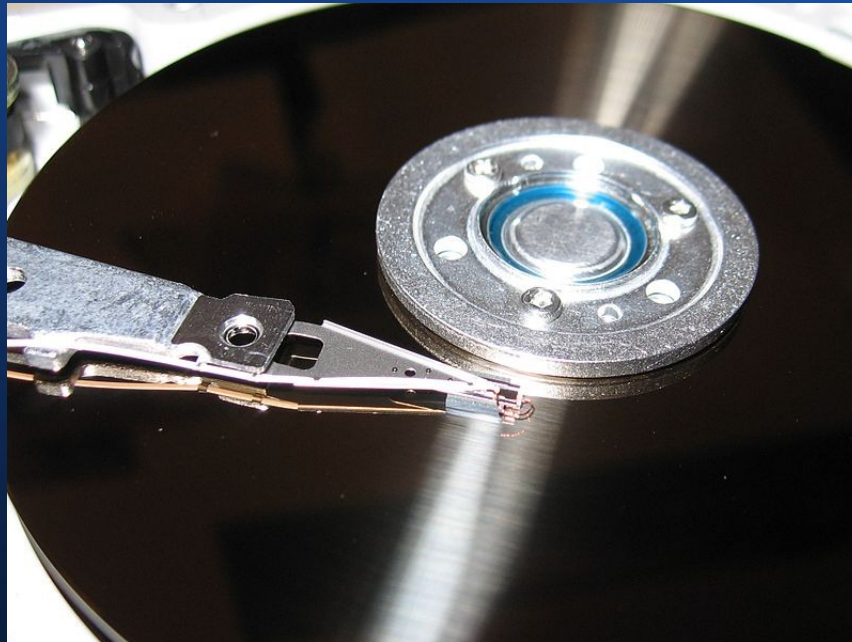


III.magnétisme et supraconductivité

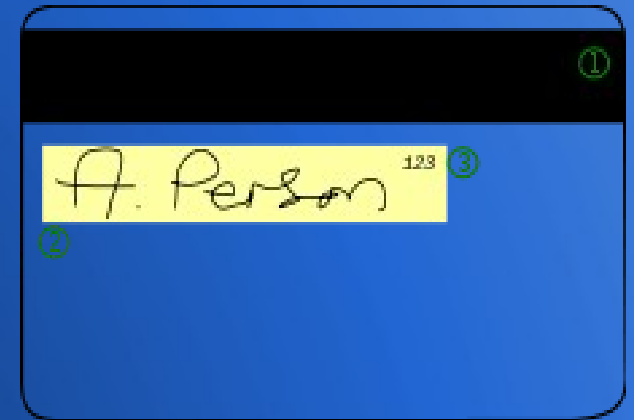


AlNiCo permanent magnet

Magnetic recording devices



Hard disk



Magnetic stripe on credit card

The periodic table

Atomic magnetic moment

Magnetism is a property of unfilled electronic shells :
Most atoms (bold) are concerned but only 22 magnetic in condensed matter

Magnetic Periodic Table

Atomic Number →

Typical ionic change →

Antiferromagnetic $T_N(K)$ →

66 Dy

162.5

3 + 4f

175 85

← Atomic symbol

← Atomic weight

← Ferromagnetic $T_C(K)$

1 H 1.00																	2 He 4.00						
3 Li 6.94 1 + 2s ¹	4 Be 9.01 2 + 2s ²																	5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00 3s	9 F 19.00	10 Ne 20.18
11 Na 22.99 1 + 3s ¹	12 Mg 24.21 2 + 3s ²																	13 Al 26.98 3 + 2p ¹	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10 1 + 4s ¹	20 Ca 40.08 2 + 4s ²	21 Sc 44.96 3 + 3d ¹	22 Ti 47.88 4 + 3d ²	23 V 50.94 3 + 3d ²	24 Cr 52.00 3 + 3d ⁵ 312	25 Mn 54.94 2 + 3d ⁵ 96	26 Fe 55.85 3 + 3d ⁶ 1043	27 Co 58.93 2 + 3d ⁷ 1390	28 Ni 58.69 2 + 3d ⁸ 629	29 Cu 63.55 2 + 3d ¹⁰	30 Zn 65.39 2 + 3d ¹⁰	31 Ga 69.72 3 + 3d ¹⁰	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80						
37 Rb 85.47 1 + 5s ¹	38 Sr 87.62 2 + 5s ²	39 Y 88.91 2 + 4d ¹	40 Zr 91.22 4 + 4d ²	41 Nb 92.91 5 + 4d ⁴	42 Mo 95.94 5 + 4d ⁵	43 Tc 97.9 4 + 4d ⁵	44 Ru 101.1 3 + 4d ⁷	45 Rh 102.4 3 + 4d ⁸	46 Pd 106.4 2 + 4d ¹⁰	47 Ag 107.9 1 + 4d ¹⁰	48 Cd 112.4 2 + 4d ¹⁰	49 In 114.8 3 + 4d ¹⁰	50 Sn 118.7 4 + 4d ¹⁰	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 83.80						
55 Cs 132.9 1 + 6s ¹	56 Ba 137.3 2 + 6s ²	57 La 138.9 3 + 4f ¹	72 Hf 178.5 4 + 5d ²	73 Ta 180.9 5 + 5d ³	74 W 183.8 6 + 5d ⁴	75 Re 186.2 4 + 5d ⁵	76 Os 190.2 3 + 5d ⁶	77 Ir 192.2 4 + 5d ⁷	78 Pt 195.1 2 + 5d ⁹	79 Au 197.0 1 + 5d ¹⁰	80 Hg 200.6 2 + 5d ¹⁰	81 Tl 204.4 3 + 5d ¹⁰	82 Pb 207.2 4 + 5d ¹⁰	83 Bi 209.0	84 Po 209	85 At 210	86 Rn 222						
87 Fr 223	88 Ra 226.0 2 + 7s ²	89 Ac 227.0 3 + 5f ¹																					
			58 Ce 140.1 4 + 4f ¹ 13	59 Pr 140.9 3 + 4f ² 19	60 Nd 144.2 3 + 4f ³ 19	61 Pm 145	62 Sm 150.4 3 + 4f ⁵ 105	63 Eu 152.0 2 + 4f ⁶ 96	64 Gd 157.3 3 + 4f ⁷ 292	65 Tb 158.9 3 + 4f ⁸ 221	66 Dy 162.5 3 + 4f ⁹ 175 85	67 Ho 164.9 3 + 4f ¹⁰ 132 20	68 Er 167.3 3 + 4f ¹¹ 95 20	69 Tm 168.9 3 + 4f ¹² 96	70 Yb 173.0 3 + 4f ¹³	71 Lu 175.0 3 + 4f ¹⁴							
			90 Th 232.0 4 + 5f ¹	91 Pa 231.0 5 + 5f ²	92 U 238.0 4 + 5f ³	93 Np 237.0 5 + 5f ⁴	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 260							

Nonmetal

 Metal

 Radioactive

Diamagnet

 Paramagnet

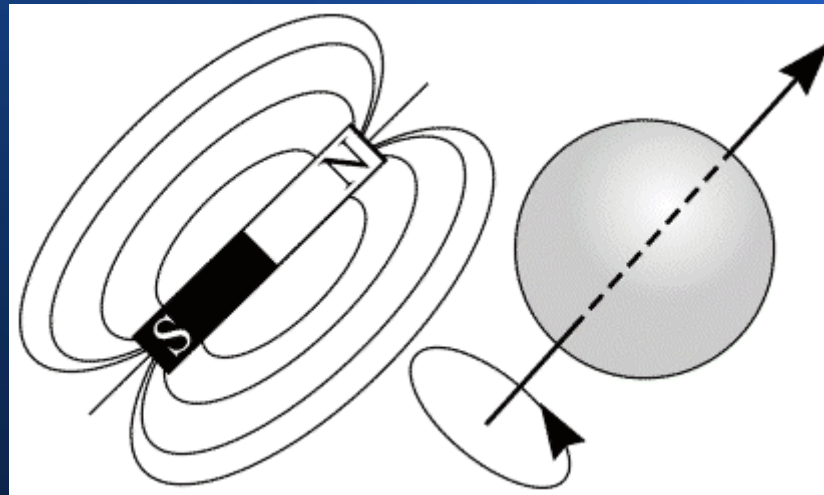
BOLD Magnetic atom

Ferromagnet $T_C > 290K$

 Antiferromagnet with $T_N > 290K$

 Antiferromagnet/Ferromagnet with $T_N/T_C < 290 K$

Magnetic moments of isolated atoms



$$\mathbf{m}_J = g m_B \mathbf{J}$$

Transition metal atoms

Element Name and Symbol	Atomic Number	Common Oxidation States	Electron Configuration	
Scandium (Sc)	21	+3	Sc: [Ar] 4s ² 3d ¹	Sc: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1}{\underbrace{\quad\quad\quad}_{3d}}$
Titanium (Ti)	22	+4	Ti: [Ar] 4s ² 3d ²	Ti: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1}{\underbrace{\quad\quad}_{3d}} \frac{1}{\quad}$
Vanadium (V)	23	+2, +3, +4, +5	V: [Ar] 4s ² 3d ³	V: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1}{\underbrace{\quad\quad}_{3d}} \frac{1}{\quad} \frac{1}{\quad}$
Chromium (Cr)	24	+2, +3, +6	Cr: [Ar] 4s ¹ 3d ⁵	Cr: [Ar] $\frac{1}{4s}$ $\frac{1}{\underbrace{\quad\quad}_{3d}} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad}$
Manganese (Mn)	25	+2, +3, +4, +6, +7	Mn: [Ar] 4s ² 3d ⁵	Mn: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1}{\underbrace{\quad\quad}_{3d}} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad}$
Iron (Fe)	26	+2, +3	Fe: [Ar] 4s ² 3d ⁶	Fe: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1\downarrow}{\underbrace{\quad\quad}_{3d}} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad}$
Cobalt (Co)	27	+2, +3	Co: [Ar] 4s ² 3d ⁷	Co: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1\downarrow}{\underbrace{\quad\quad}_{3d}} \frac{1\downarrow}{\quad} \frac{1}{\quad} \frac{1}{\quad} \frac{1}{\quad}$
Nickel (Ni)	28	+2	Ni: [Ar] 4s ² 3d ⁸	Ni: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1\downarrow}{\underbrace{\quad\quad}_{3d}} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1}{\quad} \frac{1}{\quad}$
Copper (Cu)	29	+2	Cu: [Ar] 4s ¹ 3d ¹⁰	Cu: [Ar] $\frac{1}{4s}$ $\frac{1\downarrow}{\underbrace{\quad\quad}_{3d}} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad}$
Zinc (Zn)	30	+2	Zn: [Ar] 4s ² 3d ¹⁰	Zn: [Ar] $\frac{1\downarrow}{4s}$ $\frac{1\downarrow}{\underbrace{\quad\quad}_{3d}} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad} \frac{1\downarrow}{\quad}$

Hund's rules (Hercules lectures/VSimonet)

Atomic magnetic moment

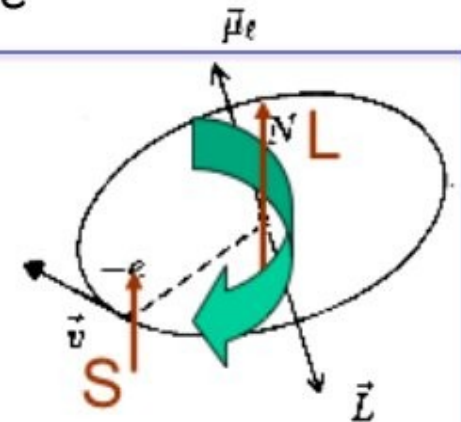
Several e- in an atom: $\hat{L} = \sum_{ne-} \hat{l}$ $\hat{S} = \sum_{ne-} \hat{s}$

Combination of the orbital and spin angular momenta of the different electrons :
related to the filling of the electronic shells in order to minimize
the electrostatic energy and fulfil the exclusion Pauli principle

Hund's rules

1 : $S = \sum_{ne-} m_s$ maximum

2 : $L = \sum_{ne-} m_l$ maximum in agreement with 1st rule



Spin-orbit coupling : relativistic expression of the magnetic induction effect
on the spin of the e- from its orbital motion $\lambda \hat{L} \cdot \hat{S} \rightarrow \hat{J} = \hat{L} + \hat{S}$
total angular momentum

3 : $J = |L - S|$ for less than $\frac{1}{2}$ filled shell $J = |L + S|$ for more than $\frac{1}{2}$ filled shell

Hund's rules (2)

Atomic magnetic moment

A given atomic shell (multiplet) is defined by 4 quantum numbers :
 L, S, J, M_J with $-J < M_J < J$

Application of Hund's rules:

Dy^{3+} : 9 electrons

m_s	1/2	1/2	1/2	1/2	1/2	1/2	1/2	-1/2	-1/2	-1/2	-1/2	-1/2	-1/2	-1/2
m_l	3	2	1	0	-1	-2	-3	3	2	1	0	-1	-2	-3

$$L = 5, S = 5/2, J = 15/2, M_J \quad (-15/2 < M_J < 15/2)$$

the ground state is 16-fold degenerated

Total magnetic moment

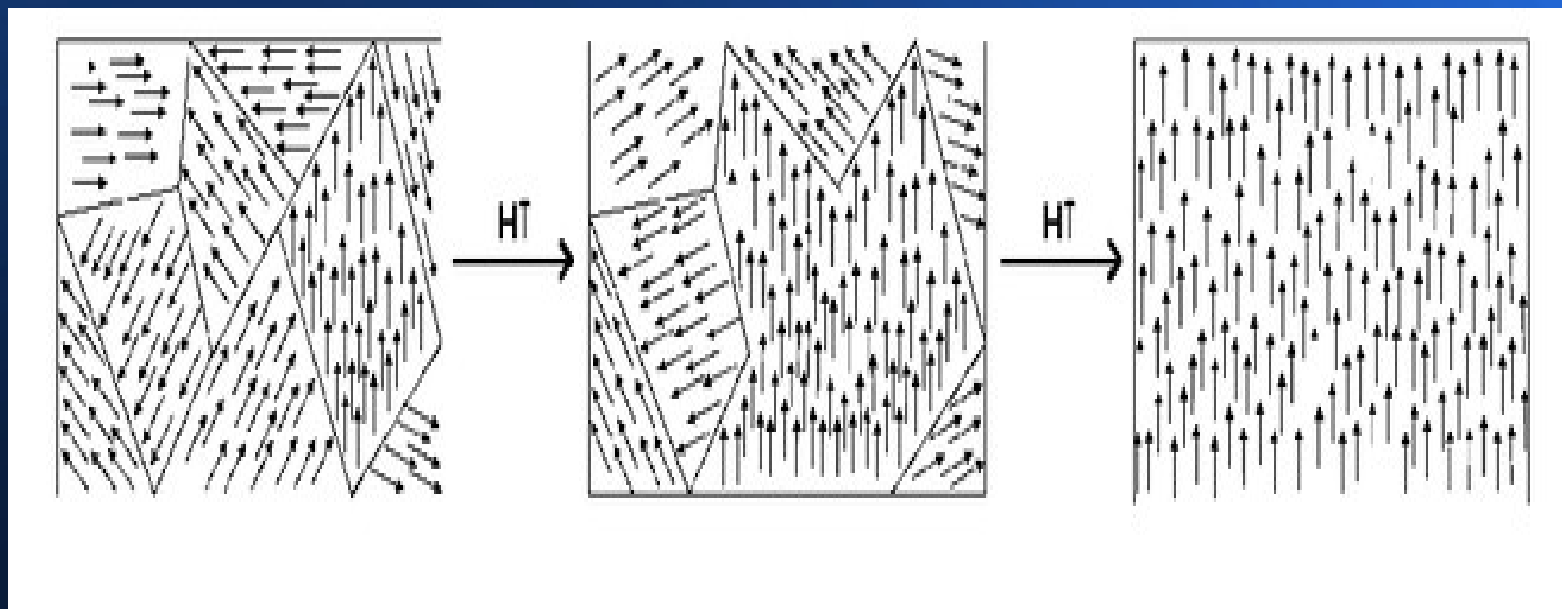
$$\hat{M} = -\mu_B (\hat{L} + 2\hat{S})$$

$$\hat{M} = -g\mu_B \hat{J}$$

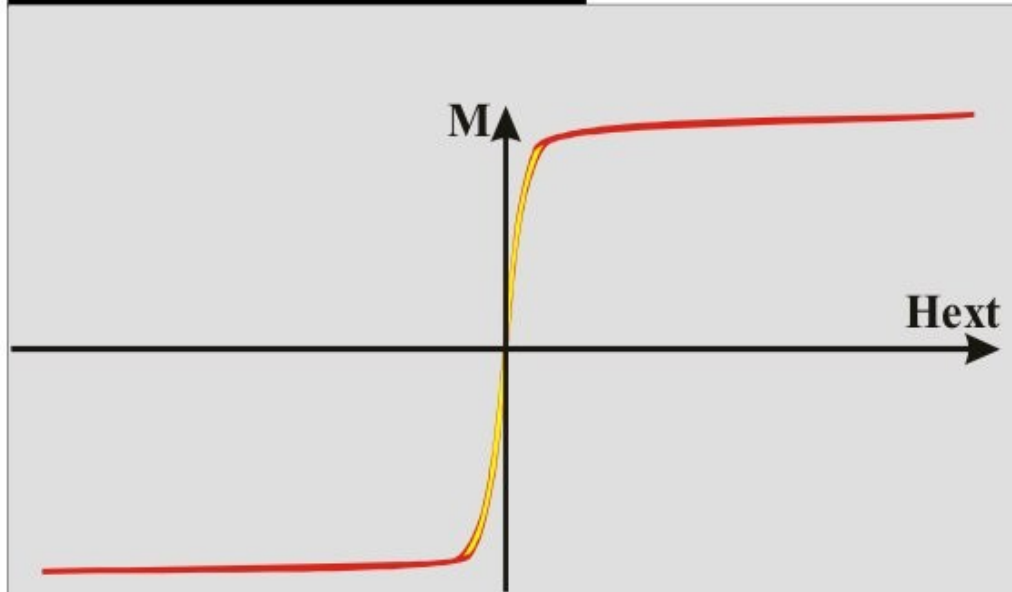
with the Lande g-factor

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

Domains in a ferromagnet



Matériaux doux

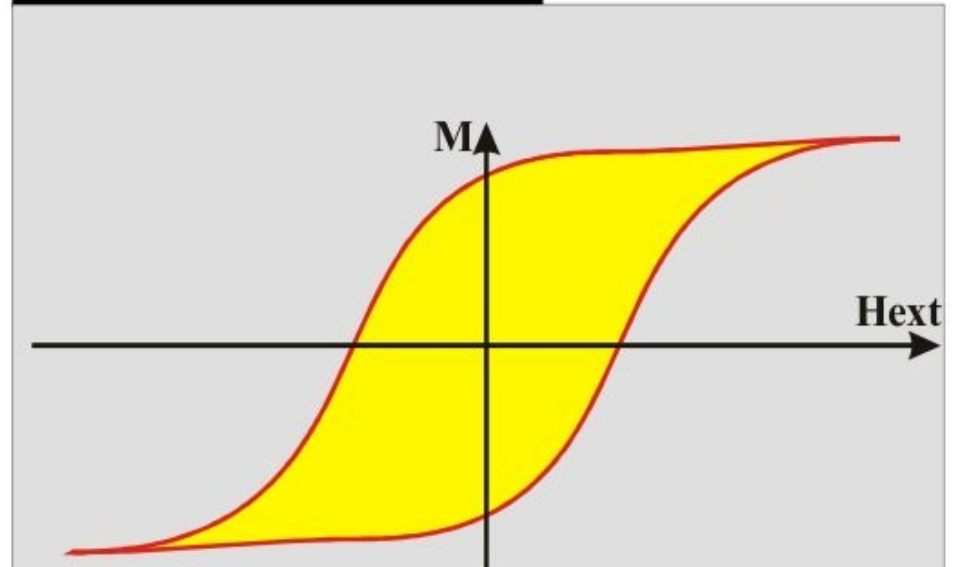


Transformateurs

Guides de flux

Blindage magnétique

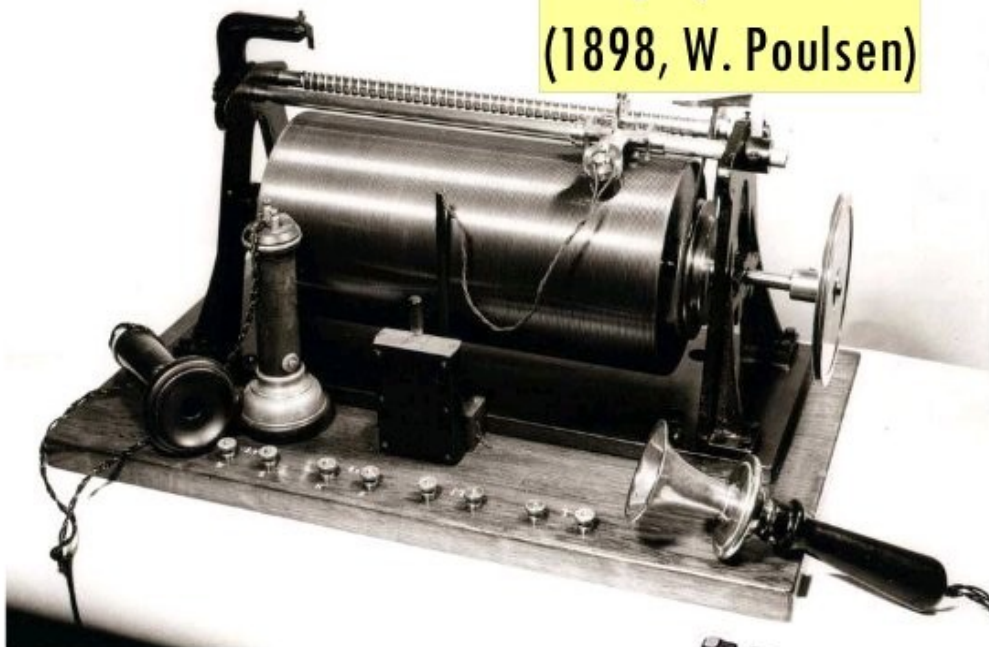
Matériaux durs



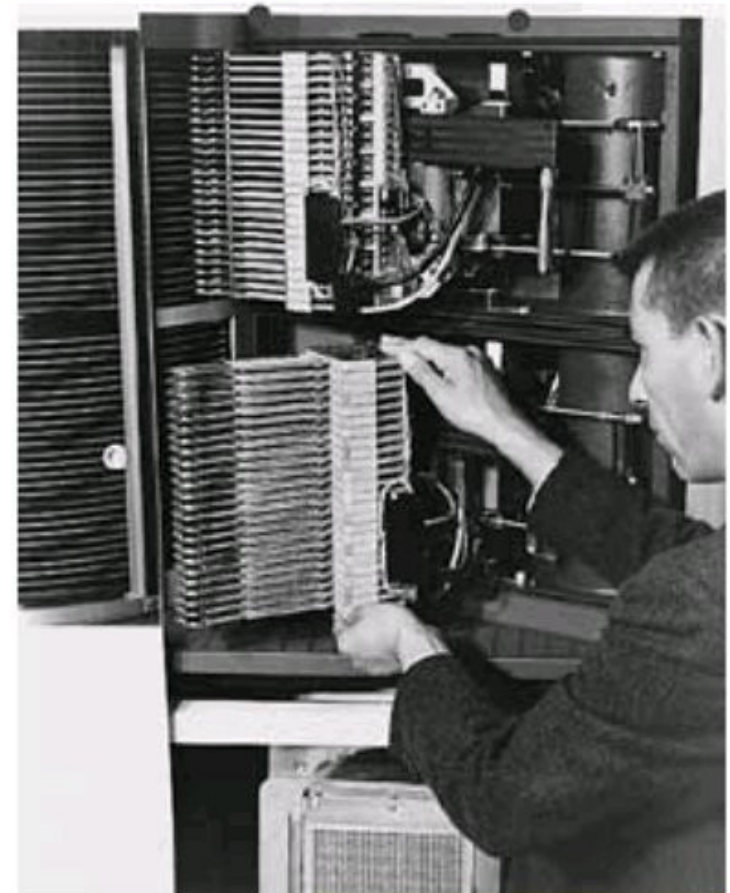
Aimants permanents, moteurs

Enregistrement magnétique

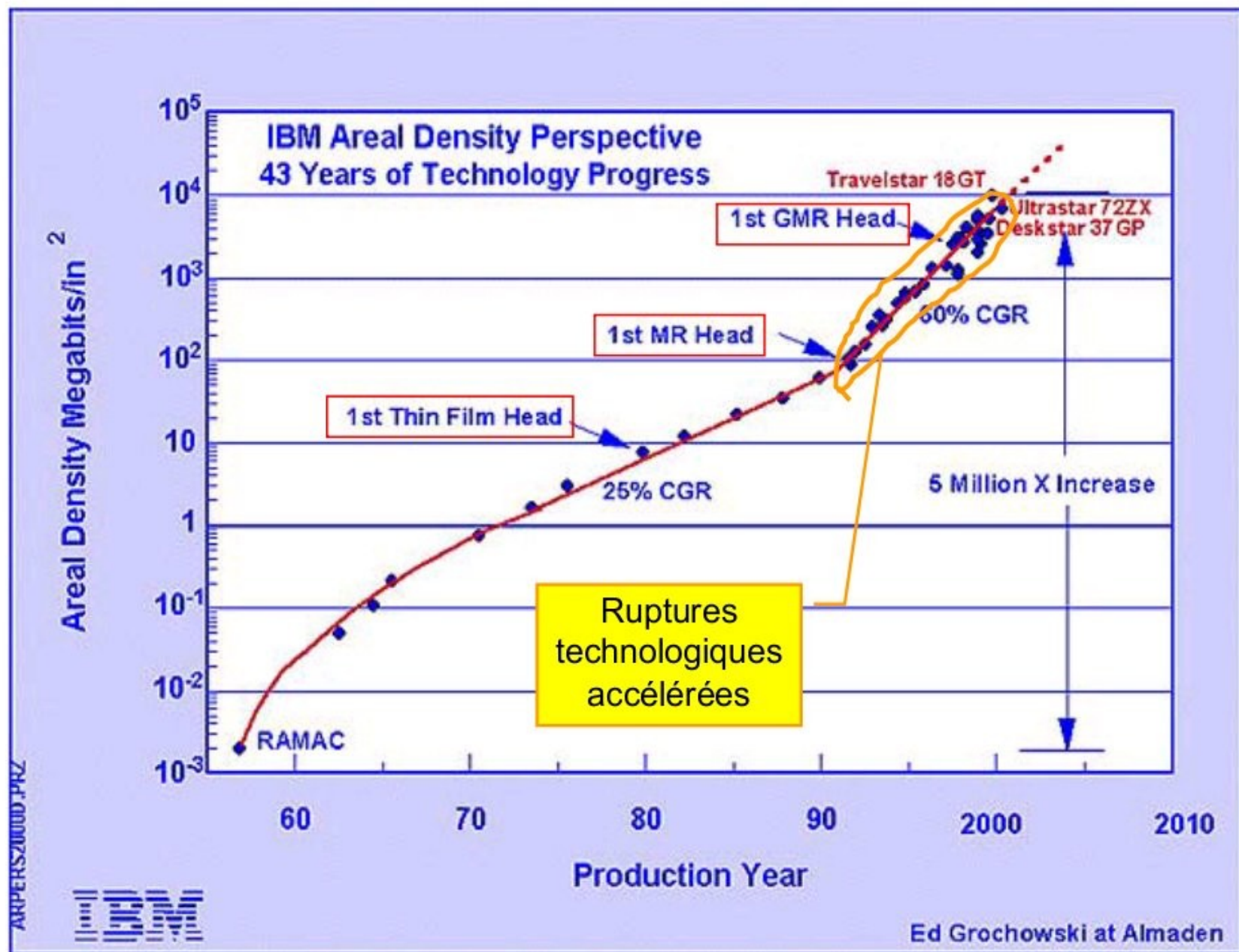
Télégraphone
(1898, W. Poulsen)



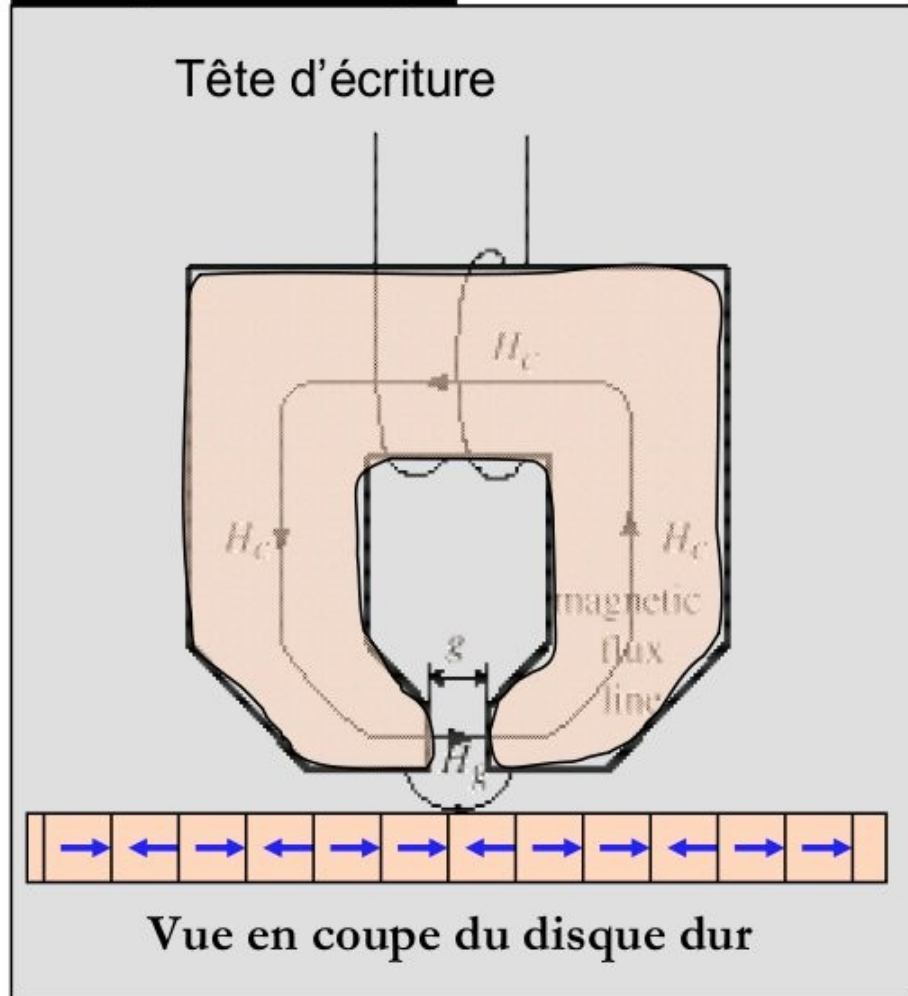
Disque dur actuel
(>200Go)



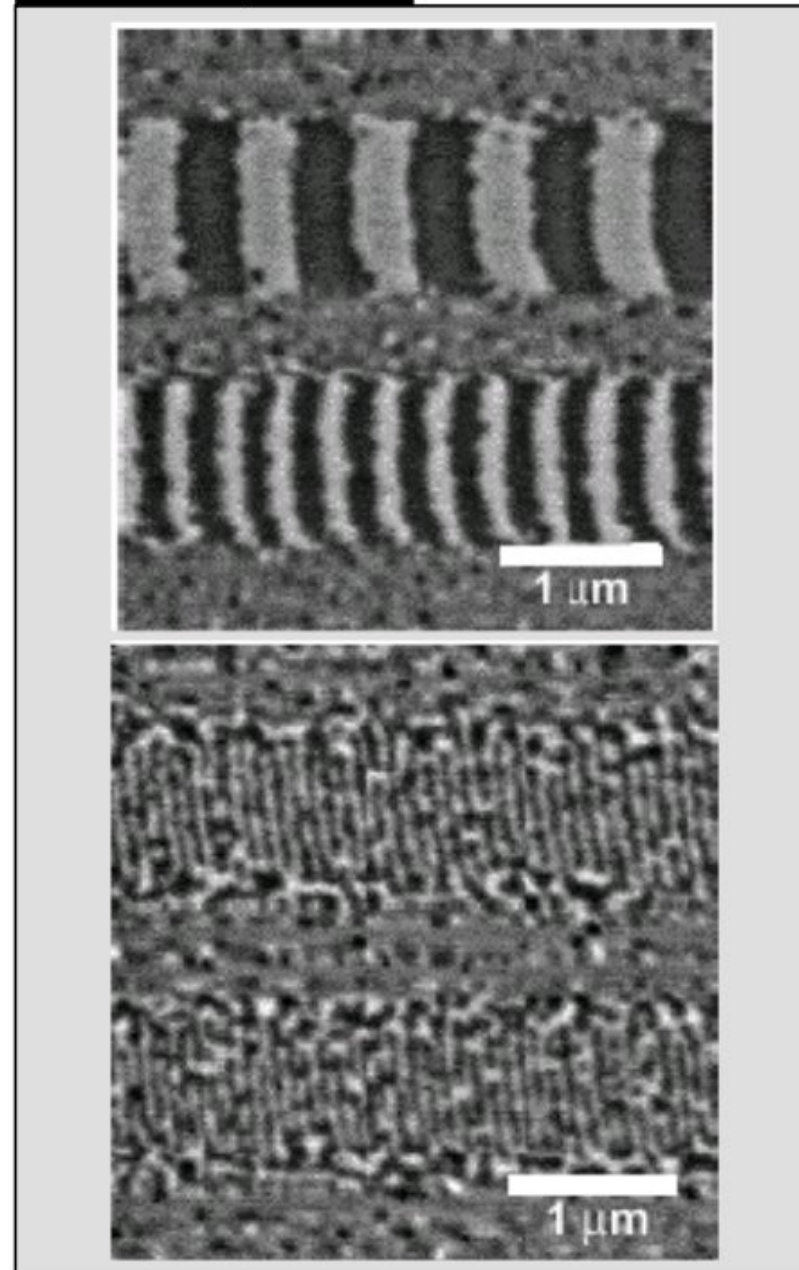
RAMAC (IBM, 1956)
2 kbit/in²
50 disques Ø 60 cm
Total 5Mo



Principe du stockage



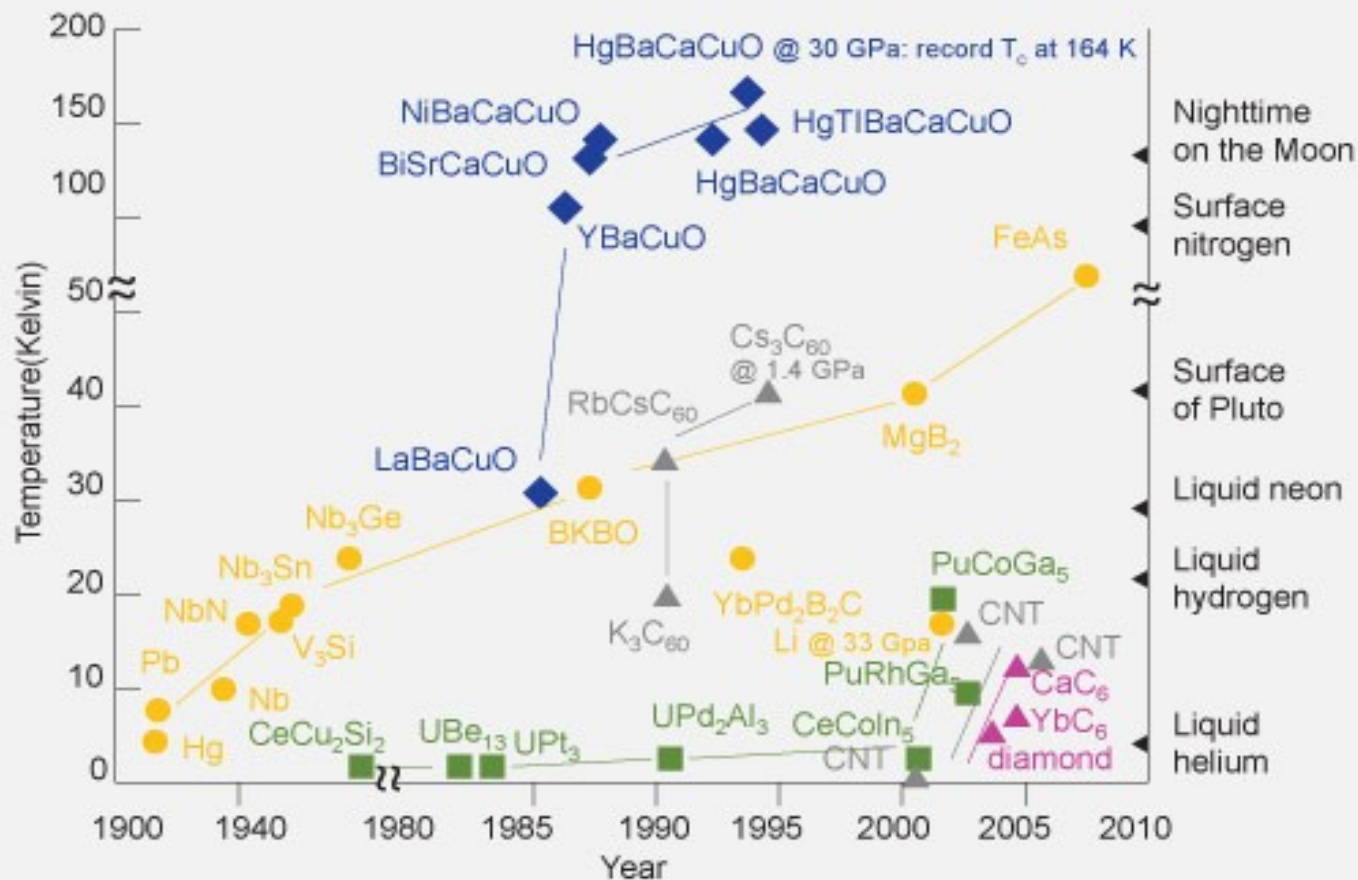
Vue du disque dur



superconductivity



superconducting compounds and their T_c

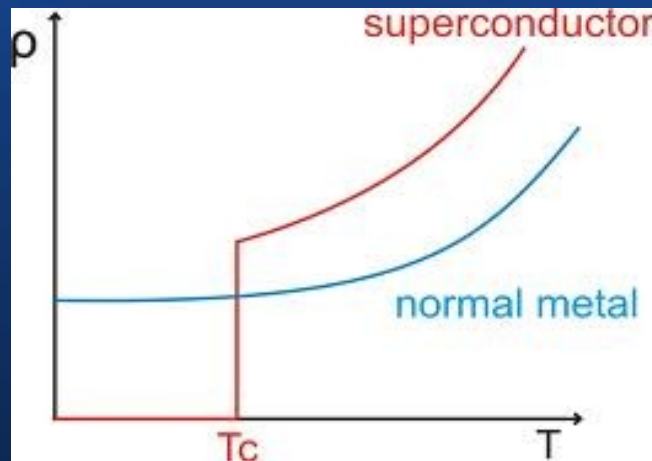


Superconducting elements

Superconducting Elements																				
1																	2			
1	H																	He		
2	3	4													5	6	7	8	9	10
	Li	Be													B	C	N	O	F	Ne
3	11	12													13	14	15	16	17	18
	Na	Mg													Al	Si	P	S	Cl	Ar
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36		
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54		
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
6	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86		
	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
7	87	88	89	104	105	106	107	108	109	110	111	112								
	Fr	Ra	Ac	Rf	Ha	Sg	Bh	Hs	Mt	Ds	Rg	Uub								
58	59	60	61	62	63	64	65	66	67	68	69	70	71							
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu							
90	91	92	93	94	95	96	97	98	99	100	101	102	103							
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr							

- In Bulk at Ambient Pressure
- At High Pressure
- In Modified Form

permanent current loops

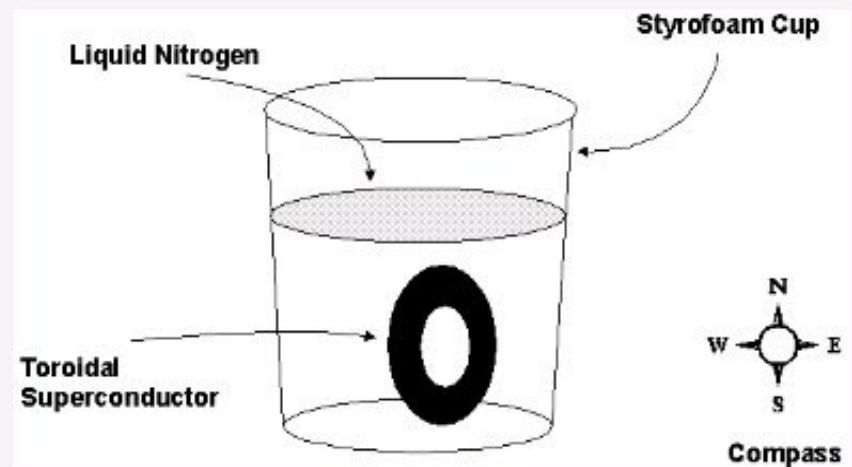


Fifth Experiment: Superconducting Energy Storage Ring



The [S6 Superconductor Energy Storage Kit](#) is simple to understand. The fundamental property of superconductors is its complete lack of resistance to electrical current. This property can be exploited by using a ring (toroid) of superconductor material to store electrical power. Once the current is induced in the toroidal, its lack of resistance allows the induced current to flow forever. These permanent currents in a superconductor are called persistent currents. The current also produces a magnetic field around the superconductor, creating a powerful electromagnet.

The primary component in the S6 kit is a superconductor toroid (see [Figure 4](#)). To perform the experiment, the toroidal is completely immersed in liquid nitrogen (see [Figure 5](#)).



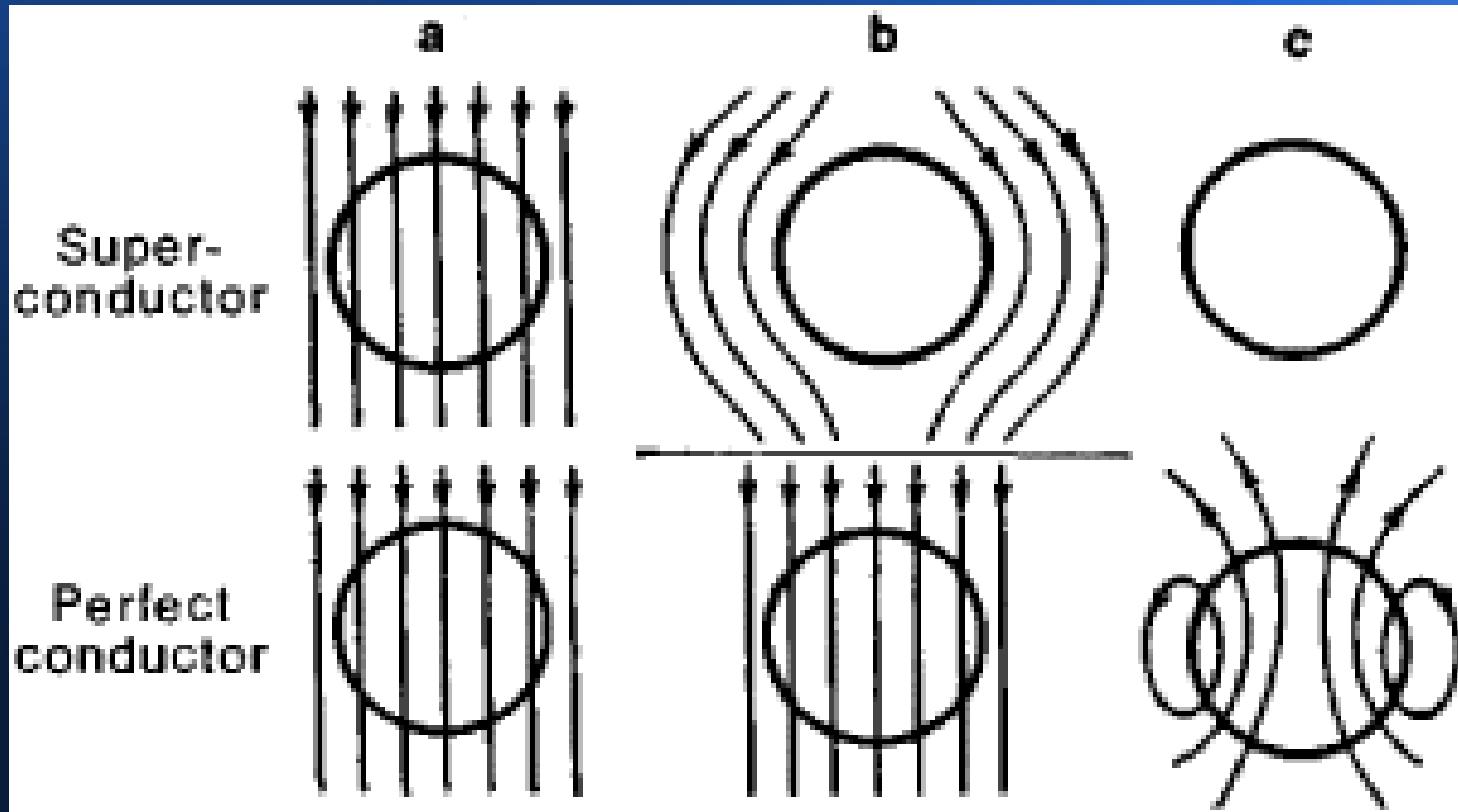
A current is induced in the toroidal ring by passing a rare earth magnet through the opening of the toroidal. The toroidal may be momentarily removed from the liquid nitrogen to perform this operation, then quickly placed back into the liquid nitrogen.

The induced current can be detected by measuring the deflection of a compass needle held in close proximity to the superconducting toroidal.

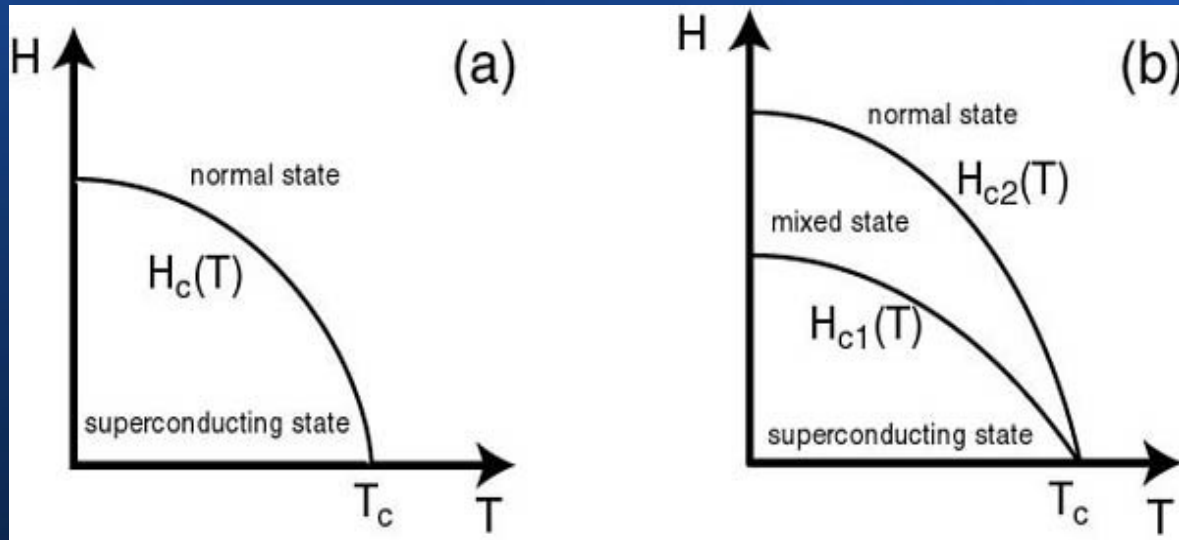
The S6 kit's experimenter's guide provides equations and procedures for estimating the current in the superconductor based on the deflection of the compass needle.

While in theory the current in the toroidal should flow forever, because of flux creep and flux flow there is a small exponential decay of the stored electrical current. It has been estimated that in 1023 years the stored current will decrease to approximately 50% of its initial value.

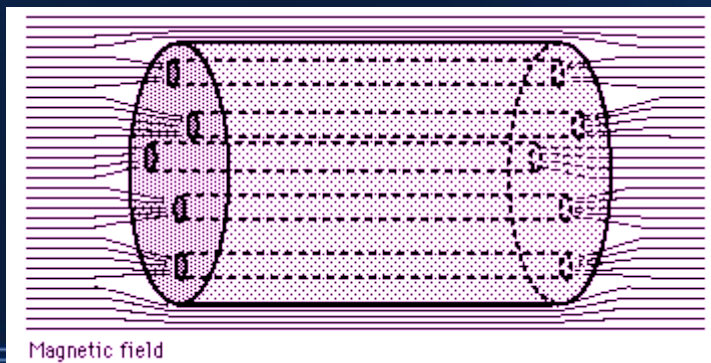
Meissner effect for a sphere



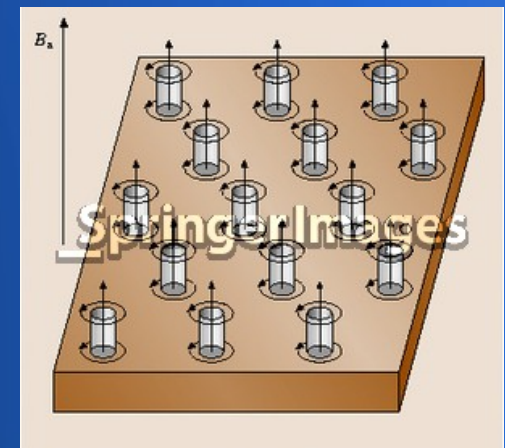
Type I and type II



The critical temperature versus Magnetic field in Type I and in Type II superconductors

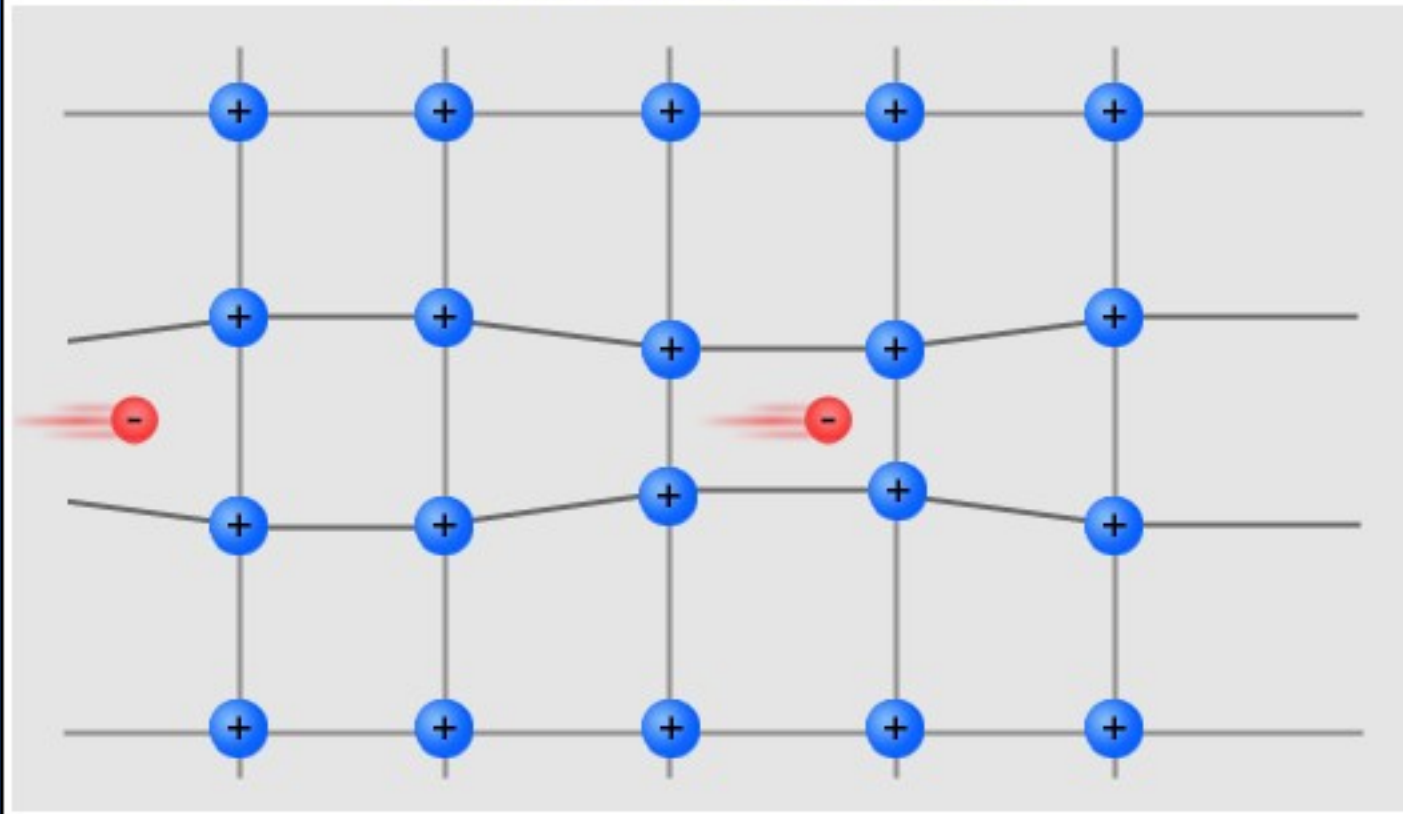


The mixed state (magnetic flux forming a vortex lattice)



BCS theory

Cooper pairs make super conductors



At extremely low temperatures, an electron can draw the positive ions in a superconducting material towards it. This movement of the ions creates a more positive region that attracts another electron to the area.

The building block for the BCS state is a boson, the Cooper pair : a pair of electrons of opposite spin that form a bound state due to their interaction via phonons

Superconductivity arises due to the electron-phonon Interaction !

The waltz of the Cooper pairs

$$|\psi_{BCS}^{(r)}\rangle = \prod_{\mathbf{k}} \frac{\left(u_{\mathbf{k}} + g_i v_{\mathbf{k}} c_{\mathbf{k}\uparrow}^{\dagger} c_{-\mathbf{k}\downarrow}^{\dagger}\right)}{\sqrt{|u_{\mathbf{k}}|^2 + g_i^2 |v_{\mathbf{k}}|^2}} |0\rangle$$

The BCS wavefunction



The ground state is stable because there is an energy gap

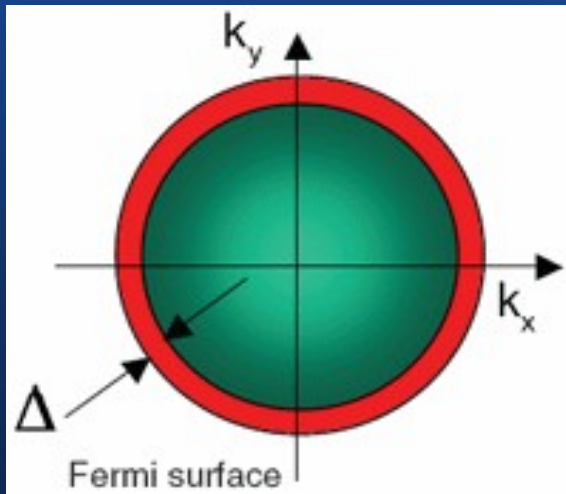
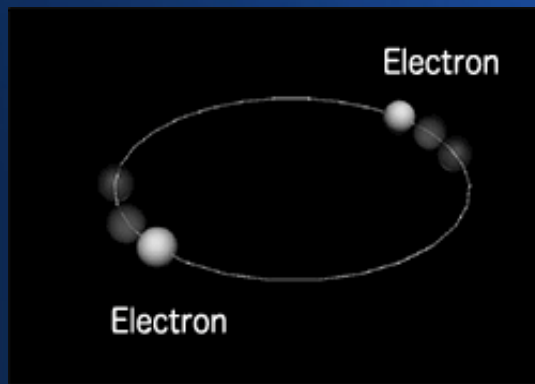
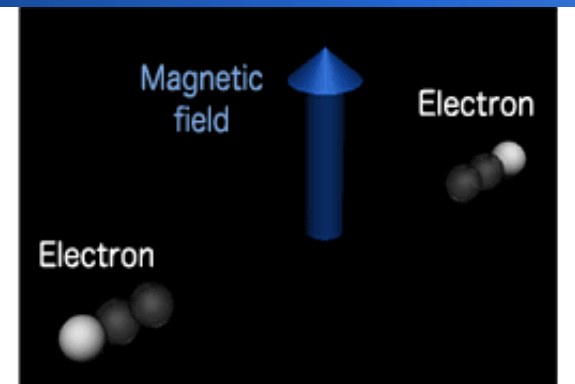


Figure showing the gap : the region (red) of forbidden energy

Cooper pairs can be broken up by increasing the **temperature** or increasing the **magnetic field** or increasing the **electrical current**



(A) Cooper pair (electron pair) exists stably in a superconducting state.



(B) Cooper pair (electron pair) is destroyed by a magnetic field, leading to the disappearance of superconductivity.

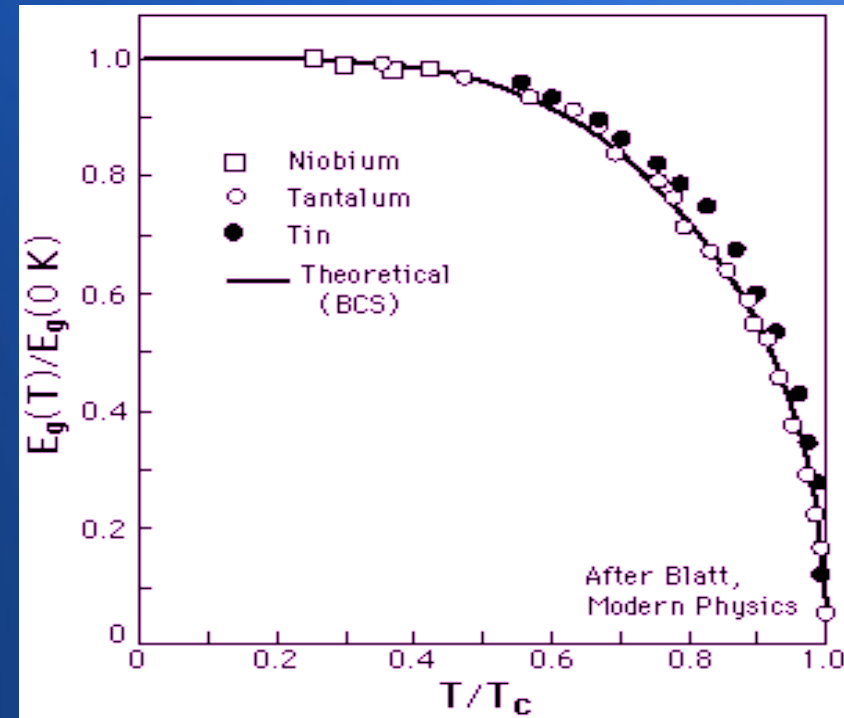
The BCS equations for the gap and for T_c

$$k_B T_c = 1.14 E_D e^{-1/N(0)V}$$

The critical temperature and the zero temperature gap depend

- 1) on the Debye energy E_D
- 2) on the density of states at the Fermi level $N(0)$
- 3) on the effective electron-electron attraction V

$$\Delta(T=0) = 2\hbar\omega_D e^{-1/n(0)V_{BCS}}$$



Web site for nonspecialists

<http://www.supraconductivite.fr/fr/index.php#supra-intro>

