Fundamentals of Solid State Physics

Magnetic Properties

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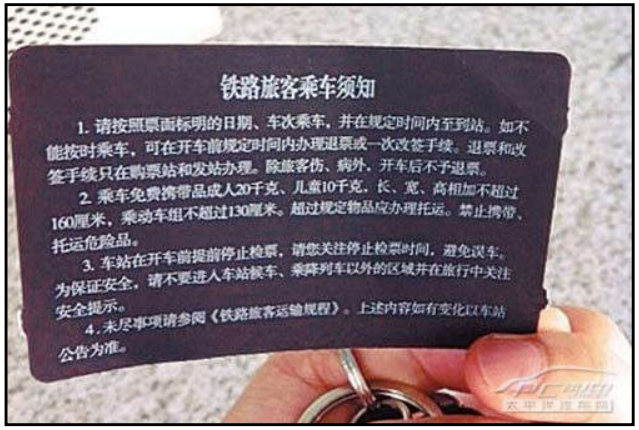
Applications of Magnetics

Compass

Hard Drive

Wind Turbine



ID ticket

MagLev 磁悬浮

MRI

Nobel Prizes in Magnetics

- 1902 Zeeman effect
- 1943 Magnetic moment of proton
- 1944 Magnetics of atomic nuclei
- 1952 Nuclear magnetic resonance (NMR)
- 1955 Magnetic moment of electron
- 1970 anti-ferromagnetism and ferri-magnetism
- 1972 BCS theory of superconductivity
- 2007 Giant magnetoresistance
- ...

incomplete list

Outline

- **Maxwell's Equations**
  - ***H*, *B*, *M*, μ_r**
  - **Magnetic Susceptibility 磁化率 χ**
- **Origin of magnetism**
  - **spin of electrons, orbital angular momentum, external field**
  - **nuclear magnetic momentum**
- **Types of magnetism**
  - **Diamagnetism 抗磁性**
  - **Paramagnetism 顺磁性**
  - **Ferromagnetism 铁磁性**
  - **Antiferromagnetism 反铁磁性**
  - **Ferrimagnetism 亚铁磁性**

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

Constitutive Relations
本构关系

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$
$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

$\varepsilon_0 \varepsilon_r$ - **Permittivity (dielectric constant)**

ε_r = 1 for vacuum

$\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

$\mu_0 \mu_r$ - **Permeability**

μ_r = 1 for vacuum

$\mu_0 = 4\pi \times 10^{-7}$ H/m

Electrodynamics

- **Maxwell's Equations**

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Constitutive Relations
本构关系

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$$
$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

For magnetic materials

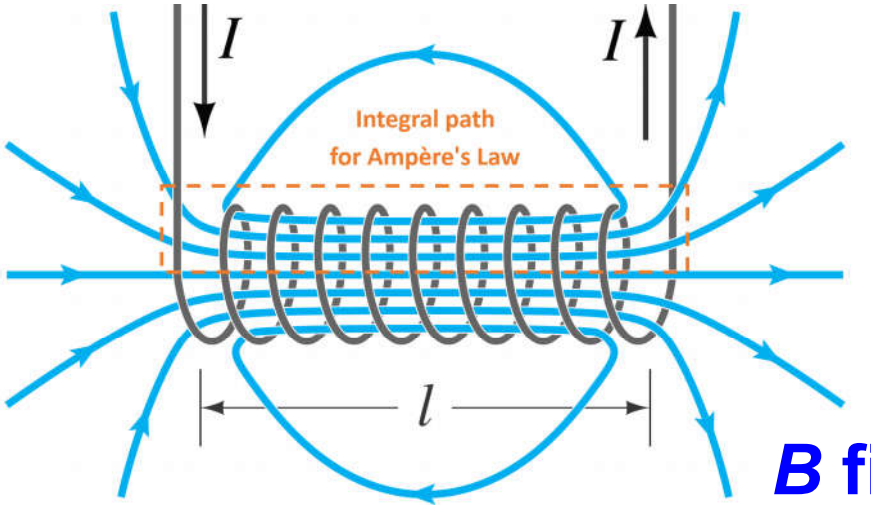
$\mu_r \neq 1$

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

Solenoid (螺线管)



***B* field**

$$\mathbf{B} = \mu_0 \mu_r n I$$

Electromagnet: Magnetic field is produced by electric currents. (Ampere's law)

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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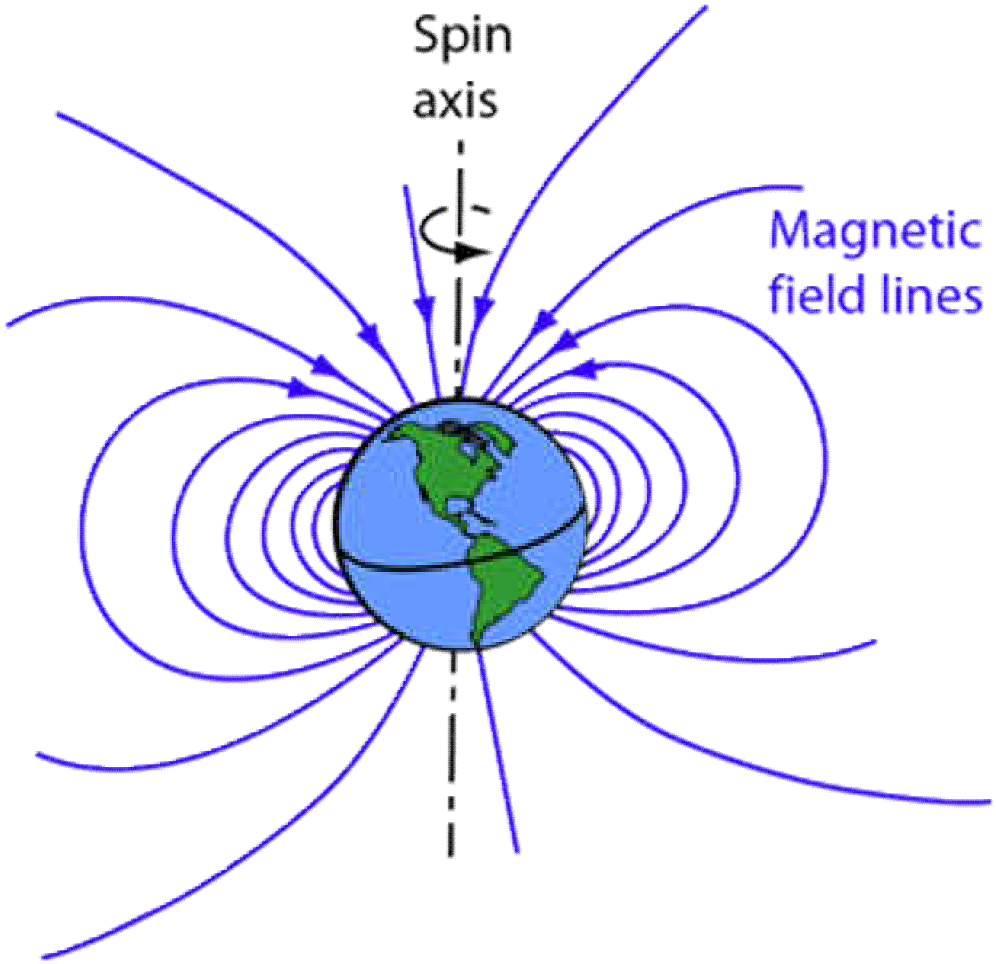


Our earth is a big electromagnet

Electrodynamics

- **Maxwell's Equations**

$$\nabla \cdot \mathbf{D} = \rho_V$$

$$\nabla \cdot \mathbf{B} = 0$$

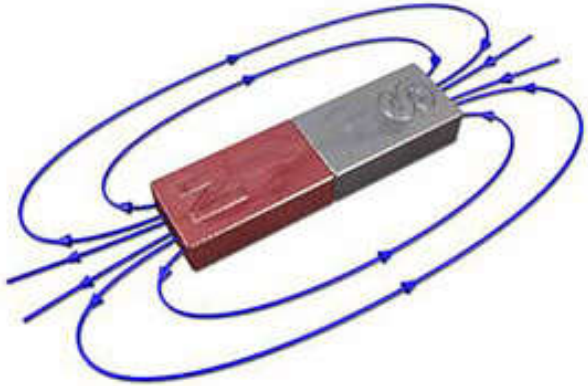
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

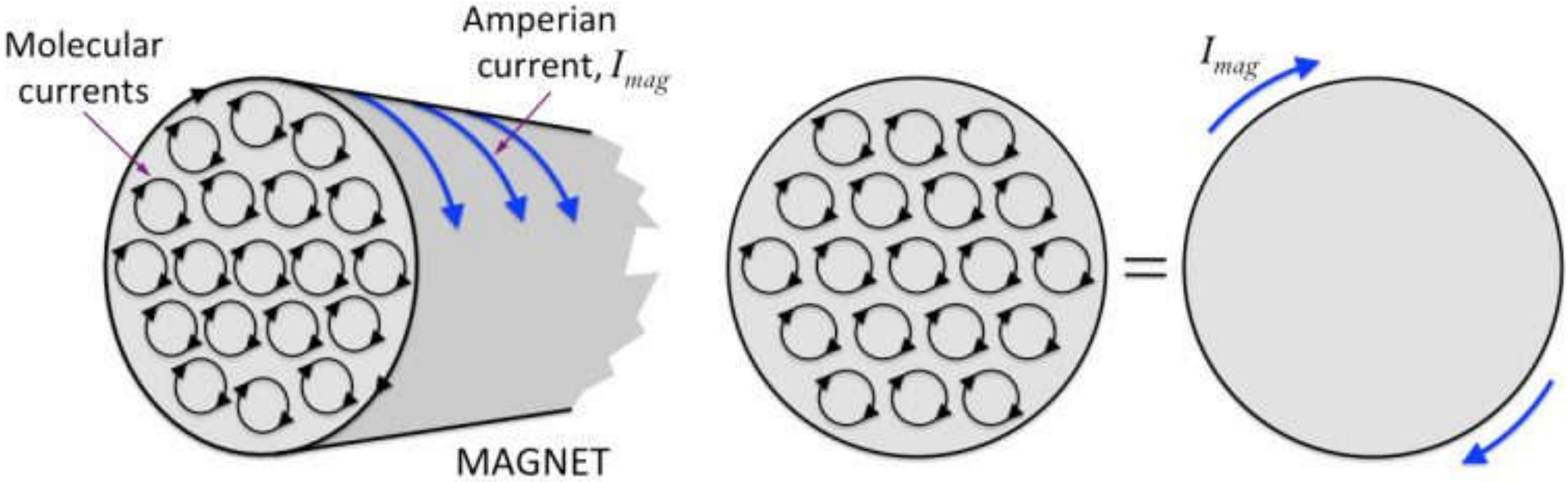
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

How about magnetic materials?

Origin of Magnetism - Old Theory

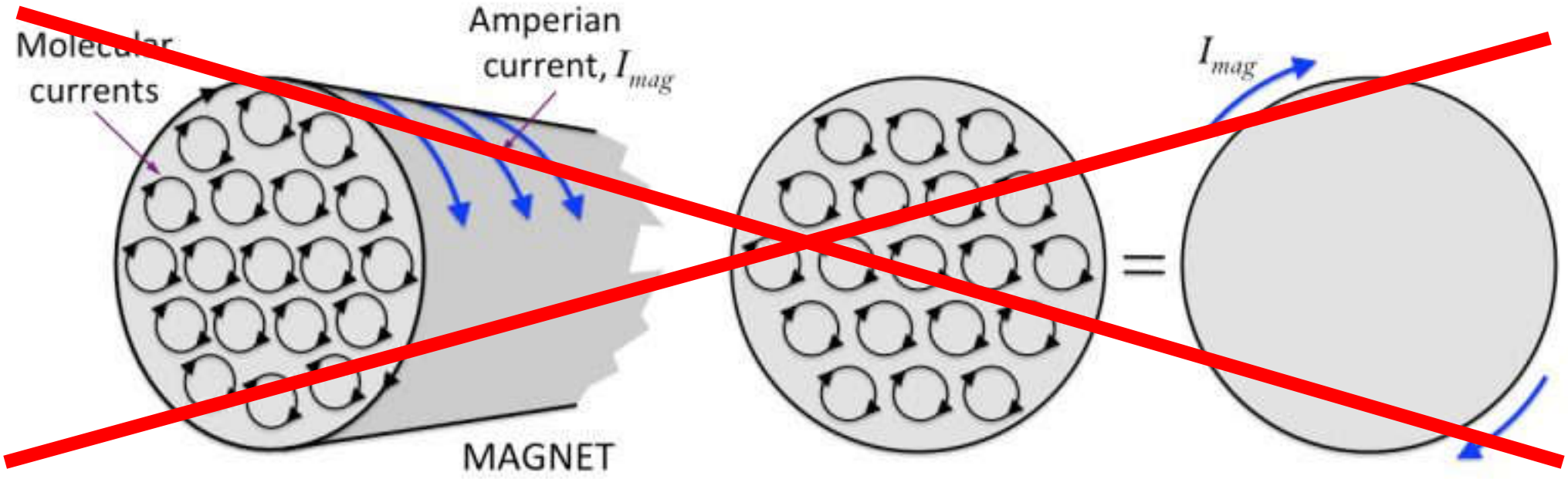
- **Ampere 安培, 1826**
  - **Molecular Currents 分子电流假说**
  - **"magnetism is electricity in motion"**





Origin of Magnetism - Old Theory

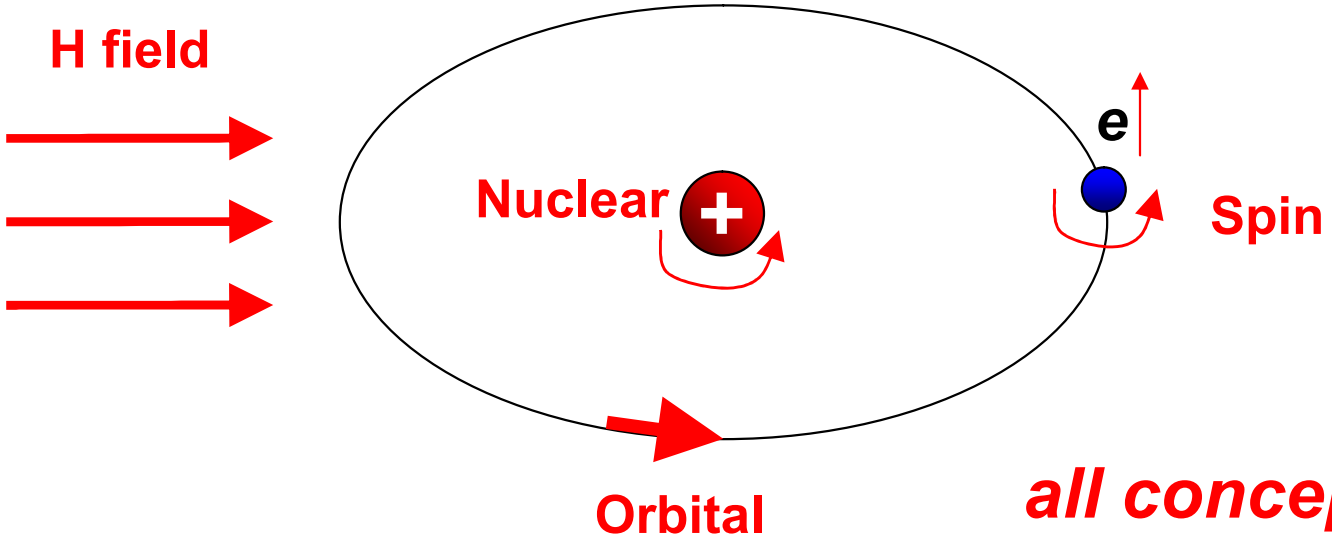
- **However**
  - **Classical mechanics give no magnet effects at all**
  - **For a steady solid, all the magnetic moments cancel out**



We can only understand magnetism with quantum mechanics

Origin of Magnetism - Modern Theory

- **Magnetic moment of atoms**
  - spin of electrons
  - orbital angular momentum
  - external magnetic field
  - magnetic momentum of nuclei (10^{-3} times smaller than that from electrons)



all concepts are quantum mechanics based

Magnetic Properties

- For solids, $\mu_r \neq 1$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} = \mu_0 (1 + \chi)\mathbf{H} = \mu_0 (\mathbf{H} + \mathbf{M})$$

$$\chi = \mu_r - 1 \qquad \mathbf{M} = \chi \mathbf{H}$$

- ***B*** **- Magnetic induction 磁感应强度**
- ***H*** **- Magnetic field 磁场强度**
- ***M*** **- Magnetization 磁化强度**
- χ **- Magnetic Susceptibility 磁化率**

Types of Magnetism

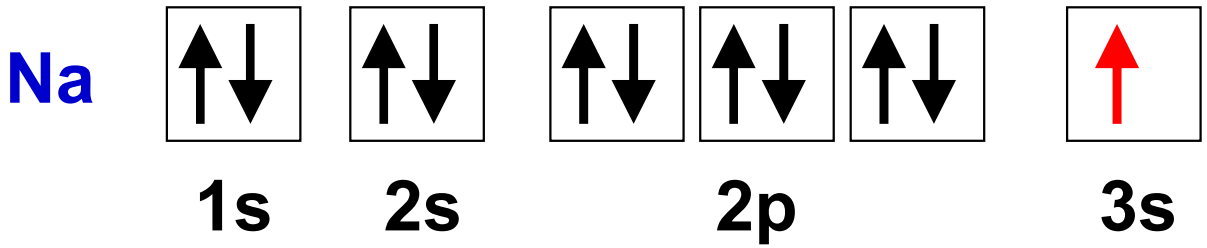
- χ - Magnetic Susceptibility 磁化率

$$\mathbf{M} = \chi \mathbf{H}$$

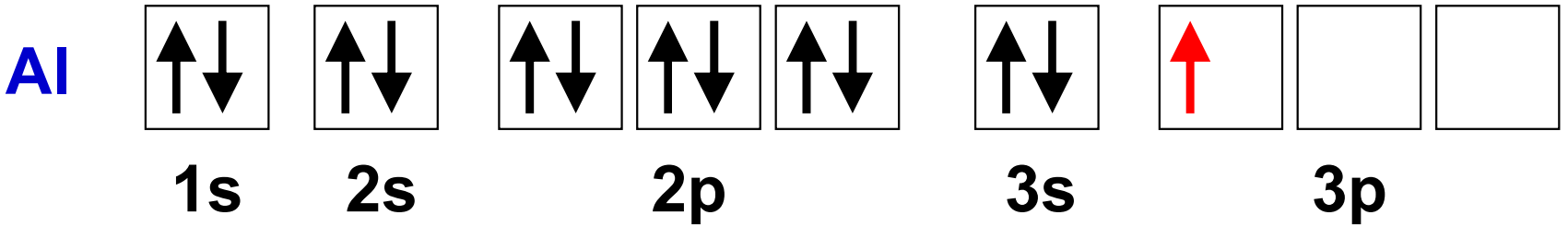
Diamagnetism 抗磁性	$\chi < 0$	$\sim 10^{-6}$
Paramagnetism 顺磁性	$\chi > 0$	$10^{-4} \sim 10^{-5}$
Ferromagnetism 铁磁性	$\chi >> 0$	$>10^{-2}$

Paramagnetism 顺磁性

- Originated from *unpaired electrons*
  - Sodium (Na) $[1s^2\ 2s^2\ 2p^6]\ 3s^1$



  - Aluminum (Al) $[1s^2\ 2s^2\ 2p^6]\ 3s^2\ 3p^1$



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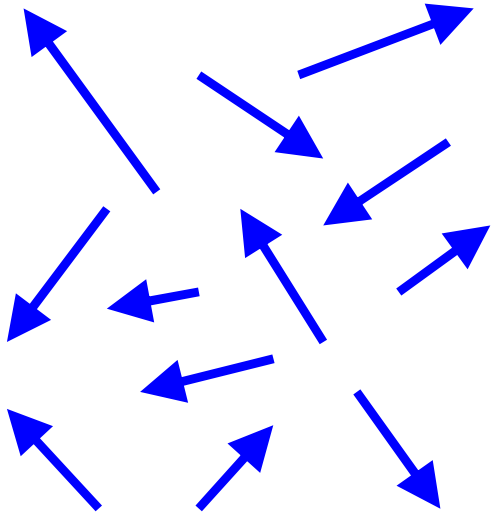
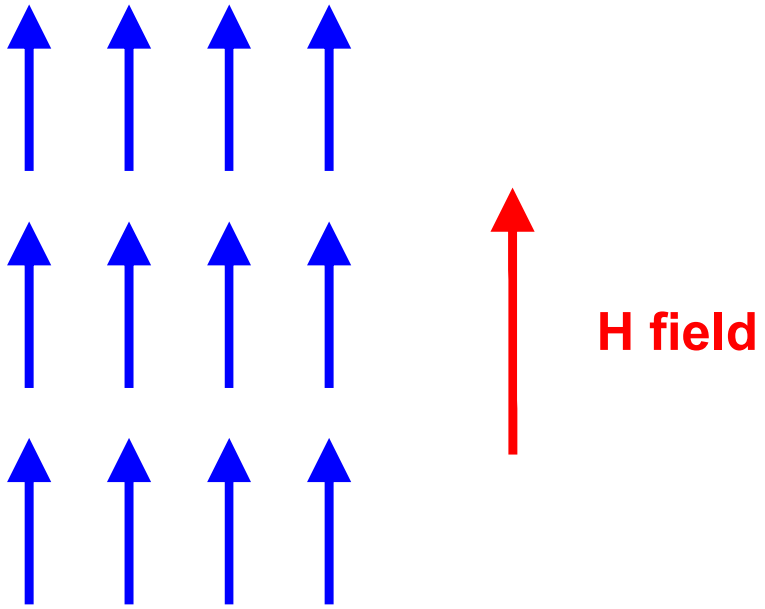


no H field



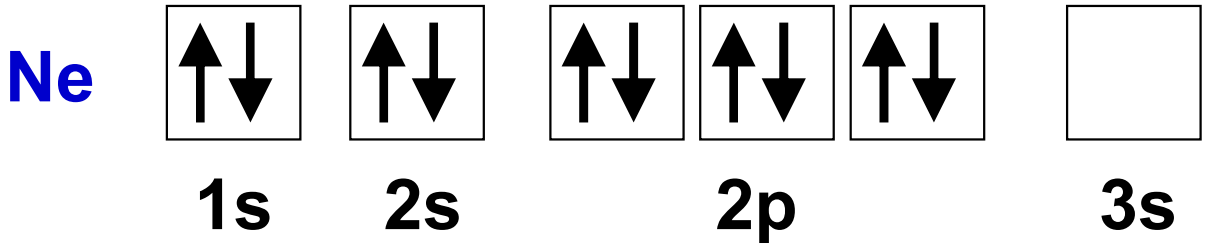
with H field

$$\mathbf{M} = \chi \mathbf{H}$$

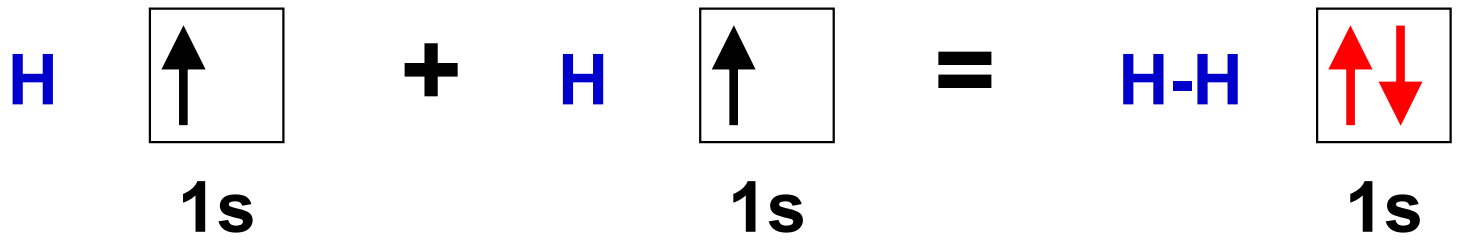
Diamagnetism 抗磁性

- Originated from *paired electrons*
  - He, Ne, Ar, ...

Detailed analysis requires quantum mechanics

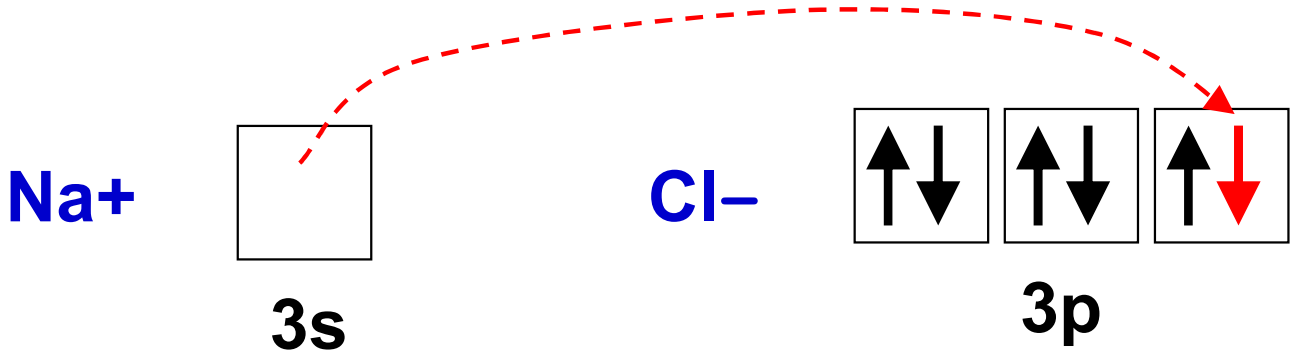


  - H_2, N_2, ...



Diamagnetism 抗磁性

- Originated from *paired electrons*
  - NaCl = Na^+Cl^-



  - Silicon crystal

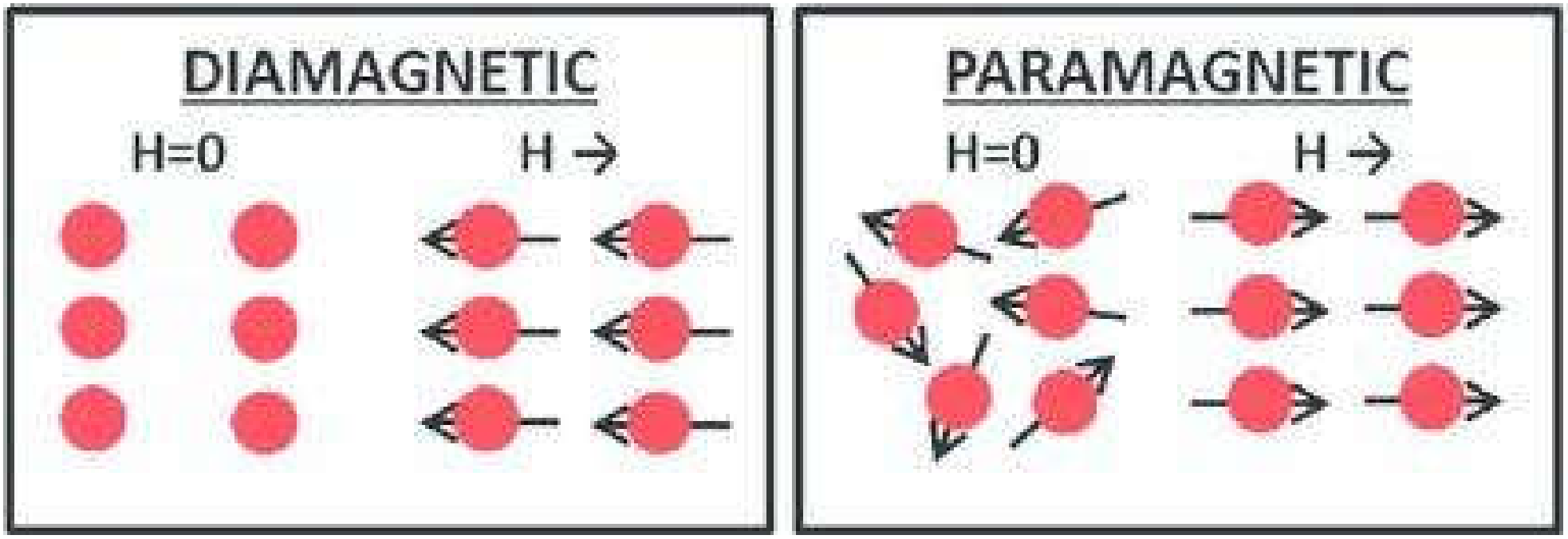
Diamagnetism 抗磁性

- **Water (H_2O) is diamagnetic**
  - **A frog is lifted by a strong magnetic field (H = 10 T)**

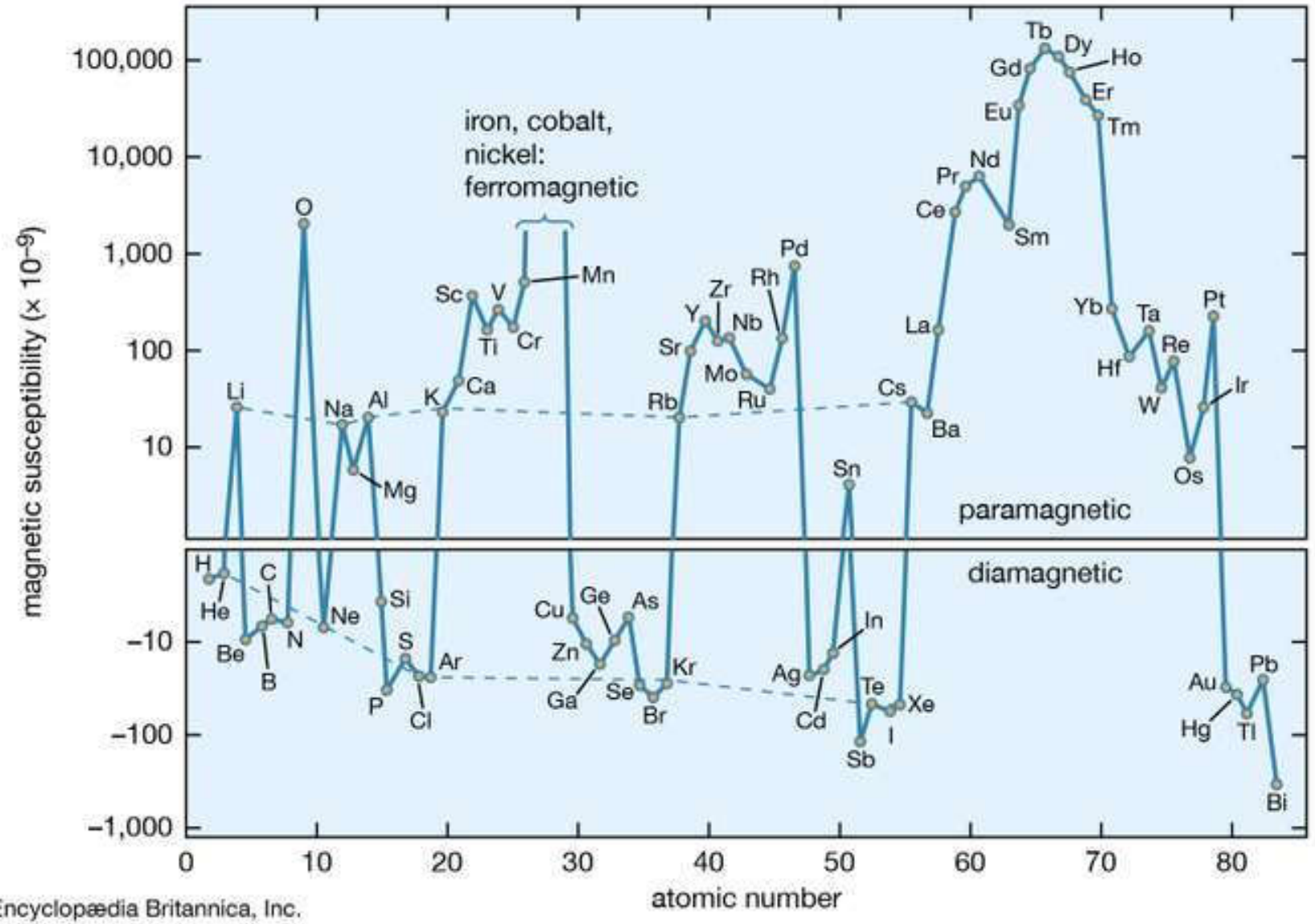
A. Geim, *Phys. Today* **51,** 9, 36 (1998)

A. Geim
Nobel Prize in 2010
Ig Nobel Prize in 2001
(搞笑诺贝尔奖)

Paramagnetism vs. Diamagnetism

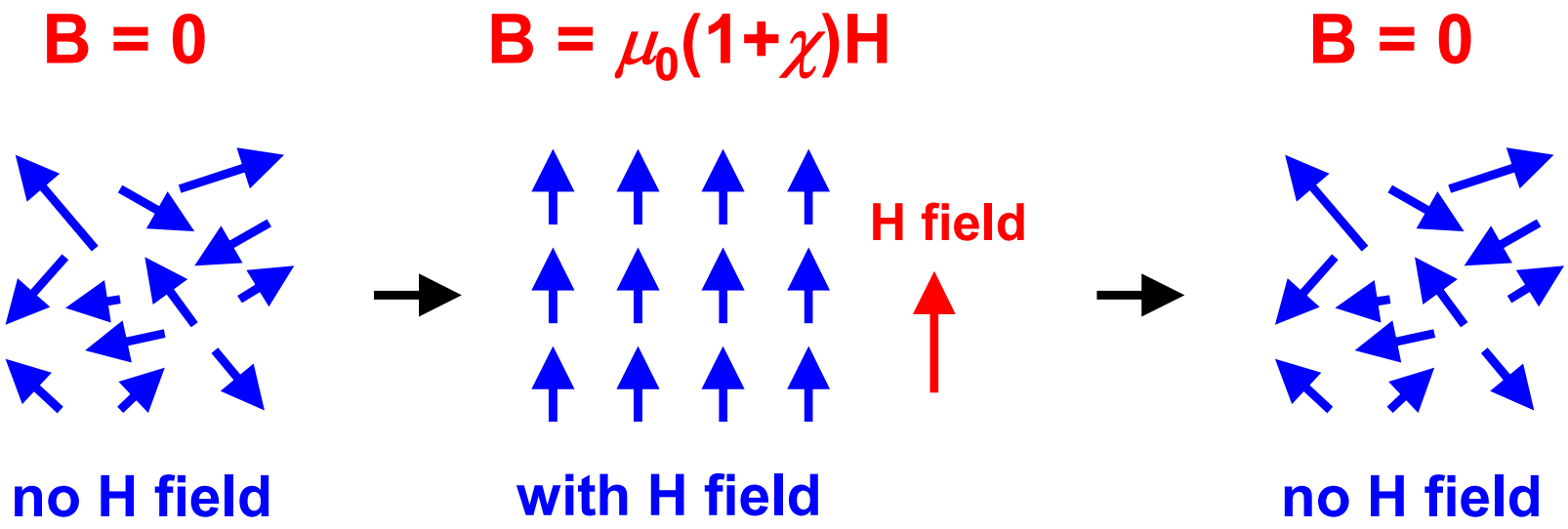


Paramagnetism vs. Diamagnetism



Magnetization Curve 磁化曲线

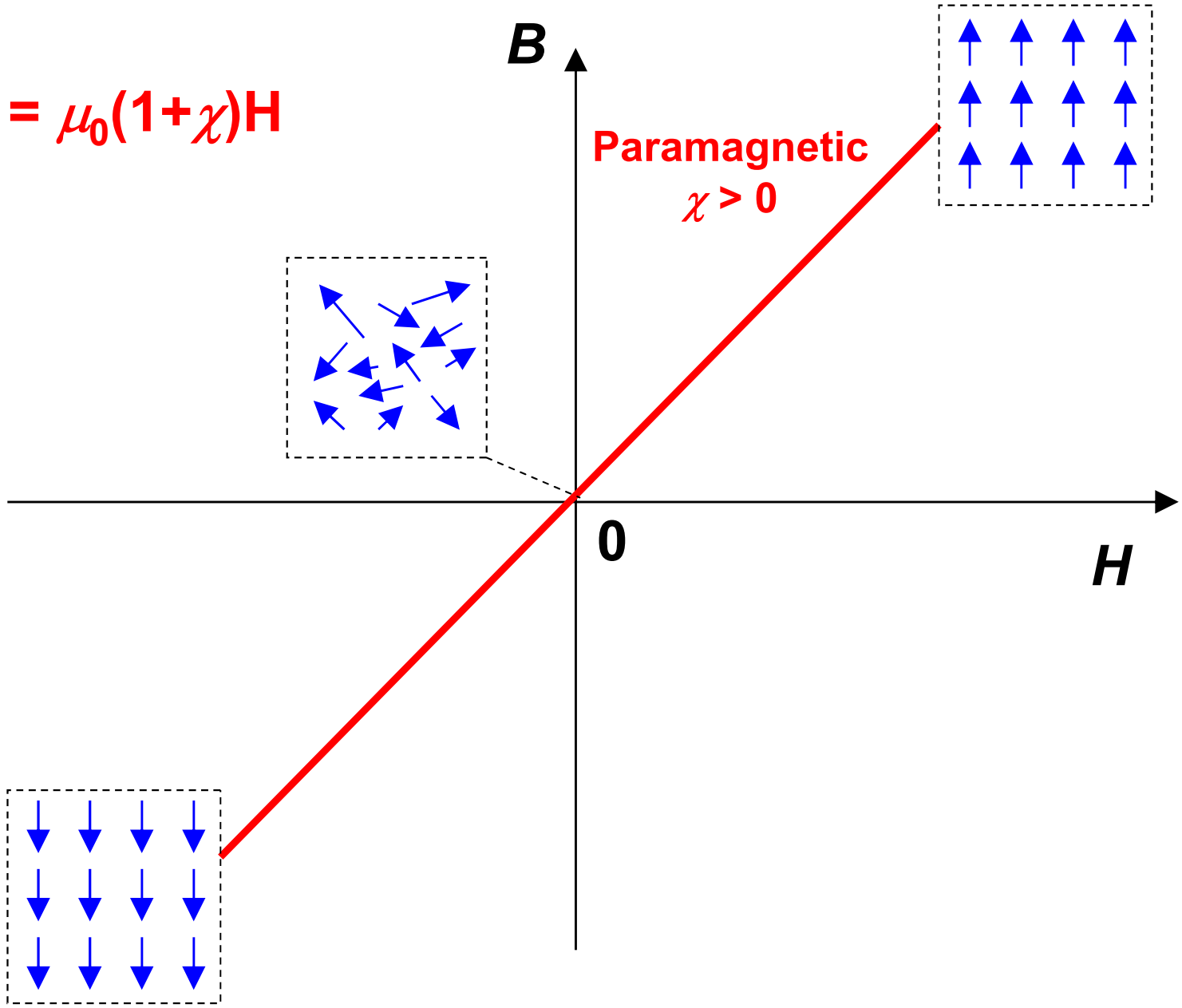
- B vs. H



Paramagnetism

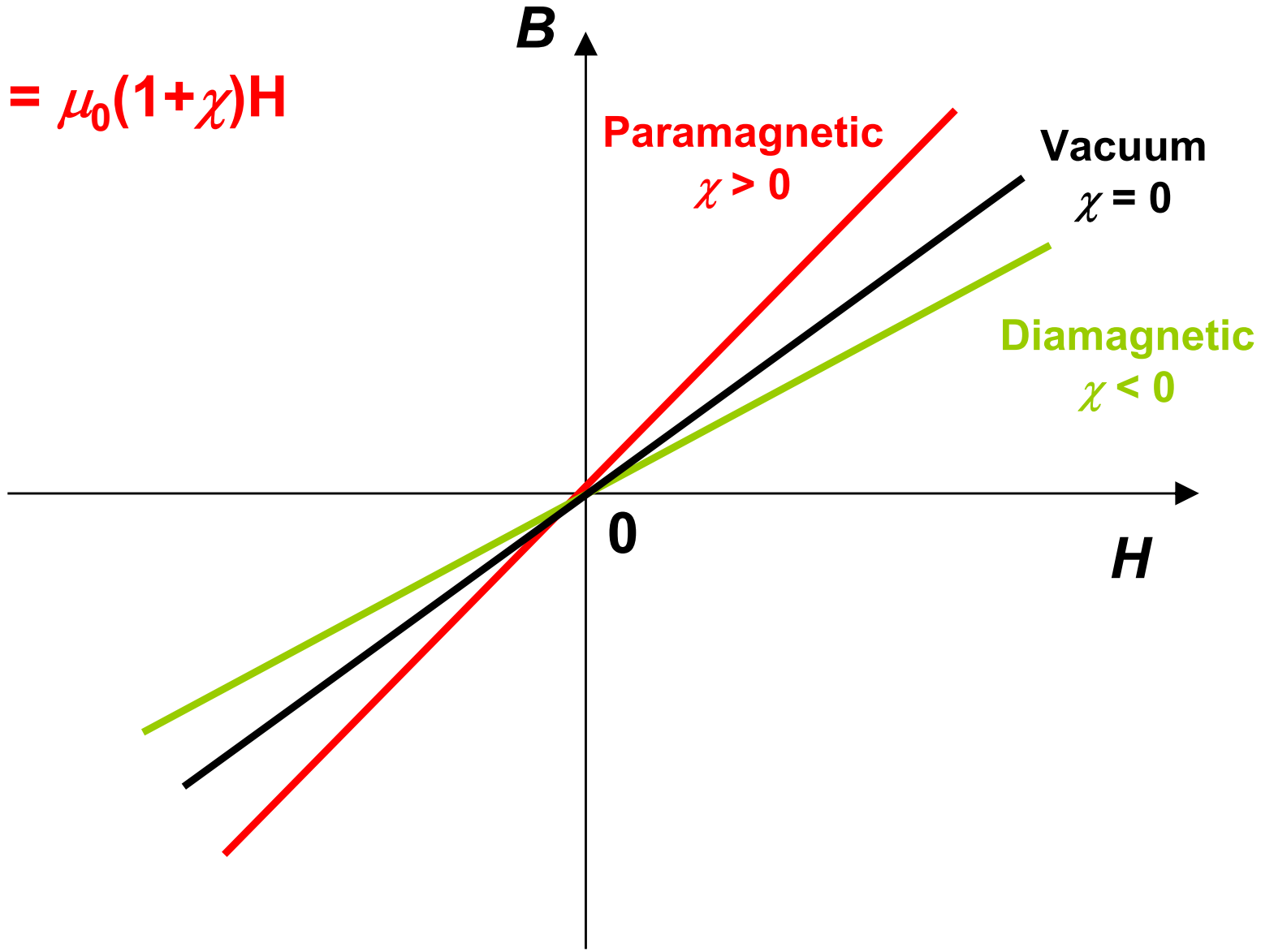
Magnetization Curve 磁化曲线

$B = \mu_0(1+\chi)H$



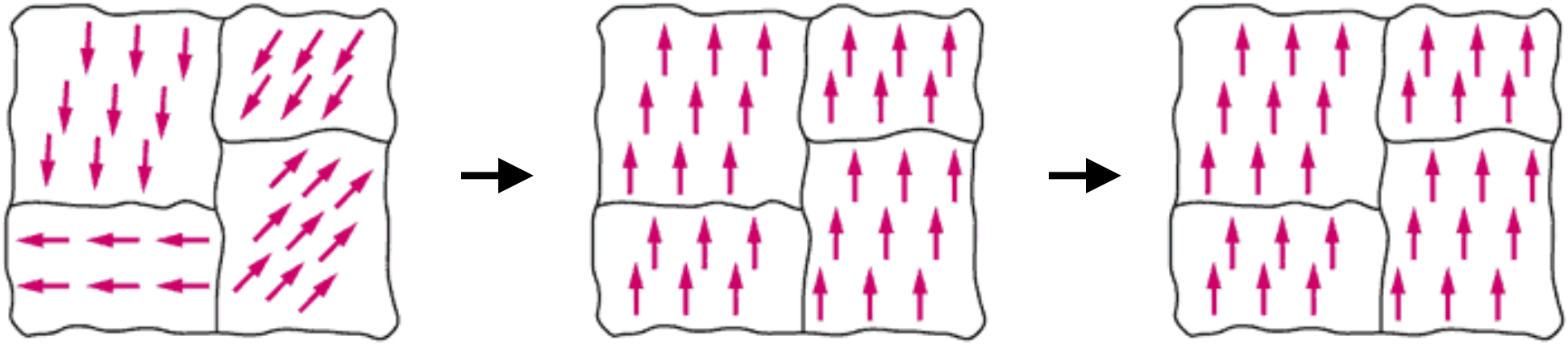
Magnetization Curve 磁化曲线

$B = \mu_0(1+\chi)H$



Ferromagnetism 铁磁性

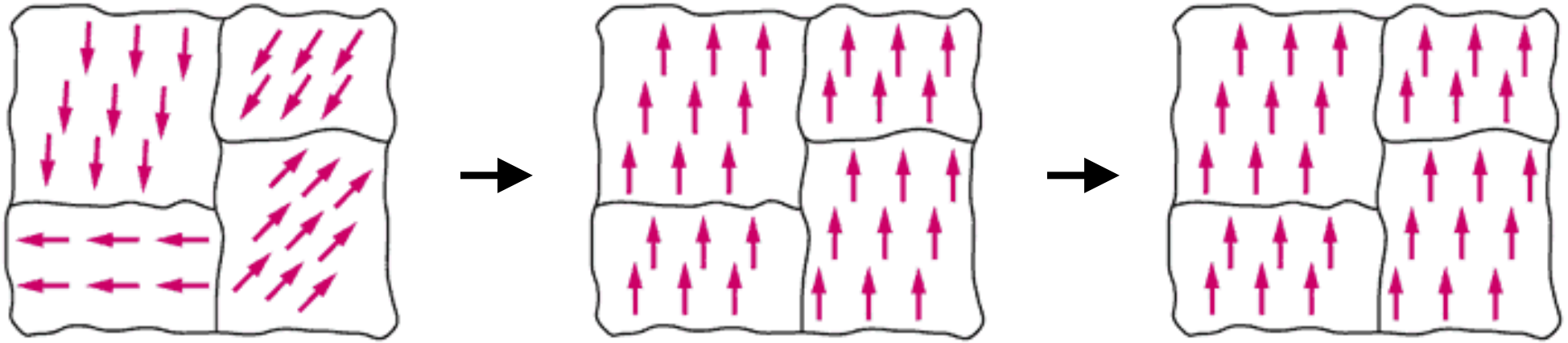
- When $H = 0$, magnetic domains (磁畴) form with spontaneous magnetization (自发磁化)
- Magnetization remains when H is removed



no H field　　with H field　　no H field

Ferromagnetism 铁磁性

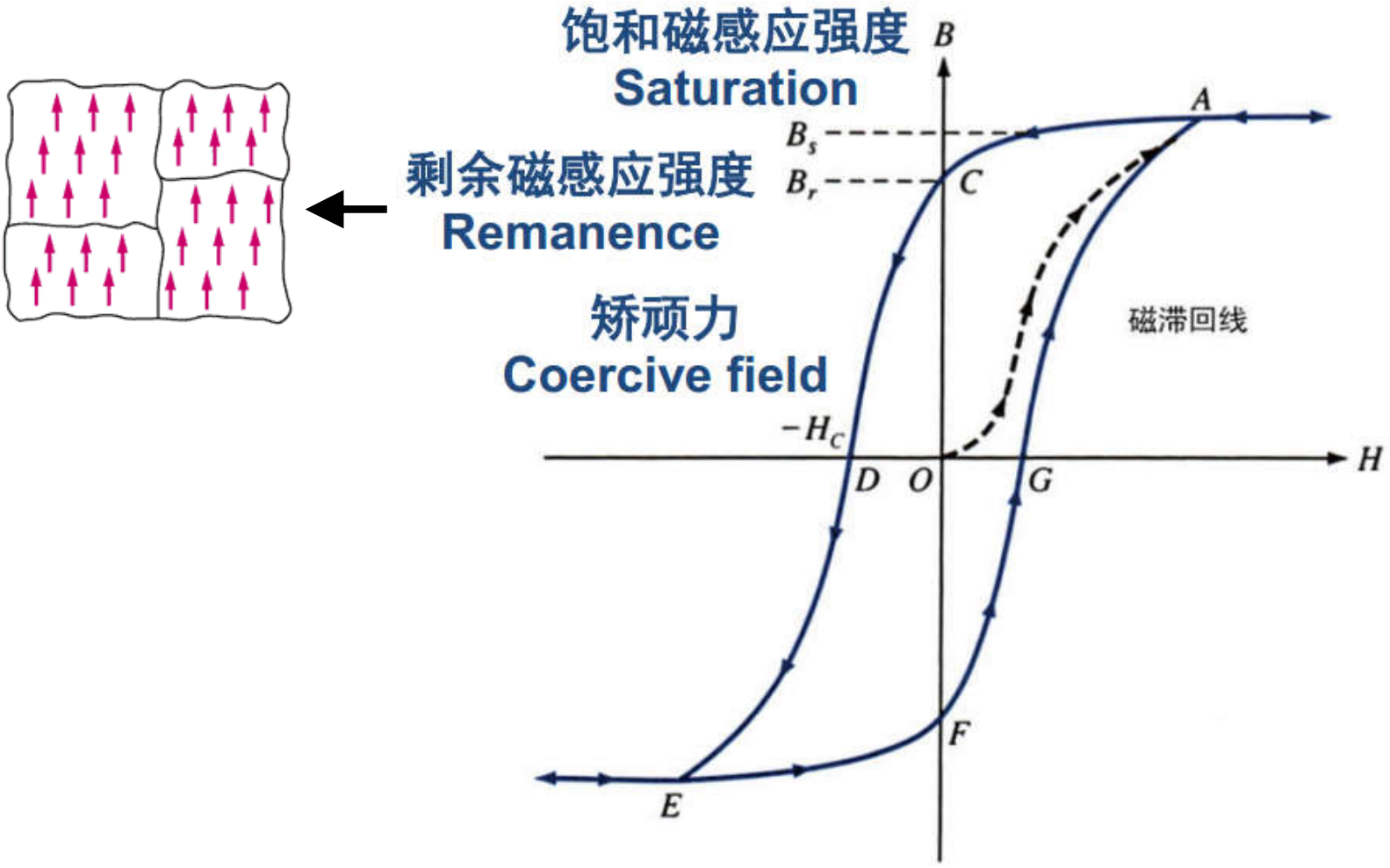
- **Permanent Magnet (永磁体)**
  - **Fe, Co, Ni (铁，钴，镍)**
  - **Alloys: NdFeB (钕铁硼), SmCo (钐钴)**



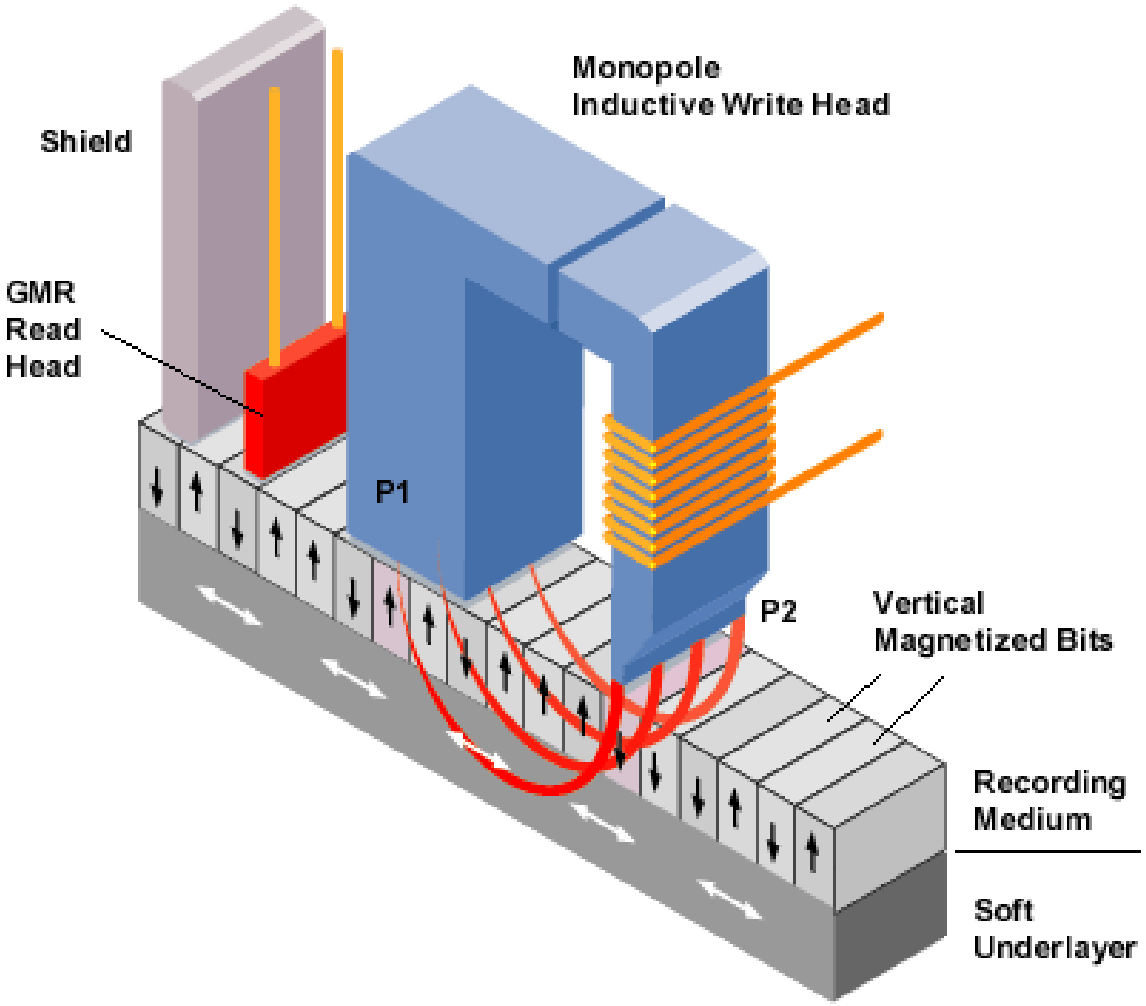
no H field **with H field** **no H field**

Ferromagnetism 铁磁性

- B-H curve forms a hysteresis loop (磁滞回线)



Magnetic recording



https://encyclopedia2.thefreedictionary.com/Perpendicular+magnetic+recording

Magnetic Tape 磁带

Hard Drive 硬盘

Evolution of Data Storage

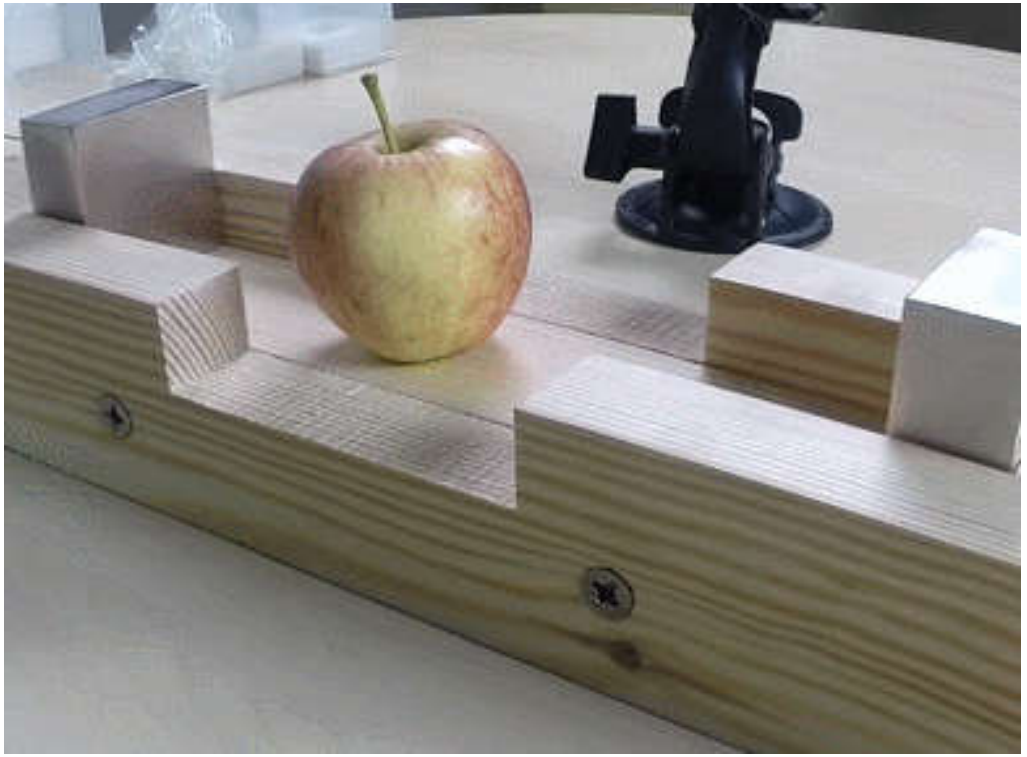
Hard Drive 硬盘

5 MB
IBM 1956

> 1 TB
Today

Ferromagnets can be Powerful

Be cautious!

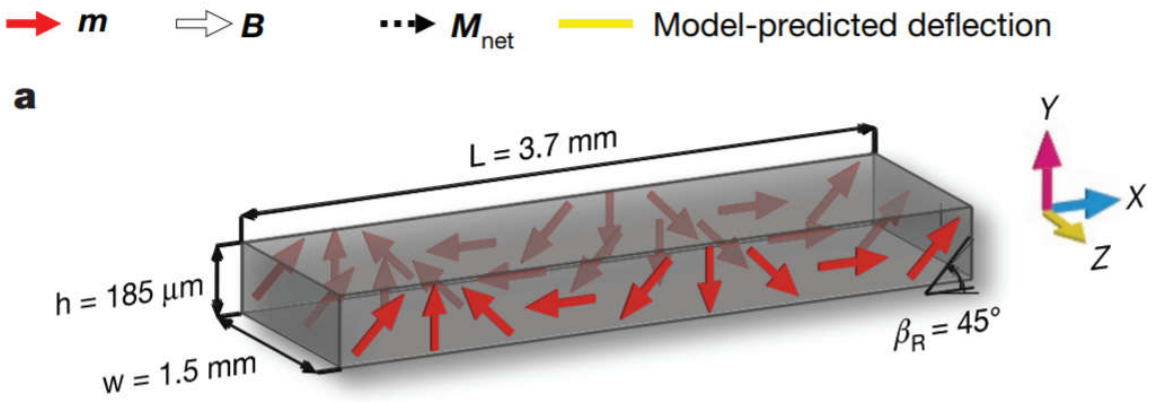


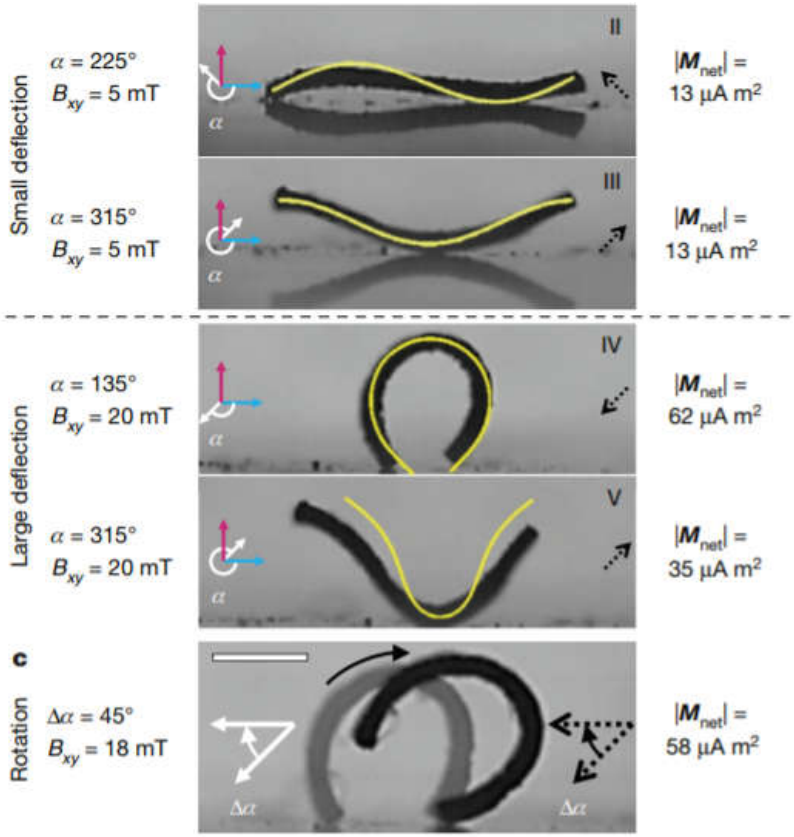
https://wonderfulengineering.com/these-15-magnet-gifs-will-show-you-the-power-of-magnetism/

Mini Magnetic Robot

Small-scale soft-bodied robot with multimodal locomotion

Wenqi Hu[1]*, Guo Zhan Lum[1]*, Massimo Mastrangeli[1] & Metin Sitti[1]



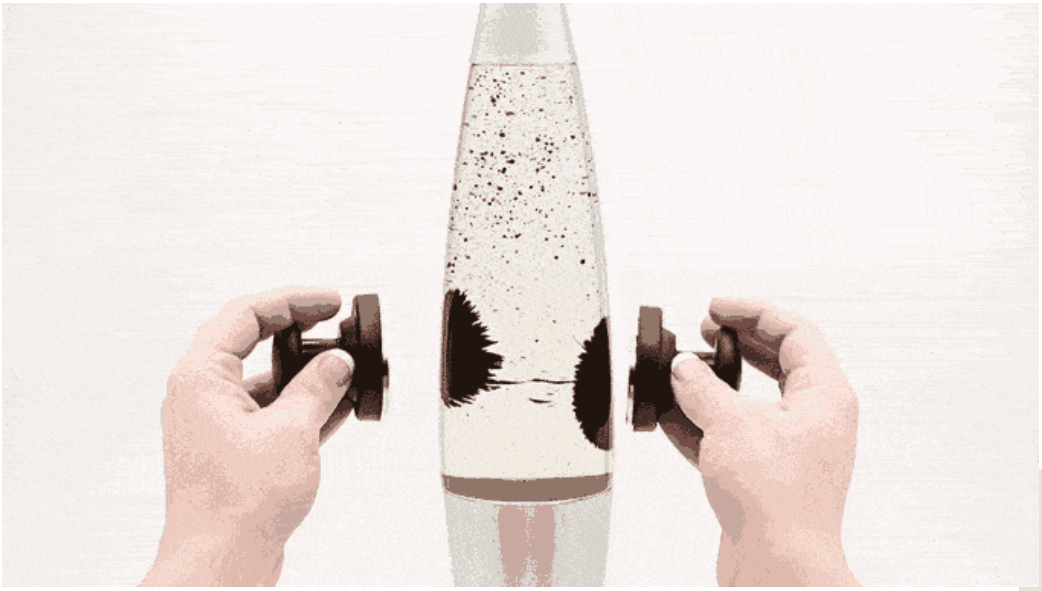


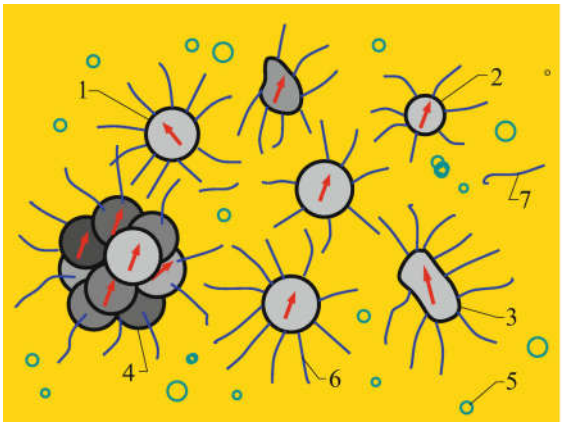
Video

W. Hu, et. al., *Nature* **554**, 81 (2018)

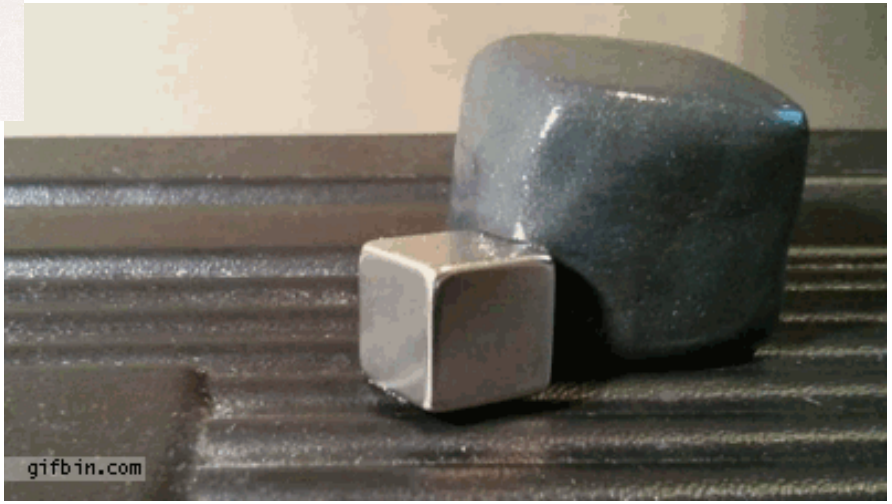
Ferrofluid 铁磁流体

- A liquid with ferromagnetic particles





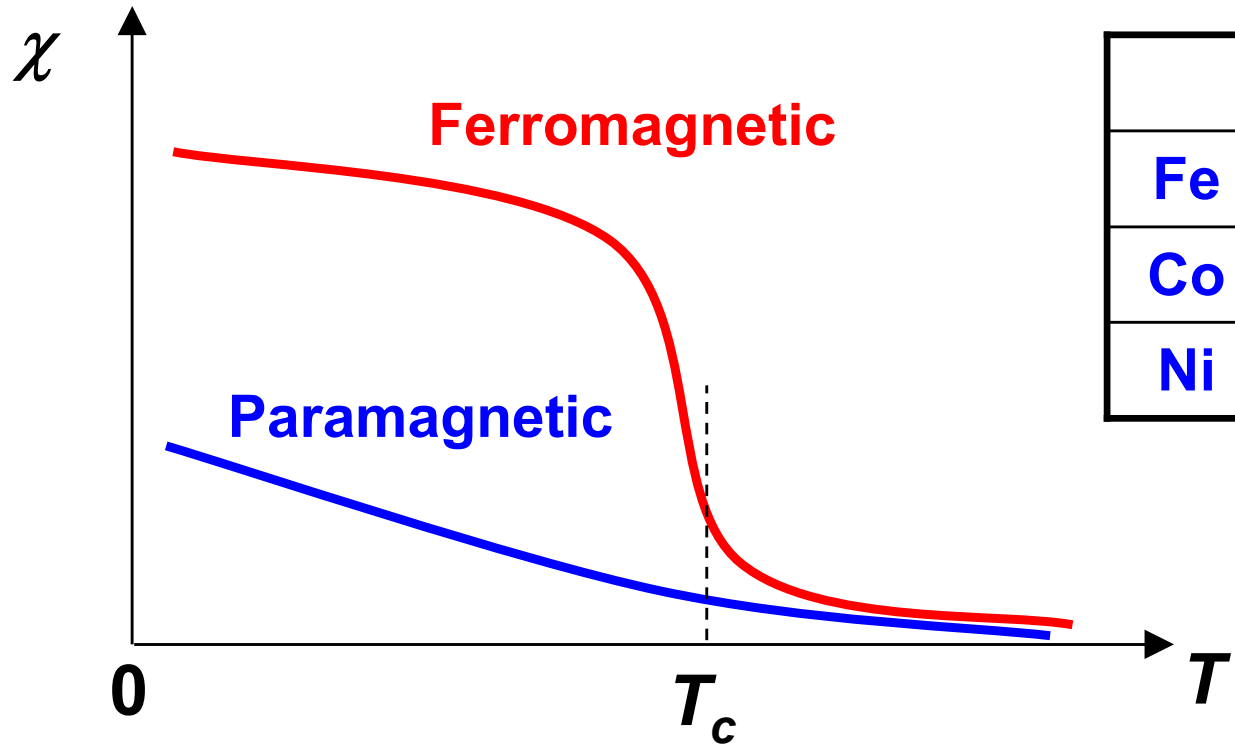
https://link.springer.com/chapter/10.1007/978-3-319-94427-2_1



https://wonderfulengineering.com/these-15-magnet-gifs-will-show-you-the-power-of-magnetism/

Temperature Effect

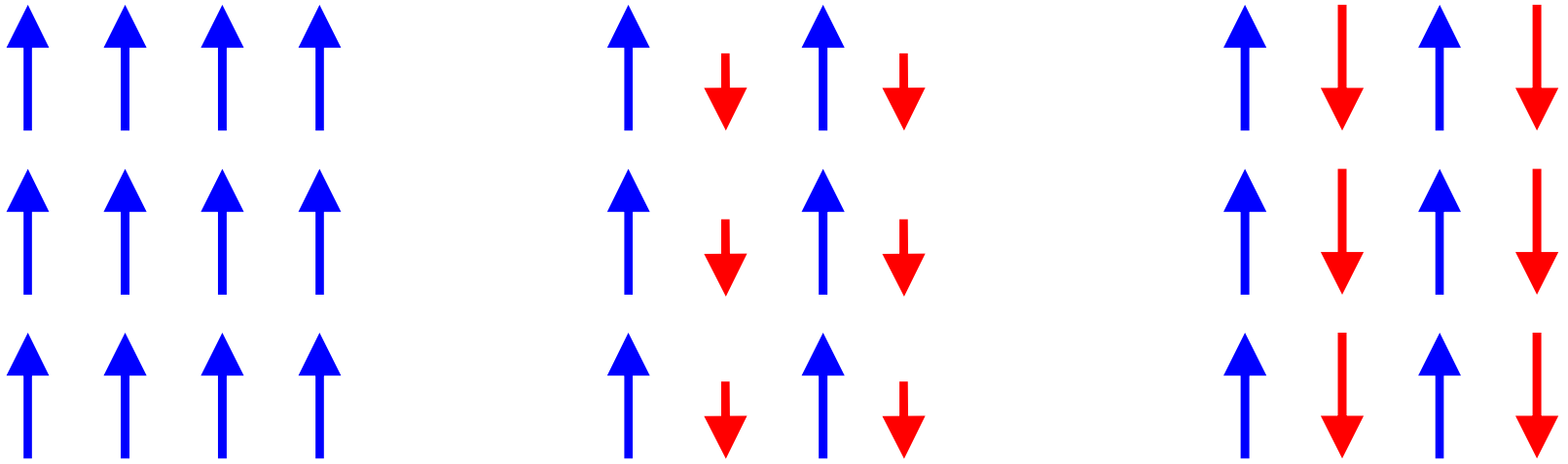
- Magnetization decreases with temperature, because of increased thermal fluctuation
- Ferromagnet becomes paramagnet above T_c (Curie Temperature 居里温度)



	T_c (°C)
Fe	770
Co	1110
Ni	350

Antiferromagnetism and Ferrimagnetism

- **Ferri**magnetism 亚铁磁性
- **Antiferro**magnetism 反铁磁性



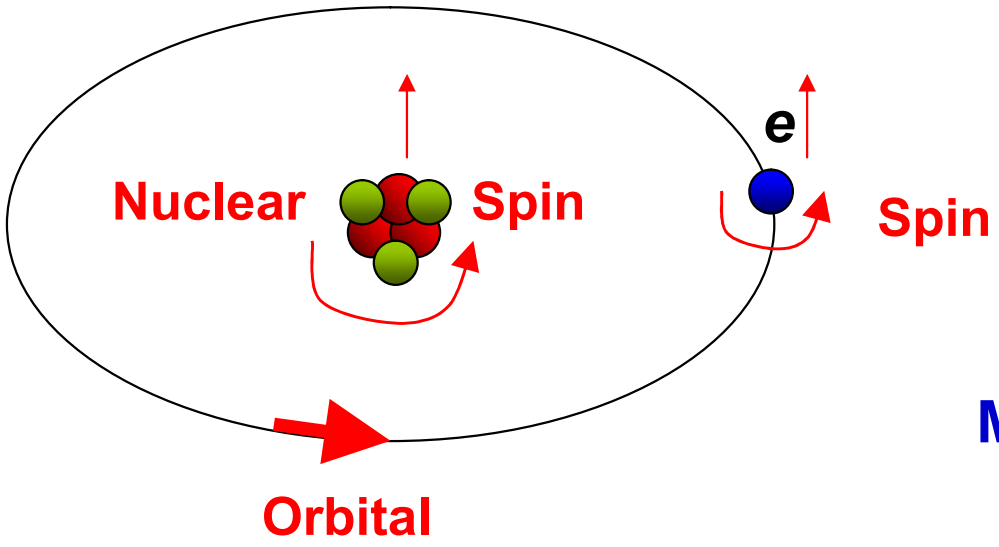
Ferromagnetic
$\chi_1 >> 0$

Ferrimagnetic
$\chi_2 < \chi_1$

Antiferromagnetic
$\chi_3 << \chi_1$

Magnetic Properties of Nuclei

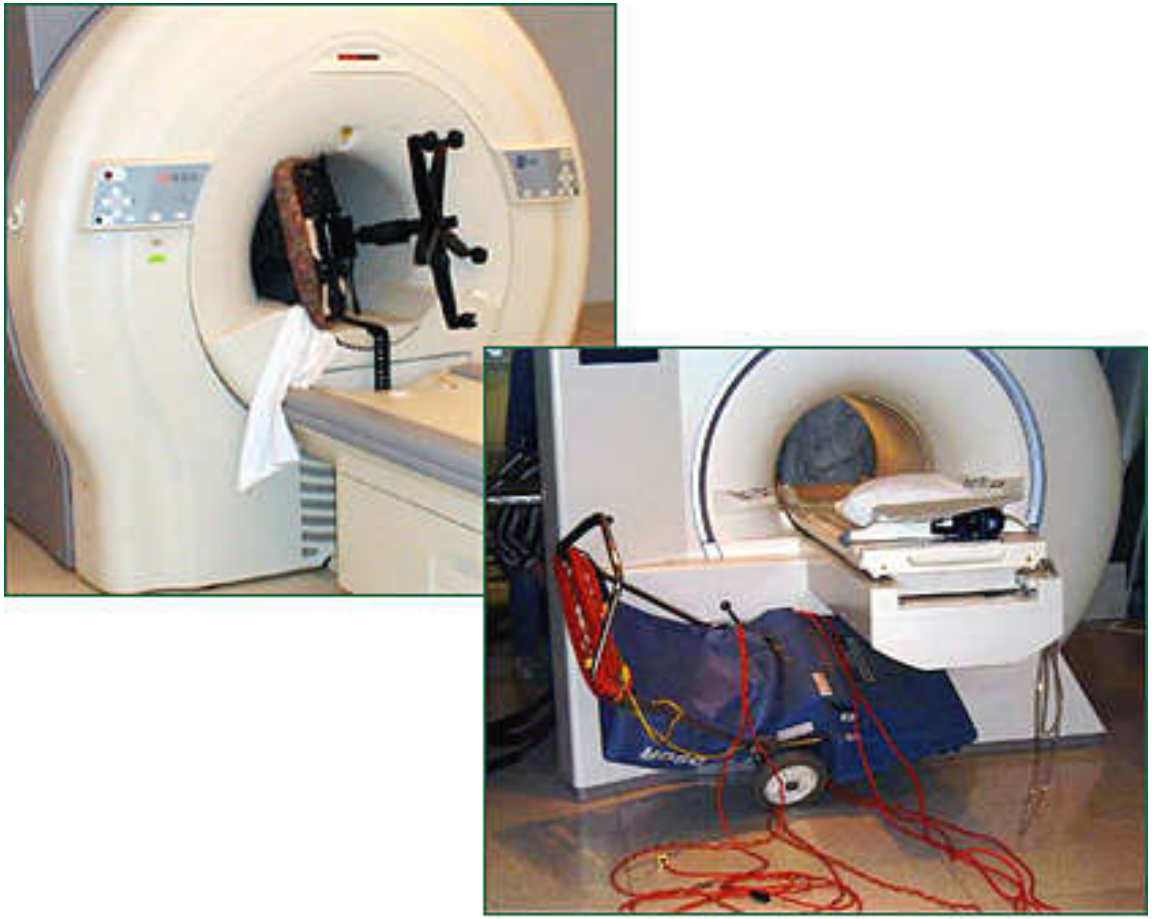
- Protons (质子) and Neutrons (中子) in the nuclei also have spins that generate magnetic moments
- Nuclei with odd numbers of protons and neutrons have a net magnetic moment
- Much smaller (< 10^{-3}) than those of electrons



Magnetic Resonance Imaging (MRI)
核磁共振成像
detect ^{1}H atoms

Be cautious when doing MRI

- **Very strong magnetic field**



Summary

- **Maxwell's Equations**
  - H, B, M, μ_r
  - Magnetic Susceptibility 磁化率 χ
- **Origin of magnetism**
  - spin of electrons, orbital angular momentum, external field
  - nuclear magnetic momentum
- **Types of magnetism**
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Thank you for your attention