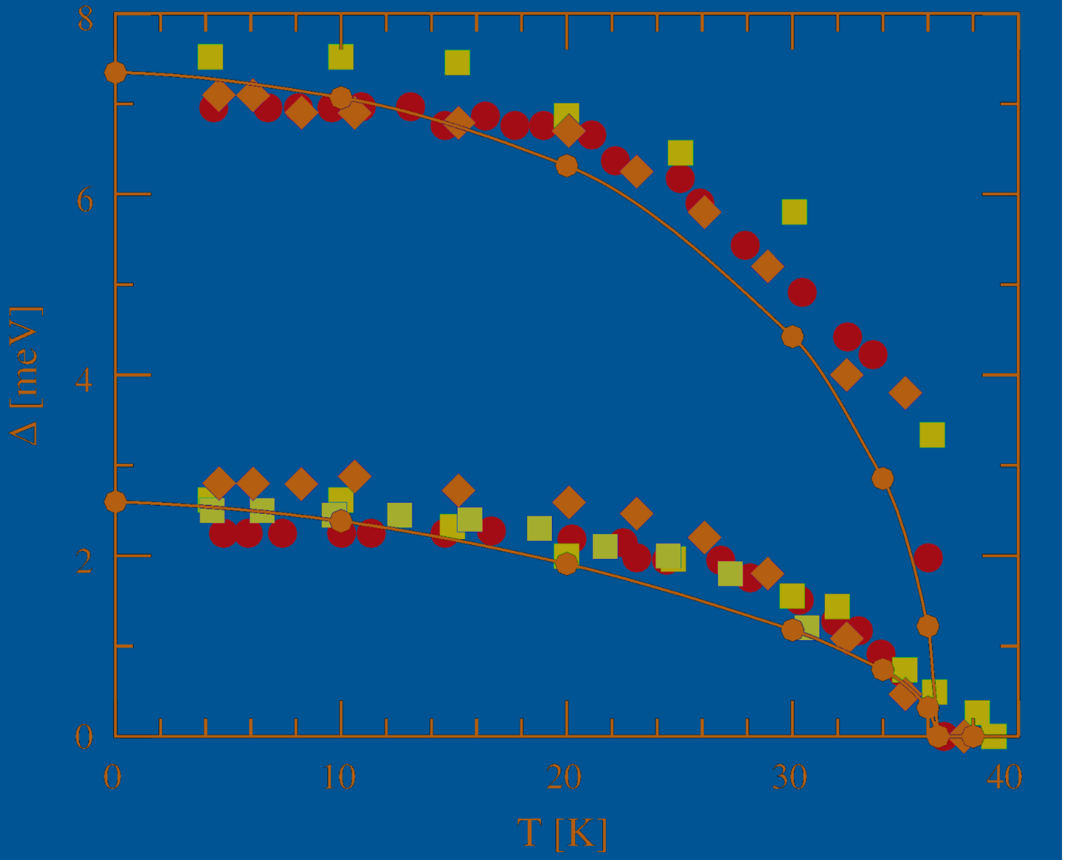
Bardeen-Cooper-Schrieffer theory: Understanding

On the left is the layered crystal structure of MgB_2, a BCS superconductor with T_C = 36 K. On the right are experiments (points) and calculations (lines) of the superconducting properties. The calculations use only the structure and composition as inputs.

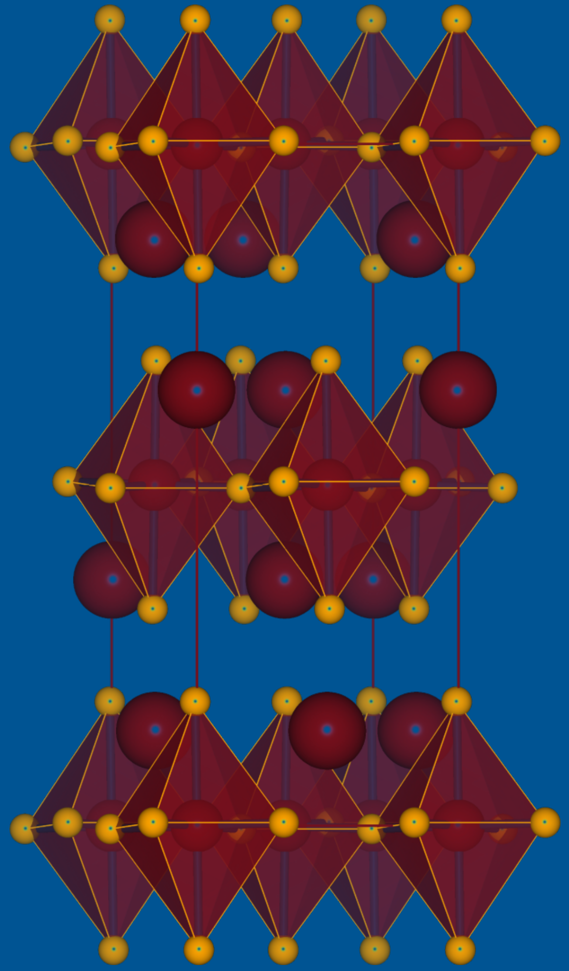




Floris *et al.* *Physica C* **456** (2007) 45—53.

High T_C

Until 1986, all superconductors possessed T_C's below 23 K. Then in 1985, Bednorz and Müller (Zurich, Switzerland) reported superconductivity above 30 K in the system $La_{2-x}Ba_xCuO_4$:



A single unit cell of $La_{2-x}Ba_xCuO_4$. Corner-connected slabs of CuO_6 octahedra are separated by double layers of La atoms.

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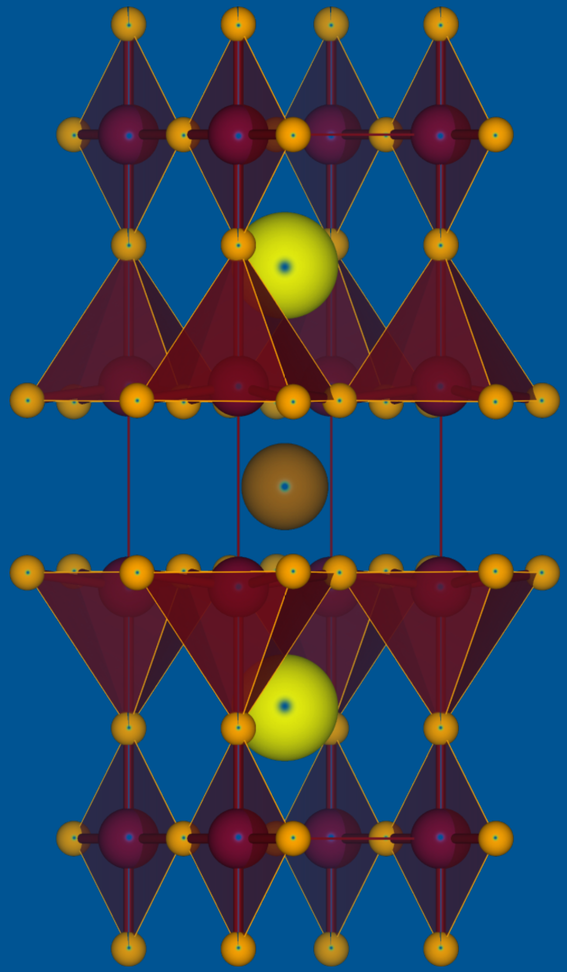
High T_C

In 1987, Paul Chu (University of Houston) and coworkers discovered the Y-Ba-Cu-O systems of oxides which are superconducting above 77 K, the boiling point of liquid N_2.



A single unit cell of $YBa_2Cu_3O_{7-\delta}$. Corner connected slabs of $Cu(2)O_5$ square pyramids are separated by layers of Y and Ba atoms, from chains of $Cu(1)O_4$.

It is this compound, with a T_C of 92 K that simplifies demonstrations of superconductivity.

These copper oxides are collectively referred to as high-T_C compounds.

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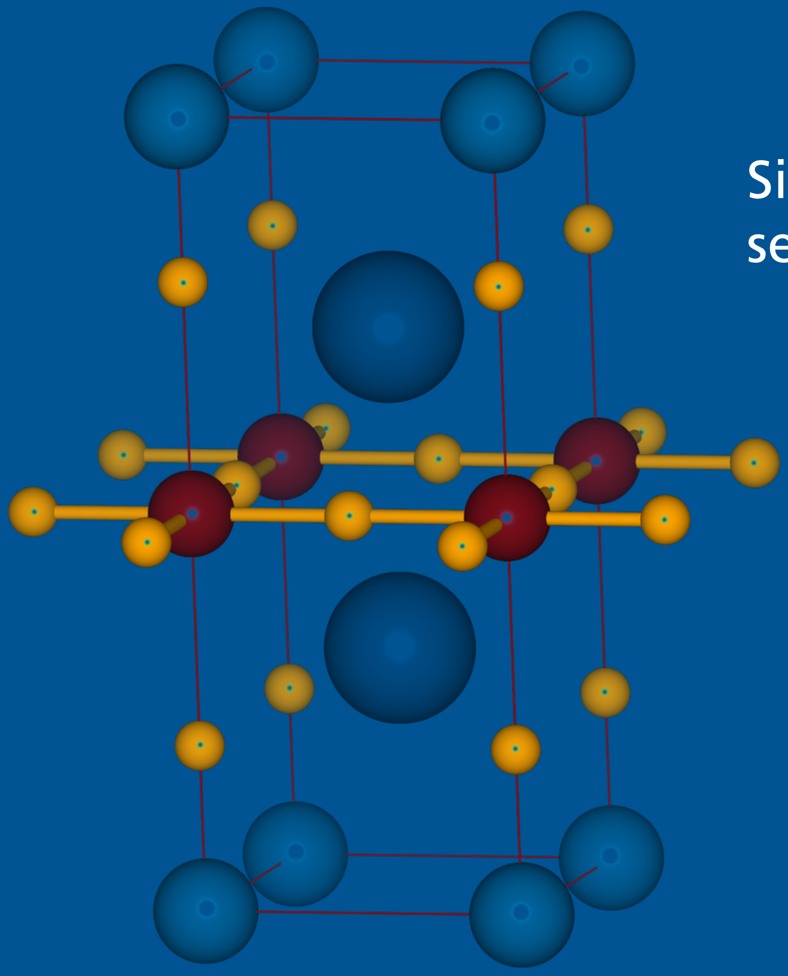
Highest T_C

Under pressure, the compound $HgBa_2CuO_4$ becomes superconducting at temperatures as high as 155 K.



Single sheets of CuO_4 square planes separated by BaO-Hg-BaO slabs.

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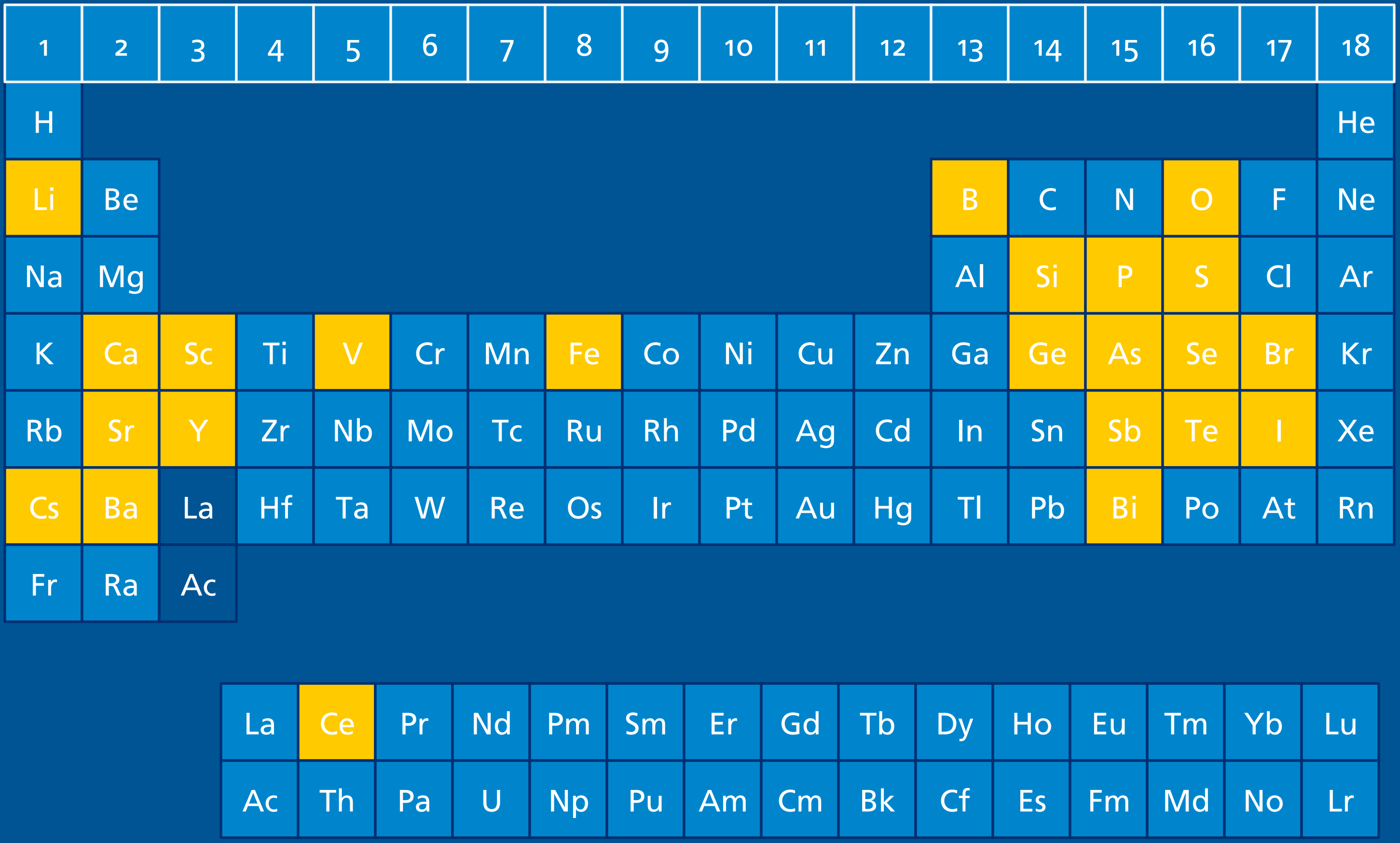
High T_C: The mechanism

After more than 20 years of intense research, is yet to be understood fully. It is NOT the BCS mechanism, as probed for example, by isotope effects.

New excitement: The superconducting elements 3

The application of pressure changes the situation drastically



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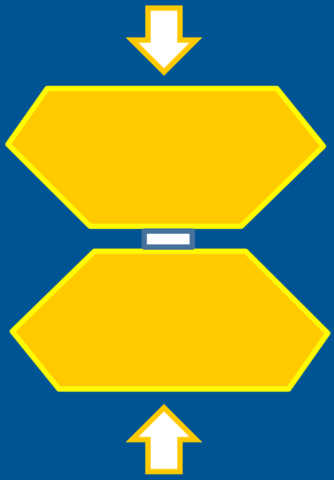
Fr	Ra	Ac															

La	Ce	Pr	Nd	Pm	Sm	Er	Gd	Tb	Dy	Ho	Eu	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

High pressures (above ~10 GPa) generated with a diamond anvil cell:



Buzea, Robbie, *Supercond. Sci. Technol.* **18** (2005) R1-R8.

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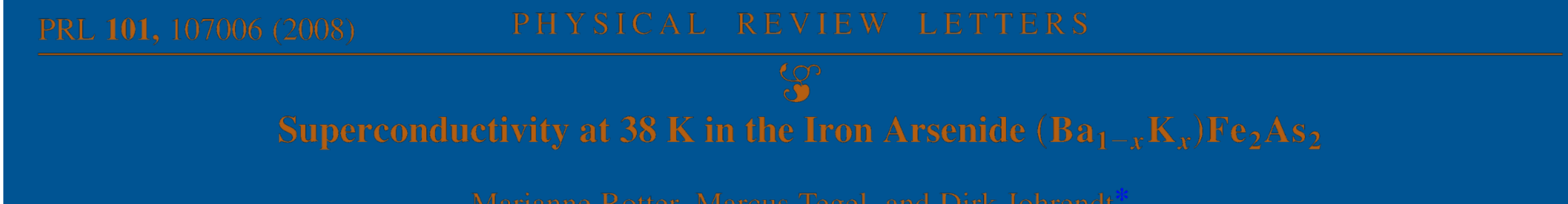
New excitement: The iron-arsenic system

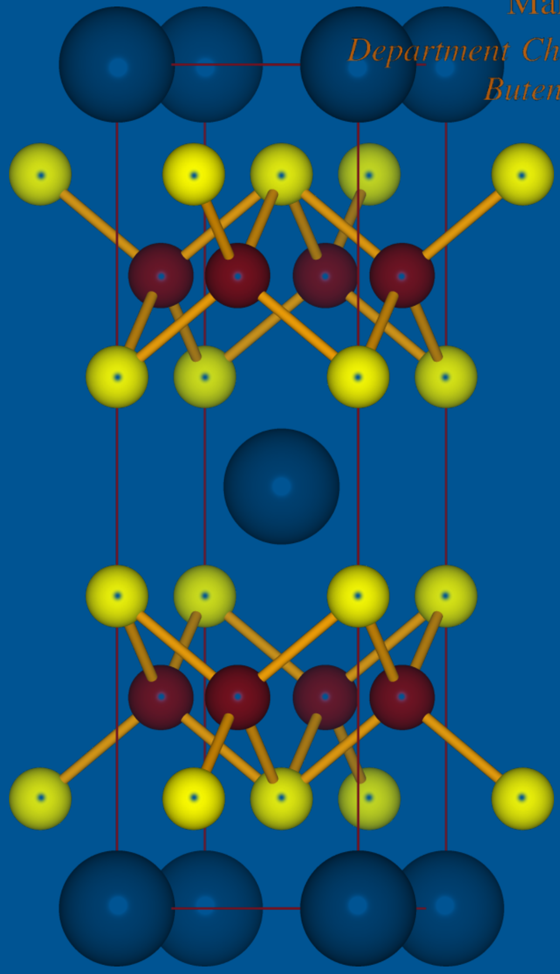


PRL **101,** 107006 (2008) PHYSICAL REVIEW LETTERS

Superconductivity at 38 K in the Iron Arsenide $(Ba_{1-x}K_x)Fe_2As_2$

Marianne Rotter, Marcus Tegel, and Dirk Johrendt*

Department Chemie und Biochemie, Ludwig-Maximilians-Universität München,
Butenandtstrasse 5-13 (Haus D), 81377 München, Germany



Superconductivity in iron-arsenic compounds with the $ThCr_2Si_2$ crystal structure.

Summary

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- The need for low temperatures and liquid He
- Superconductivity in Hg
- The superconducting elements
- The Meissner effect and superconducting levitation
- Type I and type II superconductors
- Superconducting magnets and MRI
- The rudiments of Bardeen-Cooper-Schrieffer theory
- High $T_{C:}$ A theory ?
- Newer systems: Higher T_C’s, more processible ?