PHY117 HS2026

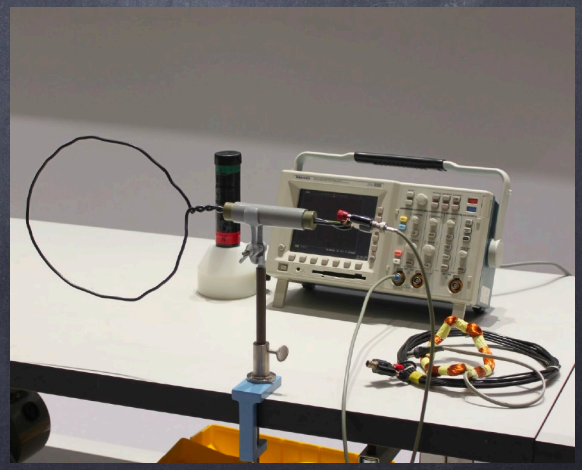
Week 11, Lecture 1

Nov. 24th, 2026

Prof. Ben Kilminster

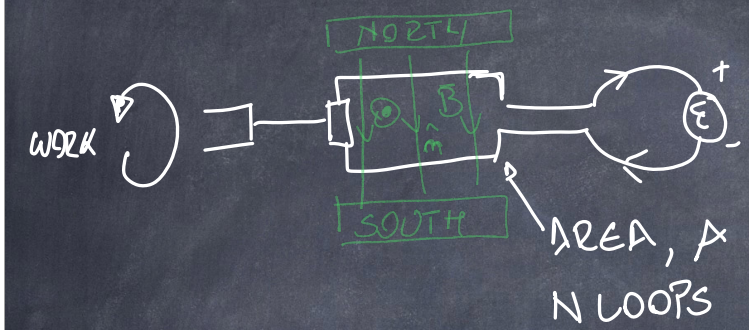
Prof. Florencia Canelli

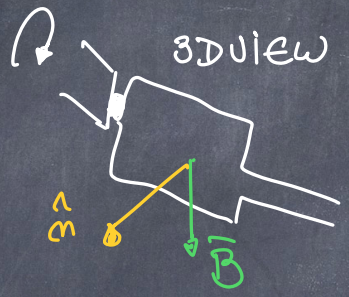
Today: electric generators + motors
magnetization
hysteresis
magnetic materials
magnetic moments atoms
superconductors



MOST ELECTRICAL ENERGY USED TODAY PRODUCED BY

AC (ALTERATING CORRENT) ELECTRIC GENERATORS





MAGNETIC FLUX Φ_m VARIES AS IT ROTATES: $\vec{B} \parallel \hat{n}$, $\theta = 180°$

→ $\cos\theta = 1, -1$

Φ_m = MAXIMAL

FLUX THROUGH LOOP $\Phi_m = NBA\cos\theta$

THE LOOP TURNS STEADLY $\theta = \omega t + \delta$

ω: ANGULAR V. δ: STARTING PHASE

FARADAY: $\mathcal{E} = -\frac{d\Phi_m}{dt} = -NBA\frac{d}{dt}\cos(\omega t + \delta)$

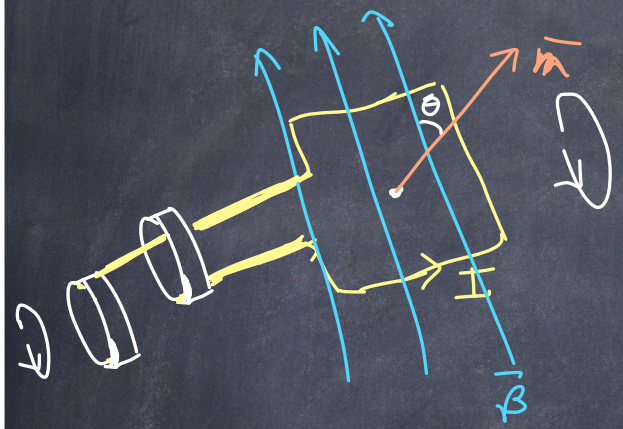
$= +NBA\omega\sin(\omega t + \delta)$

$\mathcal{E}$: UNITS [V]

$NBA\omega$: AMPLITUDE, MAX VOLTAGE

IF WE FEED AC IN THE LOOP INSTEAD OF TAKING IT OUT:

MOTORS ⇒ A LOOP CARRYING CURRENT I HAS A MAGNETIC MOMENT $\bar{m} = I A \hat{n}$



IF N LOOPS

$$\bar{m} = NIA\hat{n}$$

IN A FIELD $\bar{B}$ IT FEELS A TORQUE

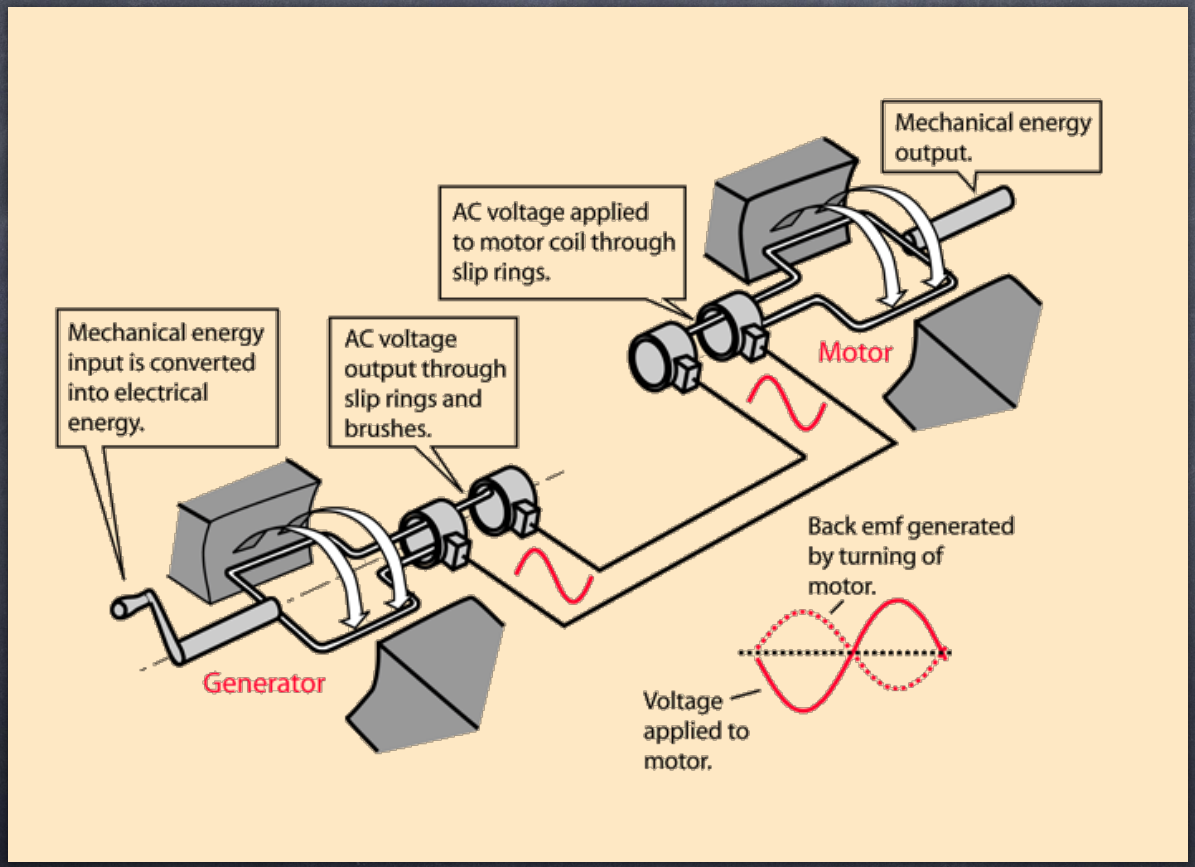
$$\bar{\tau} = \bar{m} \times \bar{B}$$

THAT TRIES TO LINE UP $\bar{m}$ UP WITH $\bar{B}$

- IF THE CURRENT IS STEADY, LOOP WOULD SWING INTO LINE AND STOP
- WITH AC $\bar{m}$ FLIPS EVERY HALF TURN AND THE TORQUE KEEPS PUSHING THE SAME WAY AROUND

ALTERNATING CURRENT GENERATOR AND MOTOR RUN IN SERIES:

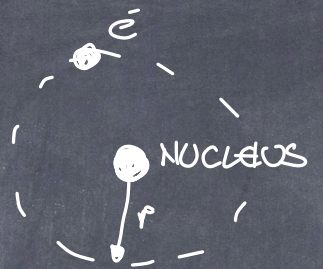
work →



→ work

ATOMIC MAGNETIC MOMENTS

EVERY ELECTRON CIRCLING A NUCLEUS IS A TINY CURRENT LOOP ⇒ ATOMS ARE TINY MAGNETS



PARTICLE : CHARGE q, MASS m_q ON A CIRCLE OF RADIUS r AT SPEED v + ANGULAR MOMENTUM $L = m_q v r$

A CHARGE GOING ROUND IS A CURRENT

$I = \frac{q}{T}$ CHARGE PASSING PER UNIT TIME

ONE LAP TAKES $T = 2\pi r / v$

SO $I = \frac{qv}{2\pi r}$

USELESS FOR ATOMS

MAGNETIC MOMENT $m = IA = \left(\frac{qv}{2\pi r}\right)(\pi r^2) = \frac{qvr}{2}$

$L = m_q v r = m_q \left(\frac{2m}{q}\right) \Rightarrow$ **$m = \frac{qL}{2m_q}$**

MAGNETIC MOMENT OF AN ORBITING PARTICLE

FOR A POSITIVE CHARGE $\bar{m} = \frac{q\bar{L}}{2m_q}$ SAME DIRECTION

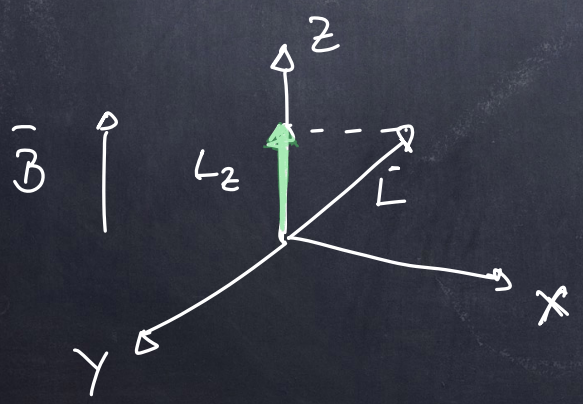
NEGATIVE CHARGE (ELECTRON) $\bar{m} = -\frac{q\bar{L}}{2m_q}$ OPPOSITE DIR

CLASSICAL RELATIONS (ASSUMES ELECTRON IS CONTINUOSLY MOVING IN ORBIT AROUND NUCLEUS)

THE RELATION SURVIVES IN QUANTUM THEORY WITH ONE CHANGE : ANGULAR MOMENTUM CAN'T TAKE ANY VALUE

L IS QUANTIZED

IN QM WE ONLY TALK ABOUT L_z ⇒ COMPONENT OF L ALONG THE FIELD DIRECTION



B IN Z DIRECTION (BY CONVENTION)

L_z PROJECTION ONTO Z-AXIS

L_z IS QUANTIZED $\Rightarrow$ COMES IN WHOLE STEPS OF $\hbar$

$$L_z = m\hbar \qquad m = 0, \pm 1, \pm 2, \pm 3, \ldots$$

$h = 6.63\ e{-}34$ J·S PLANCK CONSTANT

$\hbar = h/2\pi$

RELATES ENERGY AND TIME

SAME UNIT AS L

THE MAGNETIC MOMENT IS $m_z = \dfrac{-q}{2m_q} L_z$ FOR A NEGATIVE CHARGE

$$m_z = -\frac{m_B}{\hbar} L_z$$

CONSTANTS

m_B: BOHR MAGNETON

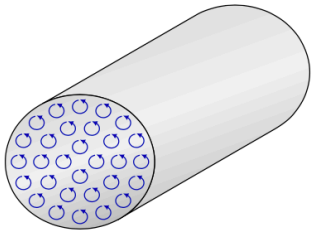
FOR AN ELECTRON $m_B = \dfrac{e\hbar}{2m_e} = 9.27e{-}24\ \dfrac{J}{T}$

THE MAGNETIC MOMENT OF AN ATOM

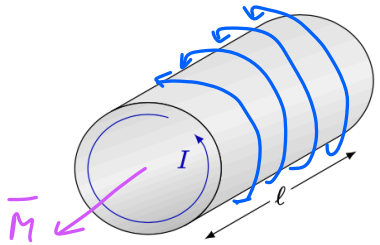
IS ROUGHLY $\sim |m_B|$ BUT DEPENDS ON # ELECTRONS AND PAIRINGS

IN A MACROSCOPIC MATERIAL

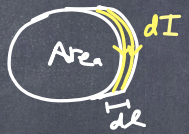
IF THE ATOMIC MAGNETS POINT IN THE SAME DIRECTION

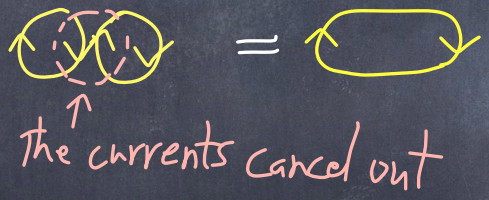


(a) Each atom has its own small current loops, and their own magnetic moment.



(b) One can think of the microscopic currents adding up to one big one.





the currents cancel out

THE MAGNETIZATION IS

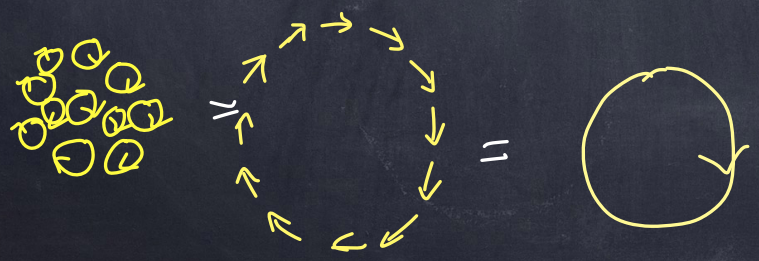
$$\vec{M} = \frac{\text{SUM OF MAGNETIC MOMENTS}}{\text{VOLUME}}$$

$$= \frac{(\text{SUM OF CURRENTS})(\text{AREA})}{(\text{AREA})(\text{LENGTH})}$$

$$= \frac{\text{CURRENT}}{\text{LENGTH}}$$

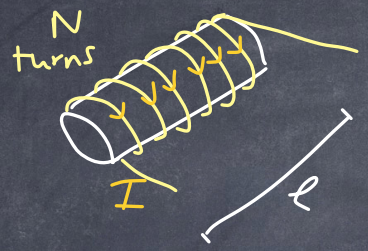
$$\vec{M} = \frac{dm}{dV} = \frac{dI}{dl}$$

$\left[\frac{A}{m}\right]$



= BAR MAGNET AND A SOLENOID HAVE THE SAME MAGNETIC FIELD

MAGNETIZATION OF A HOLLOW SOLENOID:



$$M = \frac{NI}{\ell} = nI \quad \text{where} \quad n = \frac{N}{\ell}$$

PREVIOUS LECTURES $B = \mu_0 \frac{N}{\ell} I$

FOR INSIDE A HOLLOW SOLENOID

SO ⇒ MAGNETIC FIELD RELATES TO THE MAGNETIZATION

$$\bar{B} = \mu_0 \bar{M}$$

NOTE THAT A MAGNETIZED ROD HAS THE SAME KIND OF CURRENT AROUND ITS SURFACE → IT CREATES ITS OWN FIELD $\mu_0 M$

HOW MUCH M? FOR MOST MATERIALS IT IS PROPORTIONAL TO THE FIELD APPLIED

$$\bar{M} = \chi_m \frac{\bar{B}_{ext}}{\mu_0} \quad (1)$$

χ_m : MAGNETIC SOSCEPTIBICITY

HOW READILY A MATERIAL MAGNETIZES

$$\chi_m = \frac{\mu}{\mu_0} - 1$$

μ INSIDE MATERIAL

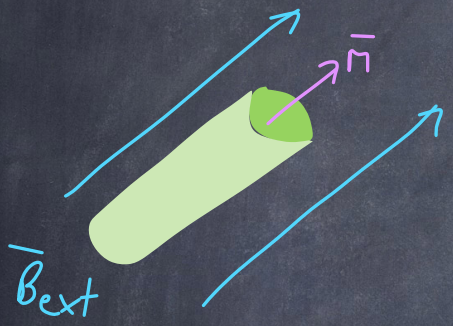
μ_0 IN VACUUM

μ: PERMEABILITY OF A MATERIAL

IT TELLS HOW MUCH FIELD A CURRENT CREATES WHEN THE COIL IS FILLED WITH THAT MATERIAL

MATERIAL	χ_m	CLASSIFICATION
EMPTY SPACE	0	
ALUMINIUM	SMALL, + ($\sim 10^{-5}$)	PARAMAGNETIC
WATER, COPPER, GOLD, BISMUTH	SMALL, − ($\sim -10^{-5}$)	DIAMAGNETIC
IRON, NICKEL, COBALT	LARGE, + ($10^2 - 10^5$)	FERROMAGNETIC

IF WE HAVE THE MATERIAL IN A MAGNETIC FIELD $\bar{B}_{ext}$ THE TOTAL MAGNETIC FIELD INSIDE IS A COMBINATION OF $\bar{M}$ AND $\bar{B}_{ext}$



$$\bar{B} = \bar{B}_{ext} + \mu_0 \bar{M}$$ SOBSTITUTE (1)

$$= \bar{B}_{ext} + \mu_0 \left(\frac{\chi_m \bar{B}_{ext}}{\mu_0} \right)$$

$$\bar{B} = \bar{B}_{ext} \left(1 + \chi_m \right) \quad (2)$$

$\bar{B}$ INSIDE THE MATERIAL WHERE THE FIELD IS UNIFORM

EX. IN ALUMINIUM FIELD GOES UP BY 0.002%
IN PURE IRON BY A FACTOR OF 200.000

PARAMAGNETISM

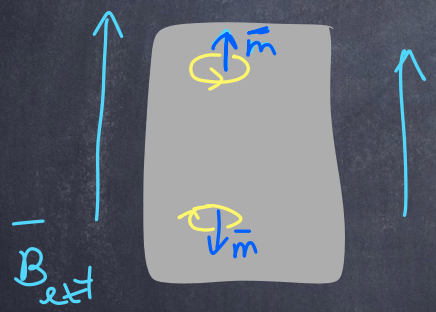
MATERIALS WITH SMALL POSITIVE χ_m

$\vec{m}$ IN ATOMS ARE RANDOMLY ALIGNED

AND TEND TO ALIGN WITH EXTERNAL MAGNETIC FIELD

BUT THERMAL MOTION COUNTERACTS THIS TENDENCY

THE 2 EFFECTS COMPETE



MAGNETIC POTENTIAL ENERGY

$$U = -\vec{m} \cdot \vec{B}$$

ΔU = ENERGY TO FLIP $\vec{m}$

$$= (+m_B)(B_{ext}) - (-m_B B_{ext})$$

$$= 2 m_B B_{ext}$$

$$= 2\left(9.27 \epsilon -24 \, J/T\right)(1T)$$

$$= 2 \epsilon -23 \, J$$

ASSUME $B_{ext} = 1T$

$m = m_B$

BOLTZMANN'S CONSTANT

ENERGY OF ATOMS DUE TO THERMAL ENERGY

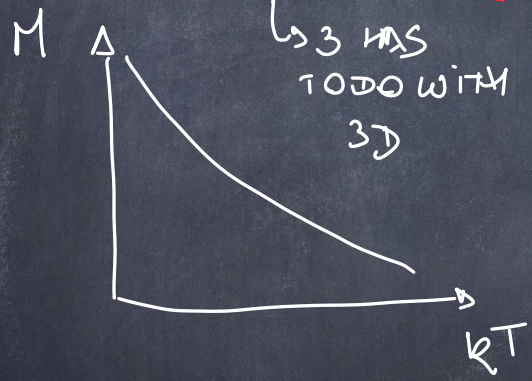
$$= kT = \left(1.38 \epsilon -23 J/K\right)(300 K) = 4 \epsilon -21 J$$

AT ROOM TEMPERATURE (300 K) ONLY A SMALL FRACTION OF ATOMS ALIGN WITH THE FIELD

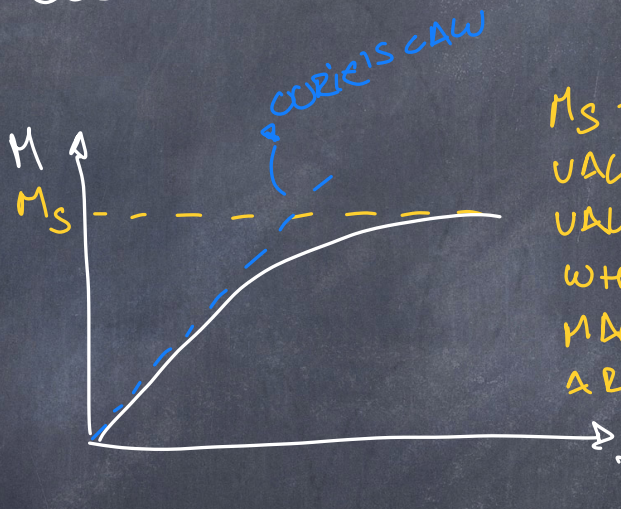
THE FRACTION GROWS AT LOWER TEMPERATURES AND HIGHER FIELD

$$M = \frac{m\, B_{ext}}{3kT} M_s$$

CURIE'S LAW



3 HAS TO DO WITH 3D



M_S = SATURATION VALUE (THE MAX VALUE OF MAGNETIZ. WHEN ALL THE MAGNETIC MOMENTS ARE ALIGNED)

CURIE'S LAW IS A GOOD APPROXIMATION



HOW DO WE MAKE A PARAMAGNET WITHOUT A BIGGER MAGNET?

FERROMAGNETISM

MATERIALS WITH LARGE POSITIVE VALUES OF χ_m
A SMALL FIELD APPLIED RELEASE A LARGE ONE

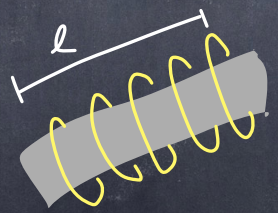


NEIGHBORING ATOMS FORCE EACH OTHER TO POINT THE SAME WAY, CAUSING ALIGNMENT IN GROUPS CALLED DOMAINS

DOMAINS: POINT IN DIFFERENT DIRECTIONS AND CANCEL

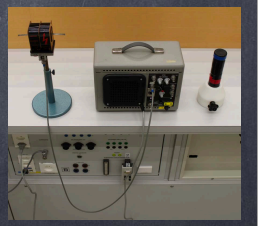
APPLYING A $\bar{B}_{ext}$ WE CAN GET THE DOMAINS TO ALIGN
- DOMAINS POINTING WITH $\bar{B}_{ext}$ GROW
- OTHERS FLIP

PUT IRON IN A SOLENOID



BARKHAUSEN EFFECT

EACH CLICK IS A DOMAIN FLIPPING

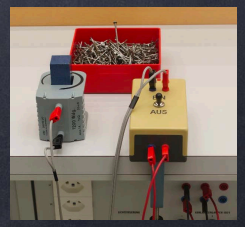


FROM ② $\bar{B} = \bar{B}_{ext}(1+\chi_m) = \mu_0 n I (1+\chi_m)$

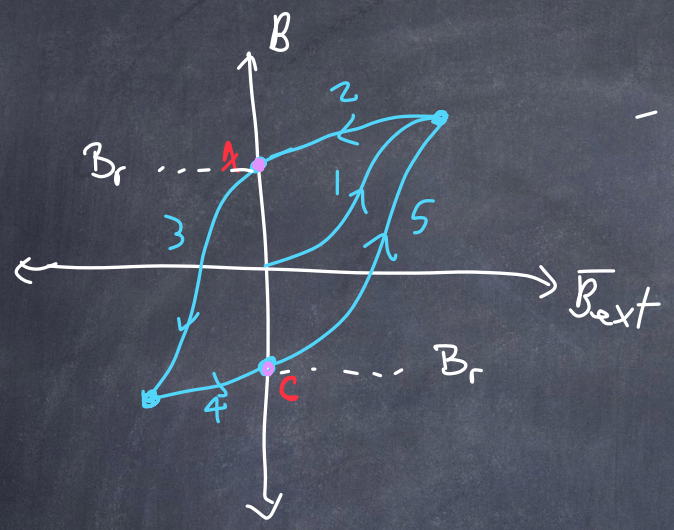
WITH $n = \frac{N_{loops}}{l}$ AND $\mu = \mu_0(1+\chi_m)$

$\Rightarrow \boxed{\bar{B} = \mu n I}$

MUCH STRONGER WITH FERROMAGNETIC



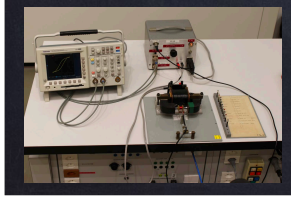
ANOTHER PROPERTY OF FERROMAGNETS IS THEIR MEMORY



B_r REMNANT MAGNETIC FIELD

$B_r = \cancel{B_{ext}^{\,0}} + \mu_0 \bar{M}_r$

A, C IS WHEN THE FERROMAGNET BECOMES PERMANENT



- START WITH A PIECE OF UNMAGNETIZED IRON
- INCREASE THE $\bar{B}_{ext}$ AND MEASURE $\bar{B}$

① INCREASE B_{ext}, THEN $\bar{B}$ INCREASES

② DECREASE B_{ext} TO ZERO
THERE IS A $\bar{B}$ IN THE MATERIAL SINCE WE HAVE ALIGNED ALL THE DOMAINS

③ SWITCH THE DIRECTION OF $\bar{B}_{ext}$
B BECOMES NEGATIVE

④ INCREASE B_{ext} TO ZERO,
B STAYS NEGATIVE

⑤ INCREASE B_{ext}, B BECOMES POSITIVE

HYSTERESIS CURVE

DIAMAGNETISM

MATERIALS WITH A SMALL NEGATIVE VALUE OF χ_m

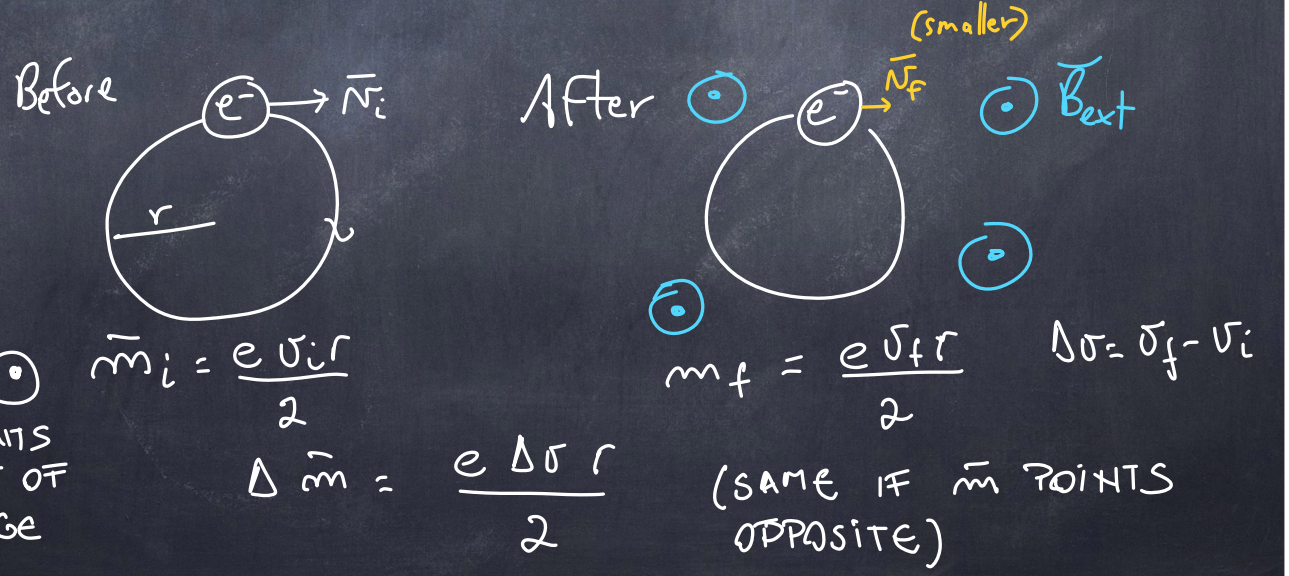
DO NOT ALIGN WITH THE EXTERNAL MAGNETIC FIELD, POSSES BACK AGAINST IT

DISCOVERED BY FARADAY IN 1846 WHEN NOTICING THAT BISMUTH IS REPELLED BY EITHER SIDE OF THE MAGNET

WHY? LENZ LAW IN AN ATOM

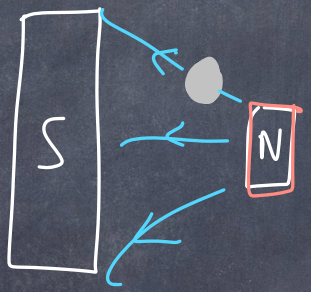
WHEN THE FLUX THROUGH A LOOP CHANGES, A CURRENT IS INDUCED THAT OPPOSES THAT CHANGE

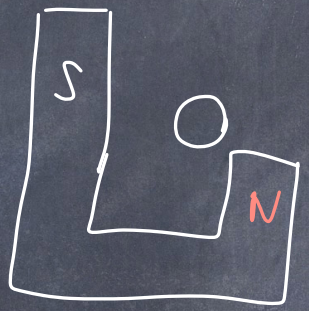
THE ELECTRON ORBIT IS THE LOOP



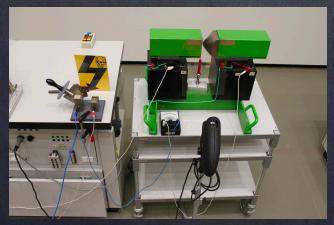
DIAMAGNETISM IS PRESENT IN EVERY MATERIAL, BUT ONLY SHOWS WHEN ALL ELECTRONS ARE PAIRED AND THERE IS NO PERMANENT MOMENT.

IT DOESN'T DEPEND ON TEMPERATURE, BECAUSE NOTHING HAS TO BE ALIGNED AGAINST THERMAL MOTION





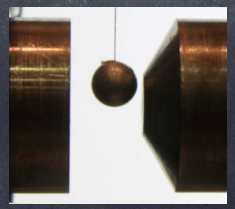
→ BISMUTH



CARBON DIOXIDE AND WATER VAPOR



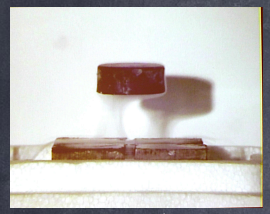
GRAPHITE ON MAGNET



THE PERFECT DIAMAGNET – SUPERCONDUCTOR

ORDINARY DIAMAGNETS REDUCE FIELD INSIDE BY A FEW PARTS IN A MILLION.

A SUPERCONDUCTOR REDUCES TO ZERO



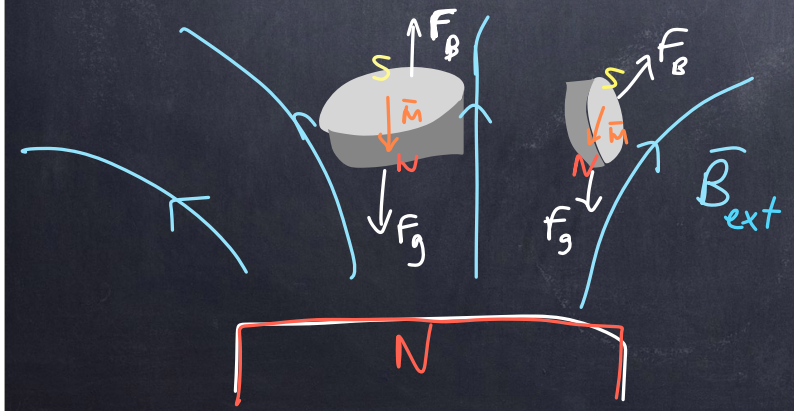
GRAPHITE

$$B_{inside} = B_{ext} + \mu_0 M = 0$$

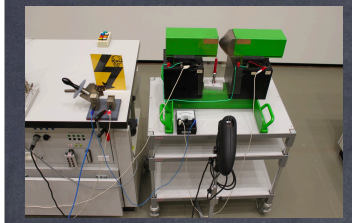
$$M = -\frac{B_{ext}}{\mu_0}$$

BELOW A CRITICAL TEMPERATURE THE MATERIAL HAS ZERO ELECTRICAL RESISTANCE

SUPERCONDUCTOR FLOATING ON A REGULAR MAGNET



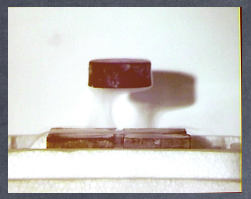
THE CURRENTS THAT LENZ'S LAW INDUCES NEVER DIE AWAY, AND ARE EXACTLY LARGE ENOUGH TO SCREEN THE FIELD OUT



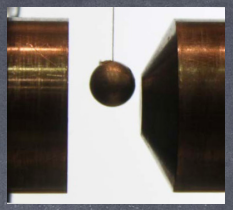
ED28



ED29



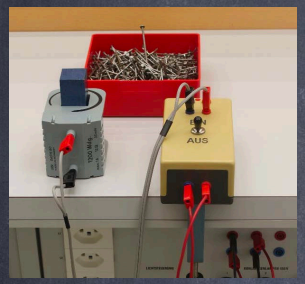
ED30



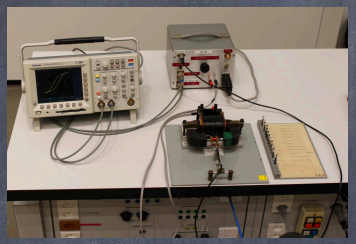
ED32



ED34



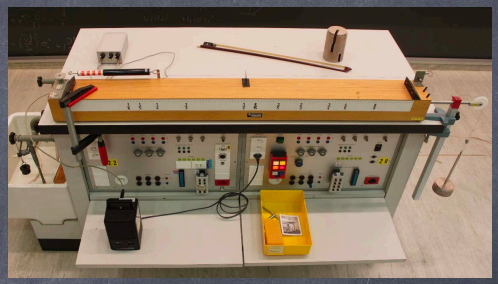
ED35



ED40



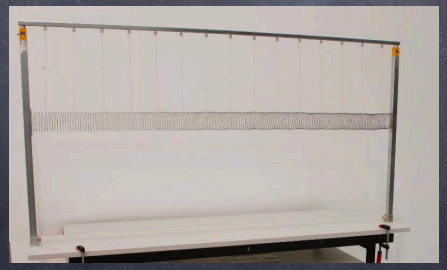
ED41



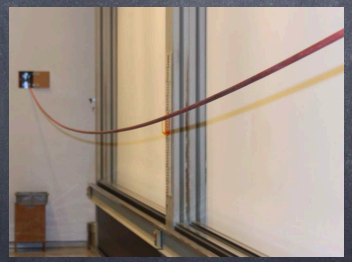
W14



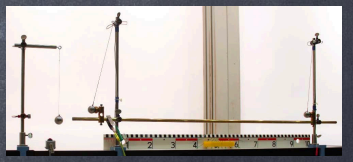
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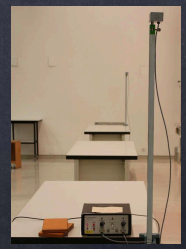
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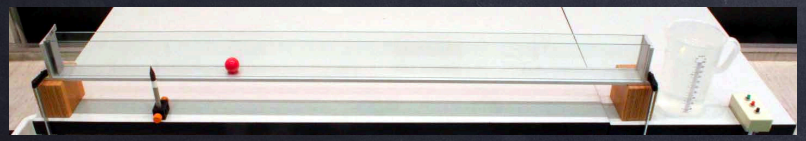
W28



W32



W33



W31