2017 Fall--Introduction to Spintronics

自旋电子学导论

韩伟

量子材料科学中心

课程简介

授课对象

物理学院低年级研究生

1）自旋电子学

2）量子材料和半导体材料

为以后科研打下基础

其他专业（信息/材料学院）的研究生

交叉学科：

Spintronics Materials → Physics→ Devices

高年级本科生

将最近科研结果介绍给高年级本科生

开阔视野

课程简介

本课程介绍自旋电子学基础知识以及其最新进展。

1） 介绍自旋电子学的基础知识，包括铁磁、反铁磁性、磁阻等。

2） 着重介绍自旋电子学的最近进展，包括自旋阀、自旋转移力矩、热自旋电子学、拓扑自旋、反铁磁自旋电子学等。

课程简介

上课地点：物理西楼563

上课时间：周五第5-6节（13：00-14：50）

教学方式：

课堂讲授（80%）

学生课堂文献讨论（20%）

学生成绩评定：

平时作业40%，课堂文献讨论20%，期末考试40%

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html

教学大纲

本课程共八章

一、自旋电子学简介

二、磁性和磁性材料

三、磁阻效应

四、自旋阀

五、自旋转移力矩

六、热自旋电子学

七、拓扑自旋流

八、反铁磁自旋电子学

参考书目

主要参考书

- “**Magnetism and Magnetic Materials**”, edited by J. M. D. COEY, Cambridge University Press, UK, 2010
- “**Spin Current**”, edited by Sadamichi Maekawa, Sergio O. Valenzuela, Eiji Saitoh, and Takashi Kimura, Oxford University Press, UK, 2012
- “**Concepts in Spin Electronics**” edited by Sadamichi Maekawa, Oxford University Press, UK, 2006
- “**Electronic Transport in Mesoscopic Systems**”, Supriyo Datta, Cambridge University Press, UK 1997
- “**Semiconductor Spintronics and Quantum Computation**”, D.D. Awschalom, N. Samarath, and D. Loss, Springer, Berlin, 2002
- “**Spintronics: Fundamentals and applications**”, I. Žutić, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004)
- **Wikipedia and Google**

Chapter 1

Overview of Spintronics

韩伟

量子材料科学中心

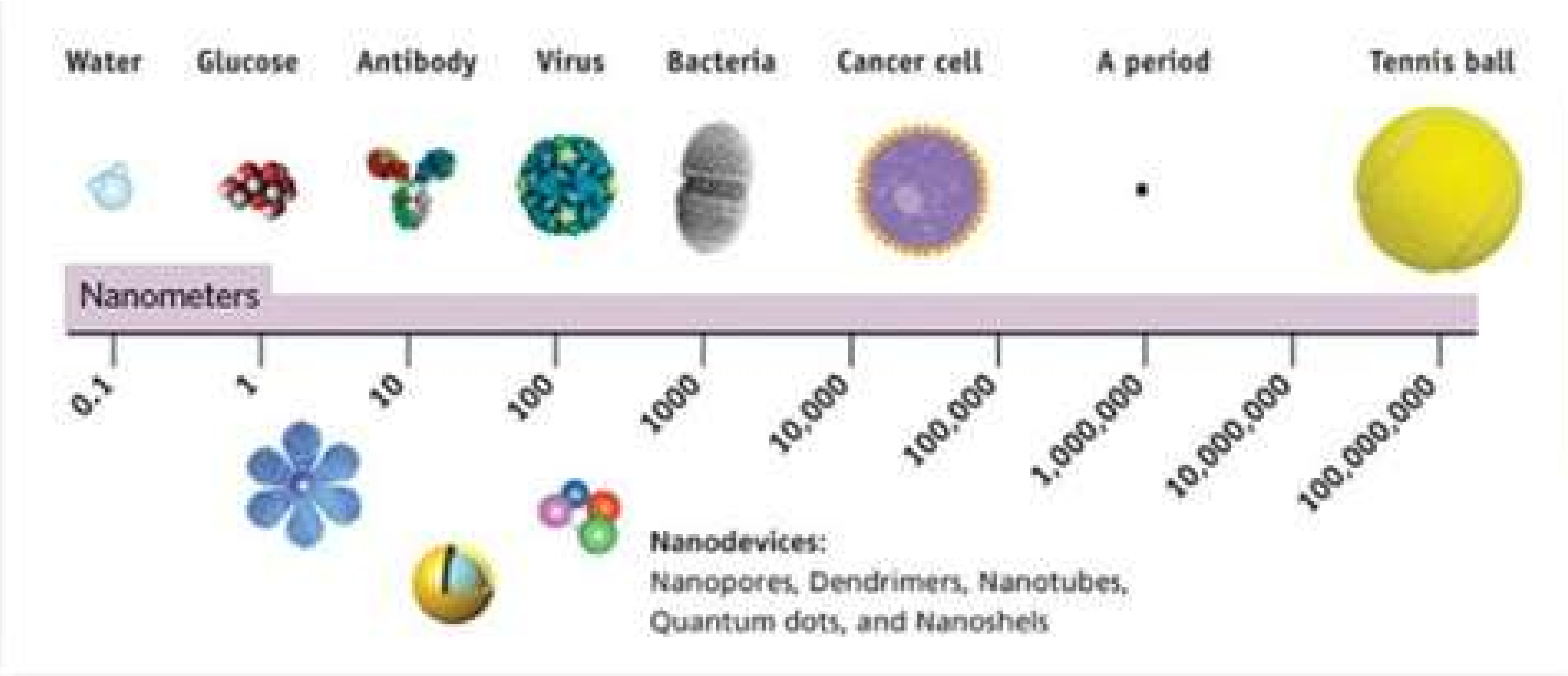
2017年9月15日

Outline

- **What is spintronics?**
- **The recent development of spintronics**

- **What is spintronics?**

Spintronics at different scales



Spin

宏观

“故郑人之取玉也，载司南之车，为其不惑也。”

《鬼谷子·谋篇第十》

司南

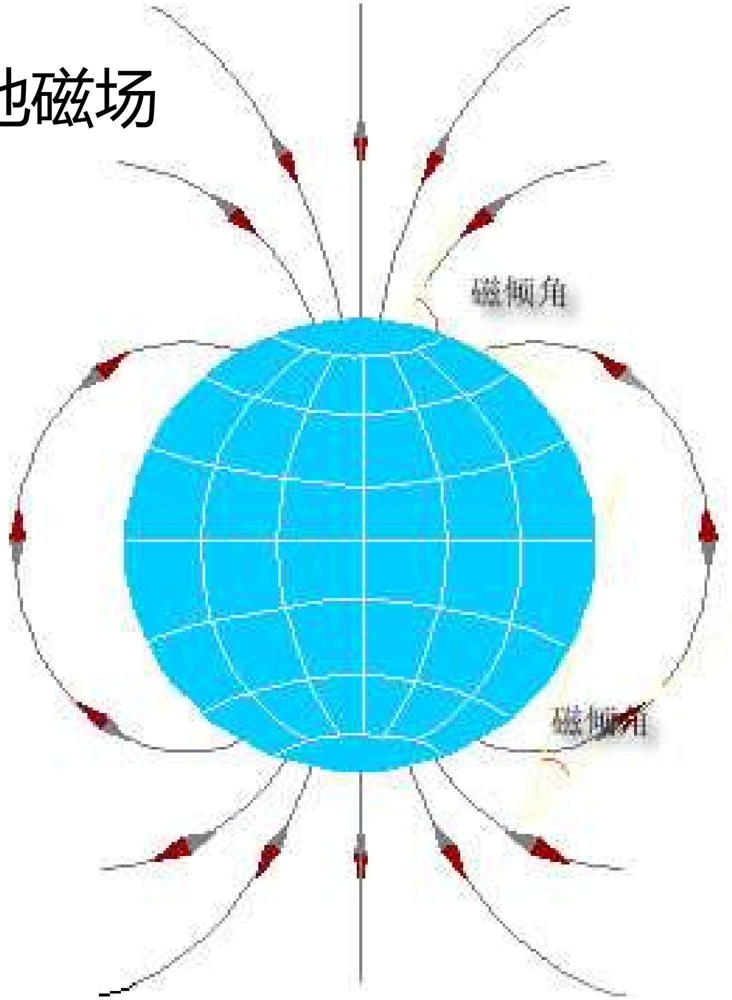
鬼谷子（战国）清人绘

Spin

宏观

司南

地磁场



Spin

宏观

司南

Spin

宏观→微观

司南

Spin

宏观→微观

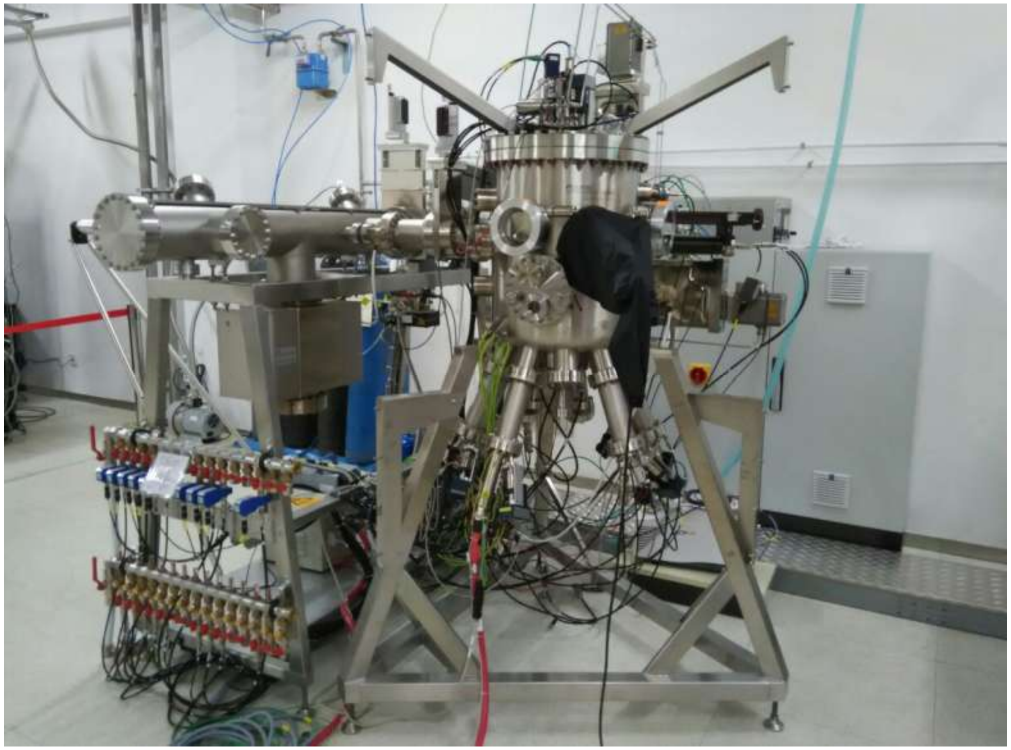
司南

Fe_3O_4

Large crystalline

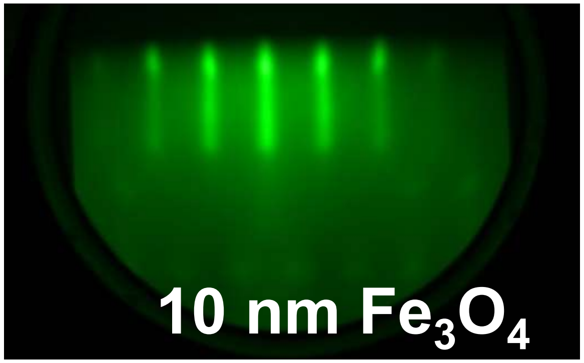
Spin

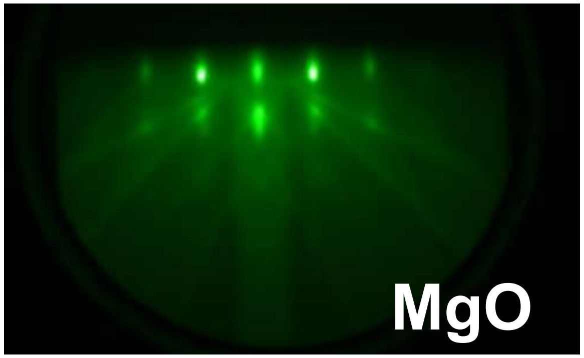
宏观→微观



Molecular Beam Epitaxy

Thin crystalline film

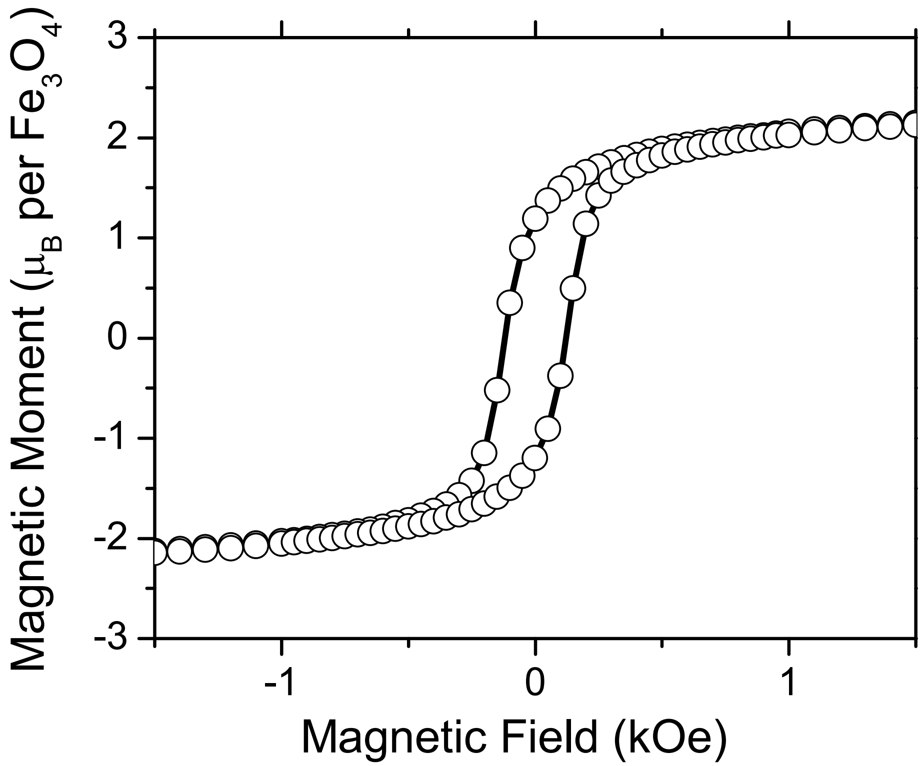




Lab for Spintronics and Emergent Materials

Spin

宏观→微观



Quantum Design—SQUID

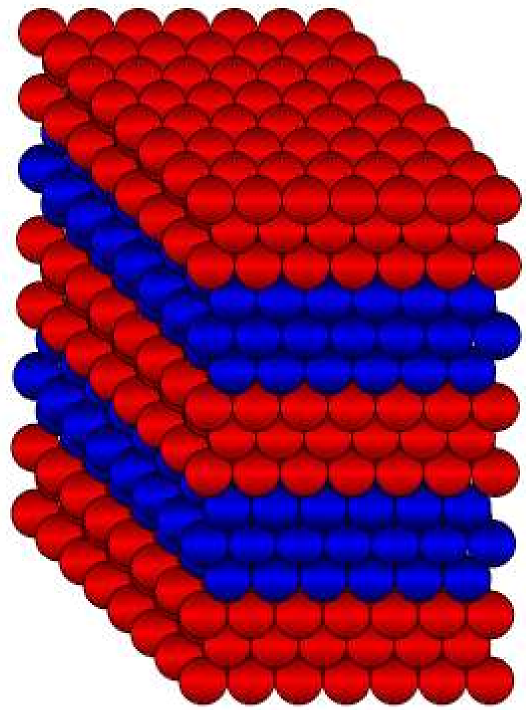
Lab for Spintronics and Emergent Materials

Spin

宏观→微观

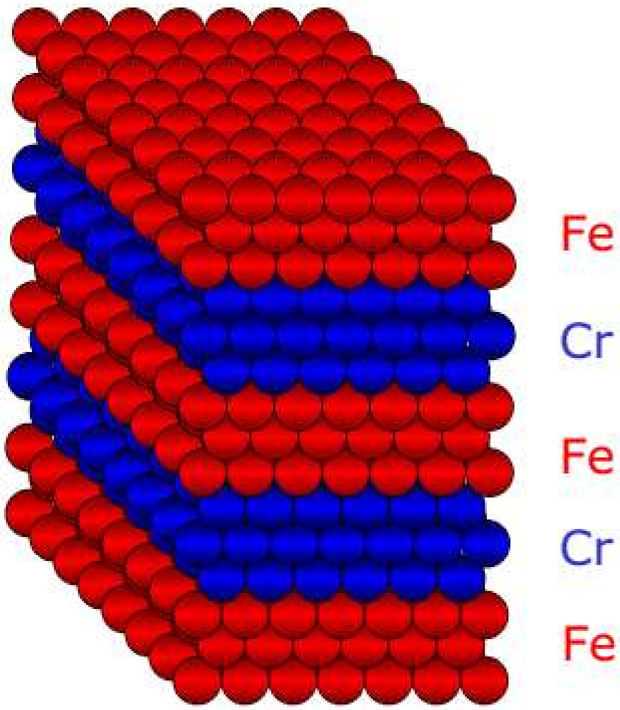
Magnetic field sensor

磁性纳米结构

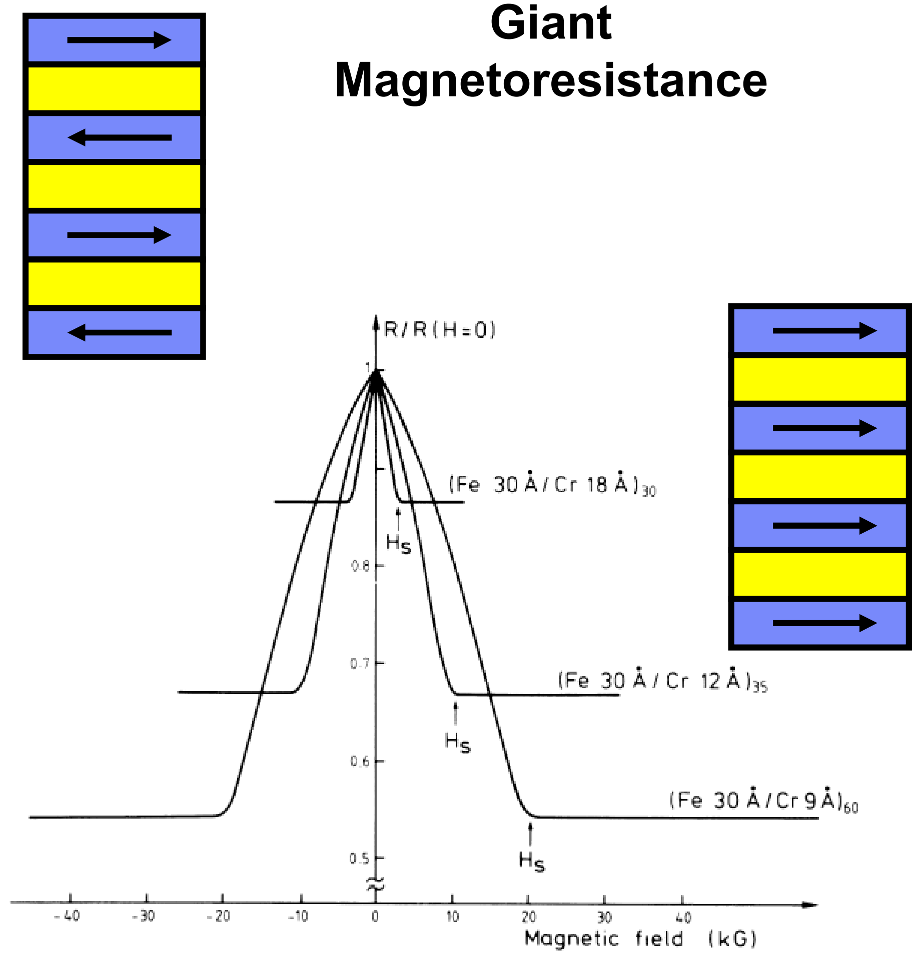


Spin

宏观→微观



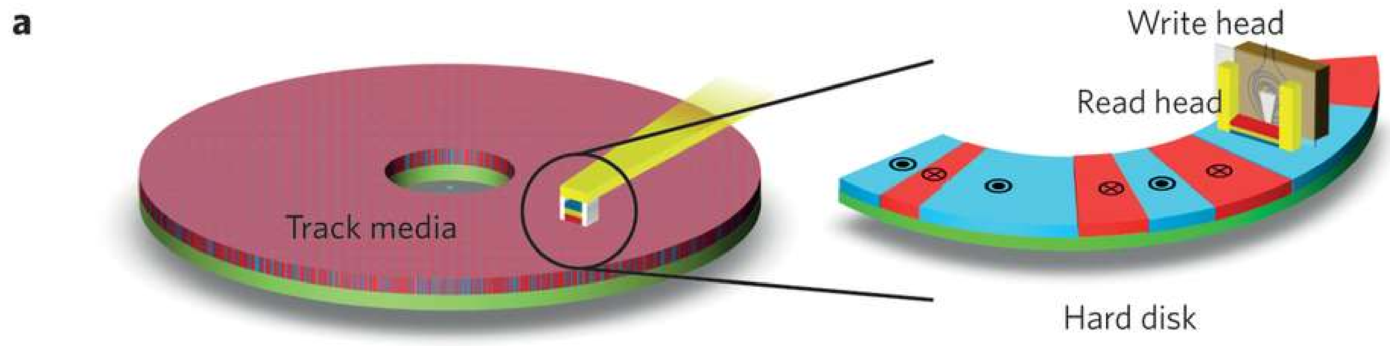
Giant Magnetoresistance



Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

Spin

宏观→微观



Read Head

Yang & Parkin, Nature Nanotech (2014)

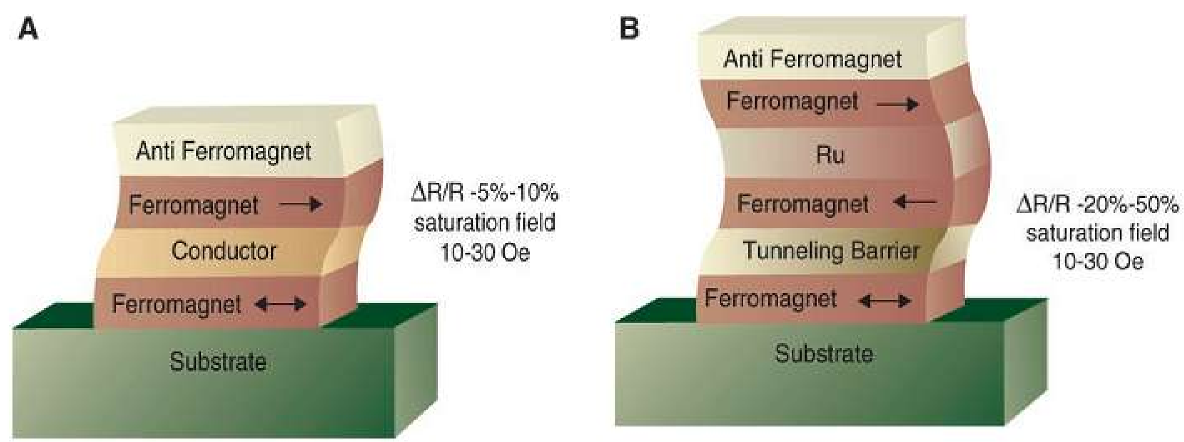
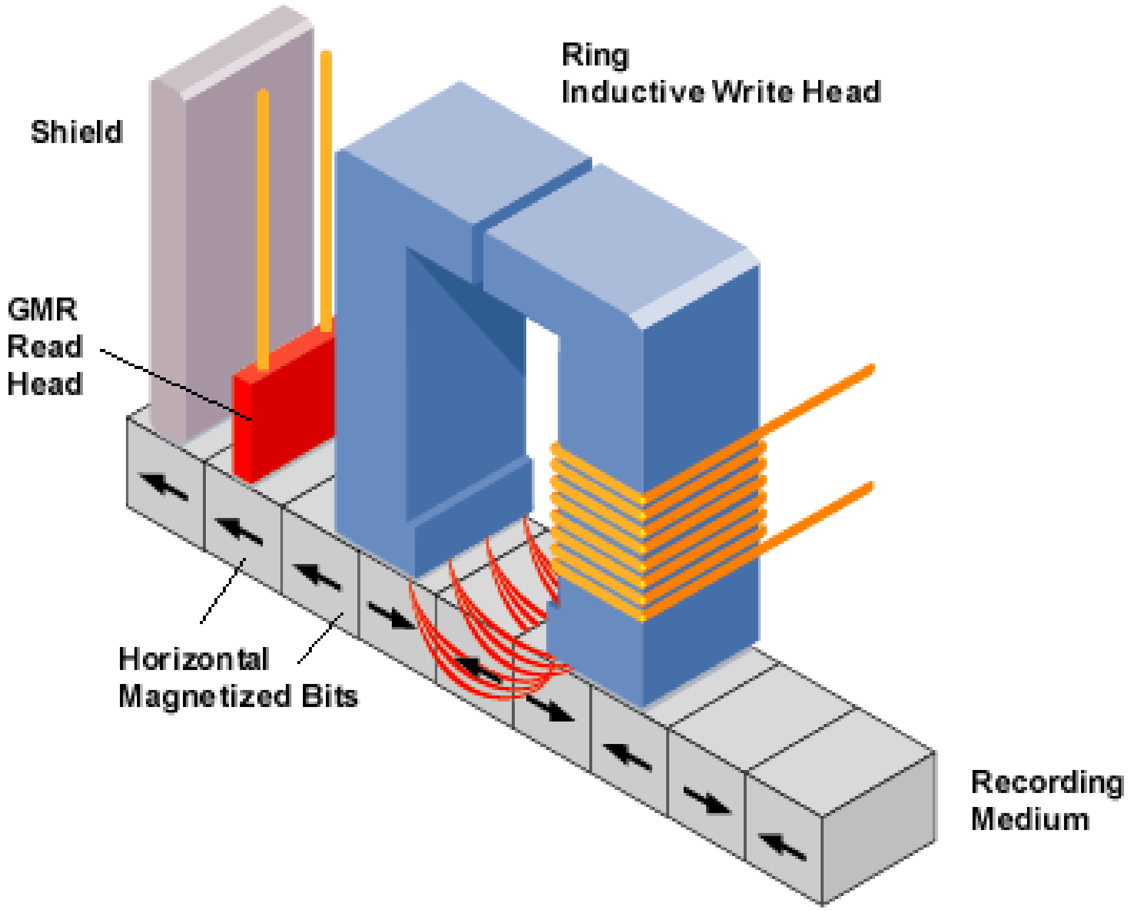


Fig. 1. Spin-dependent transport structures. (**A**) Spin valve. (**B**) Magnetic tunnel junction.

Wolf, et al, Science (2001)

Spin

宏观→微观

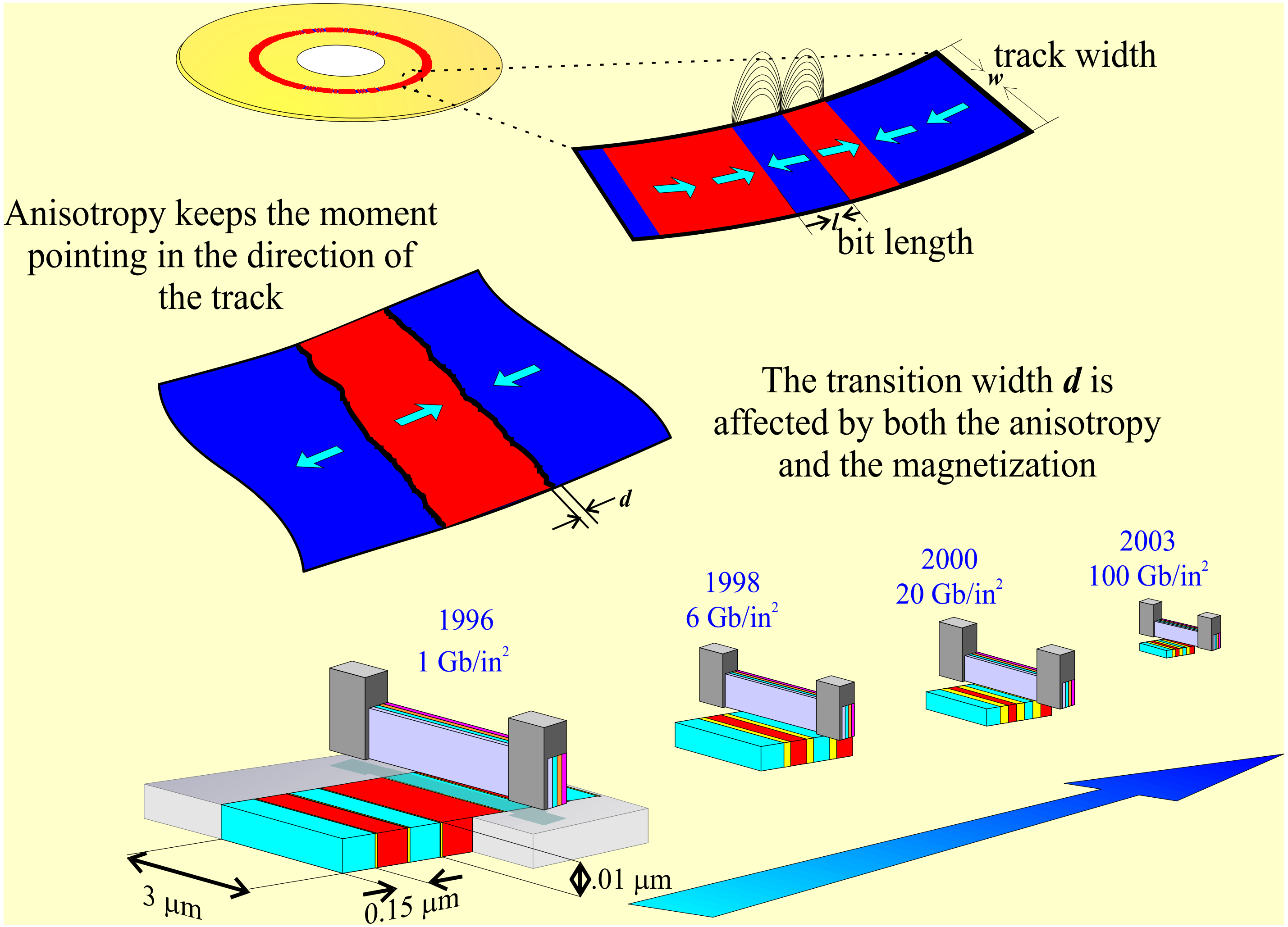


Shield
Ring
Inductive Write Head
GMR
Read
Head
Horizontal
Magnetized Bits
Recording
Medium

Spin

宏观→微观

Stuart Parkin(IBM)



Spin

Peter Gruenberg Albert Fert

The Nobel Prize in Physics 2007 was awarded ***"for the discovery of Giant Magnetoresistance"***

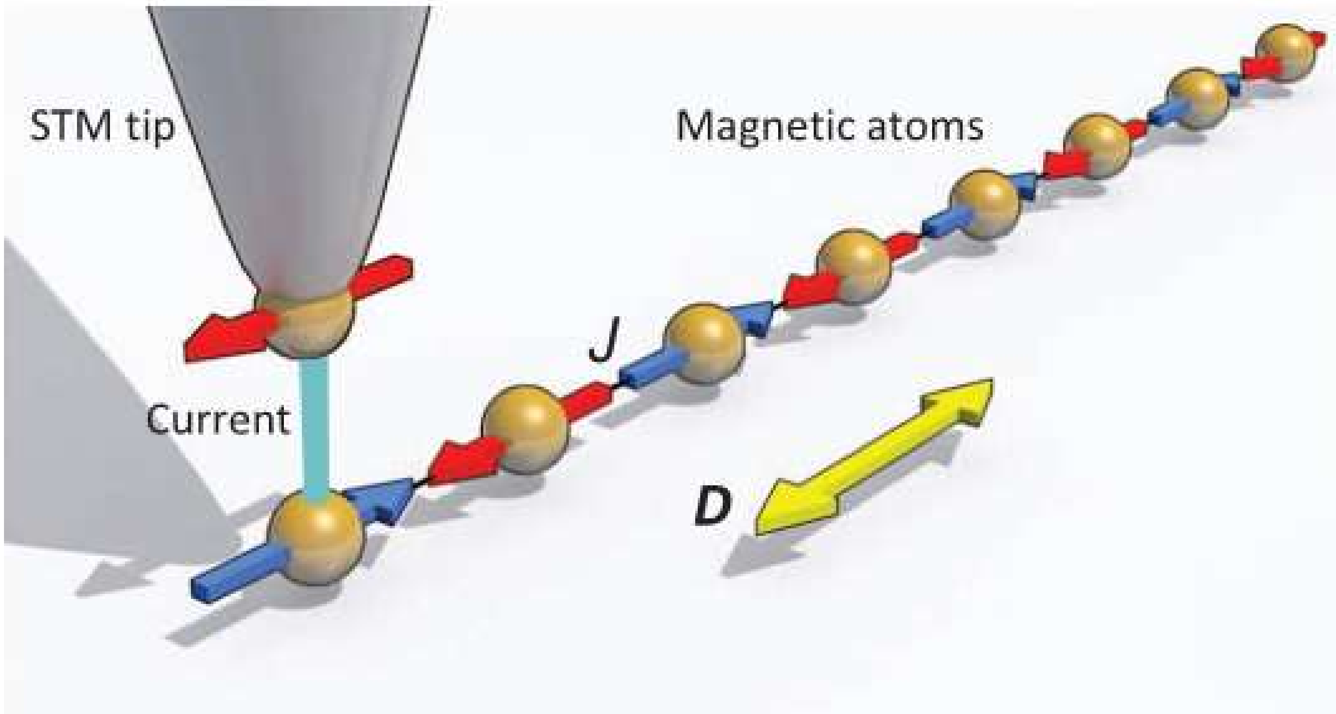
Spin

Computer
~2002

Apple IPAD
~2014

Spin

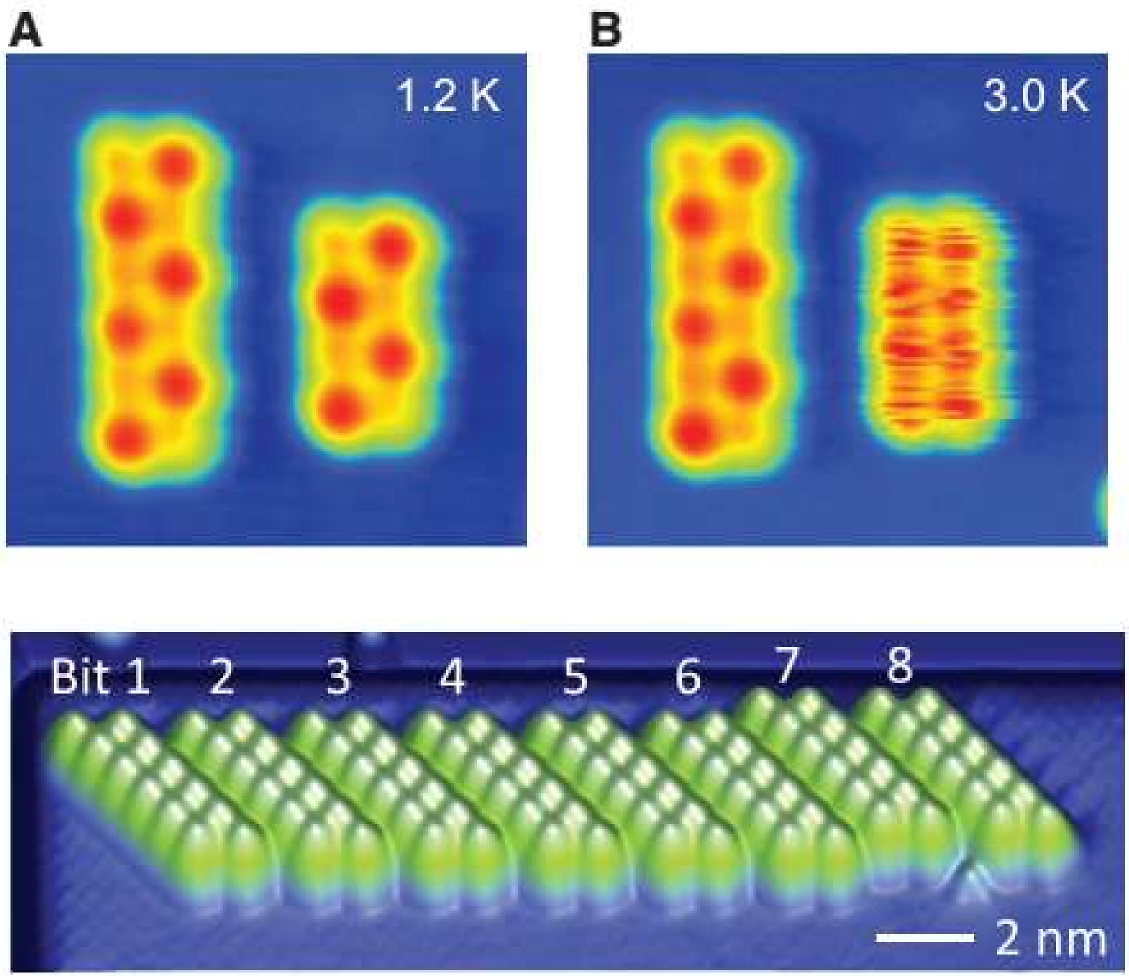
Spin polarized tunneling microscopy



Loth, et al. Science (2012)

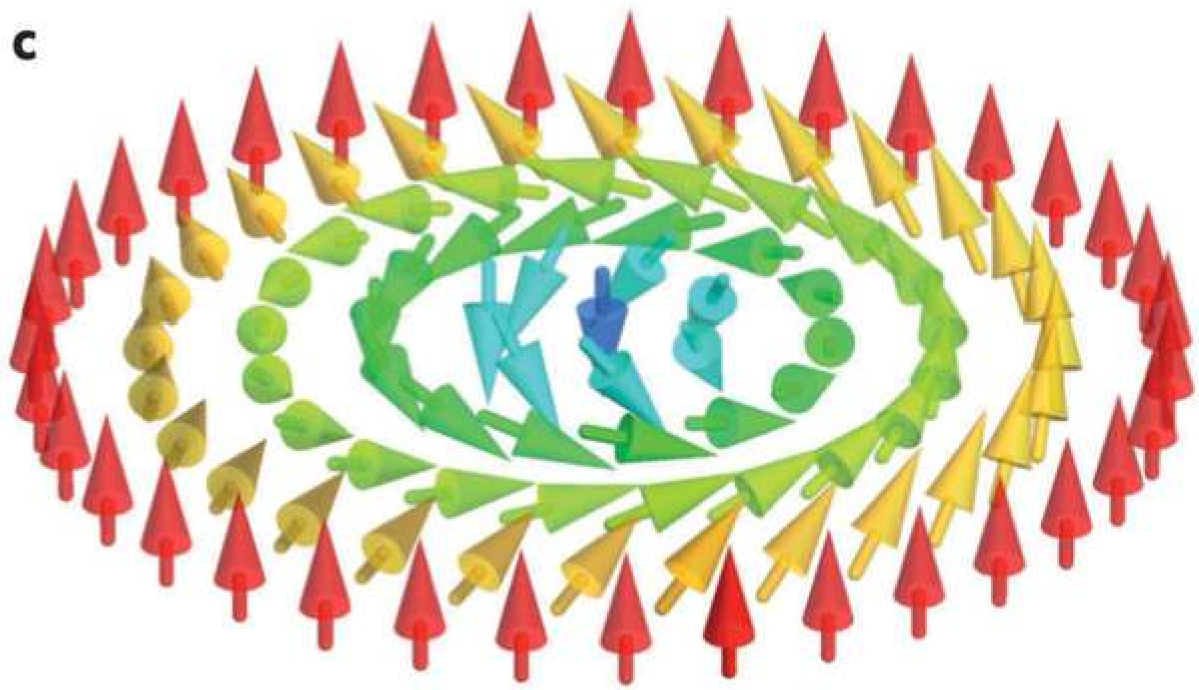
Spin

Spin polarized tunneling microscopy



Spin

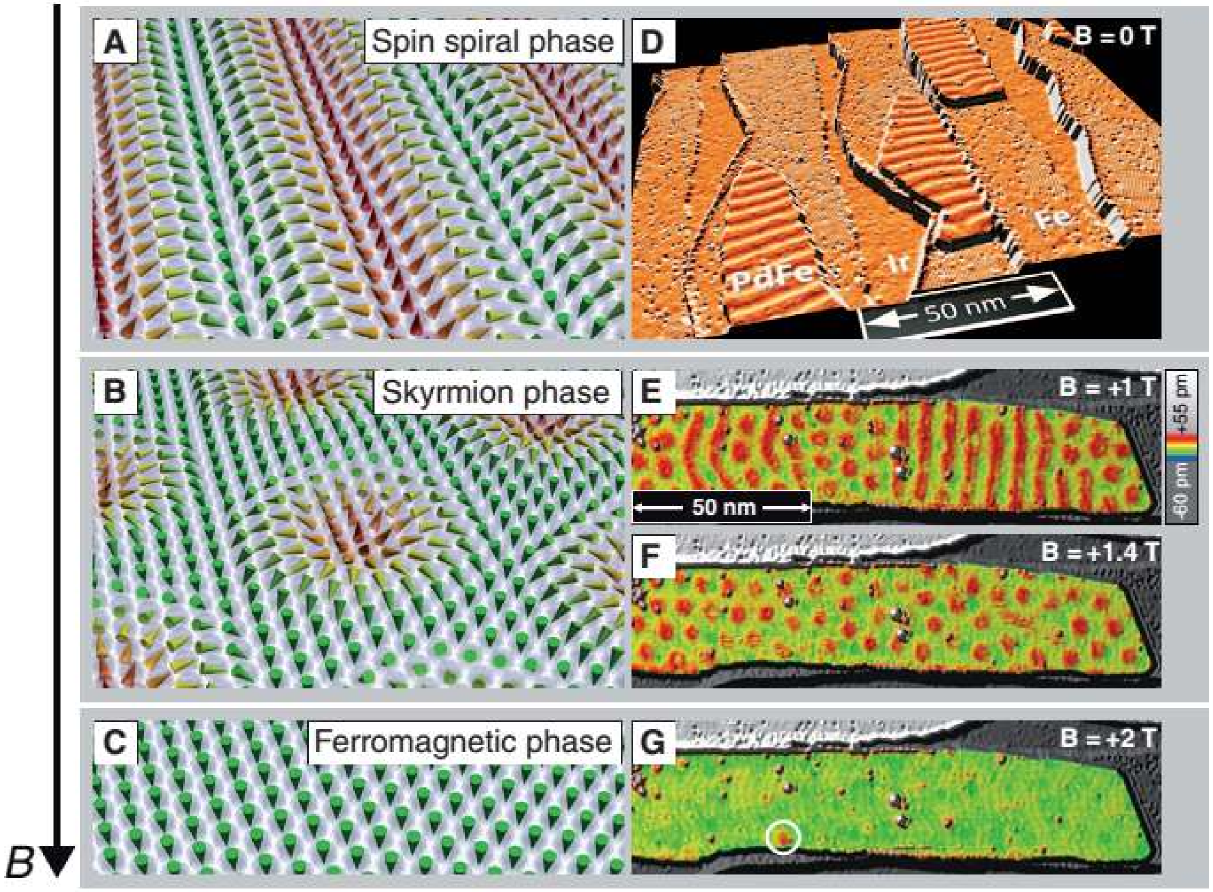
Skyrmion



Pfleiderer, Nat. Phys. (2011)

Spin

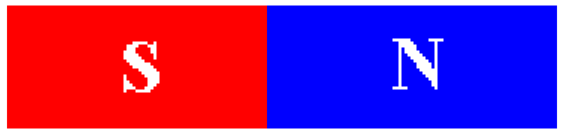
Skyrmion



Romming, et al. Science (2013)

Spin

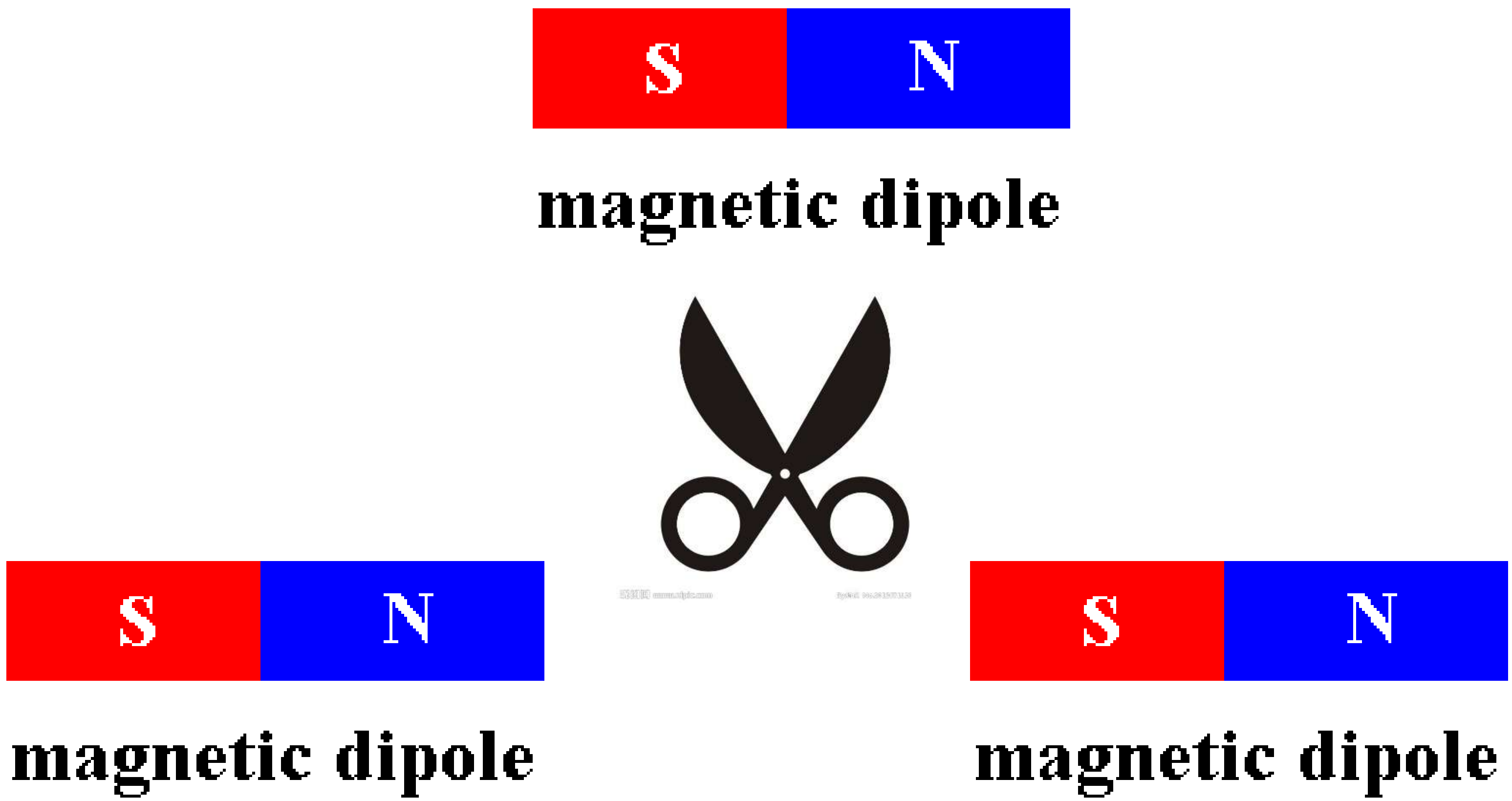
Magnetic monopole



magnetic dipole

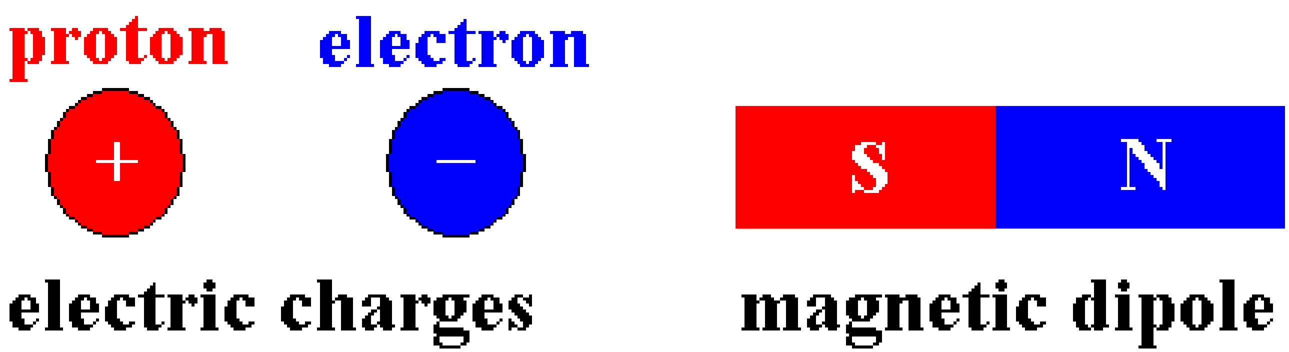
Spin

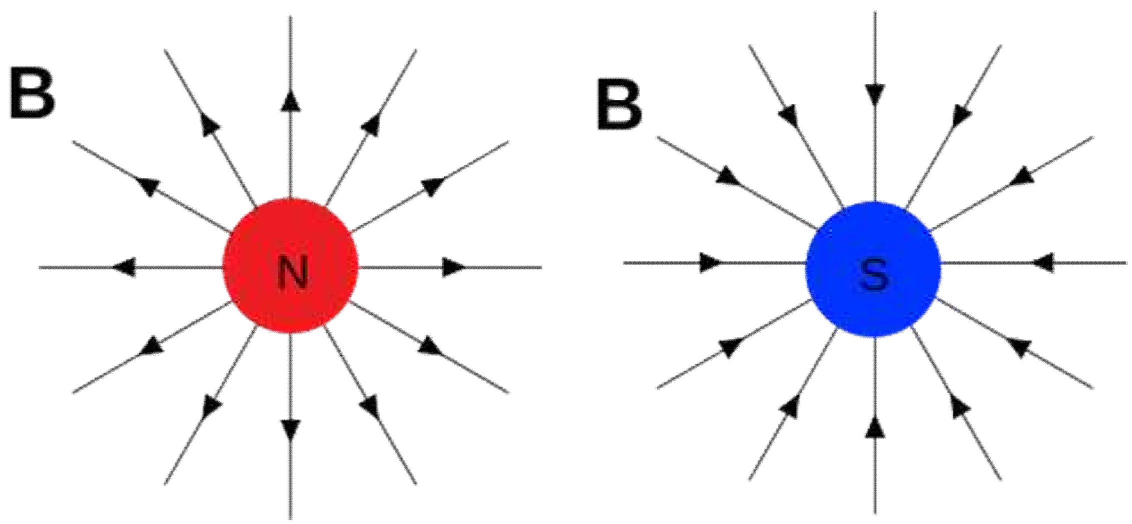
Magnetic monopole



Spin

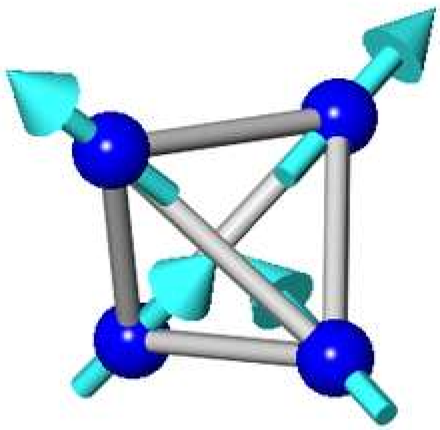
Magnetic monopole

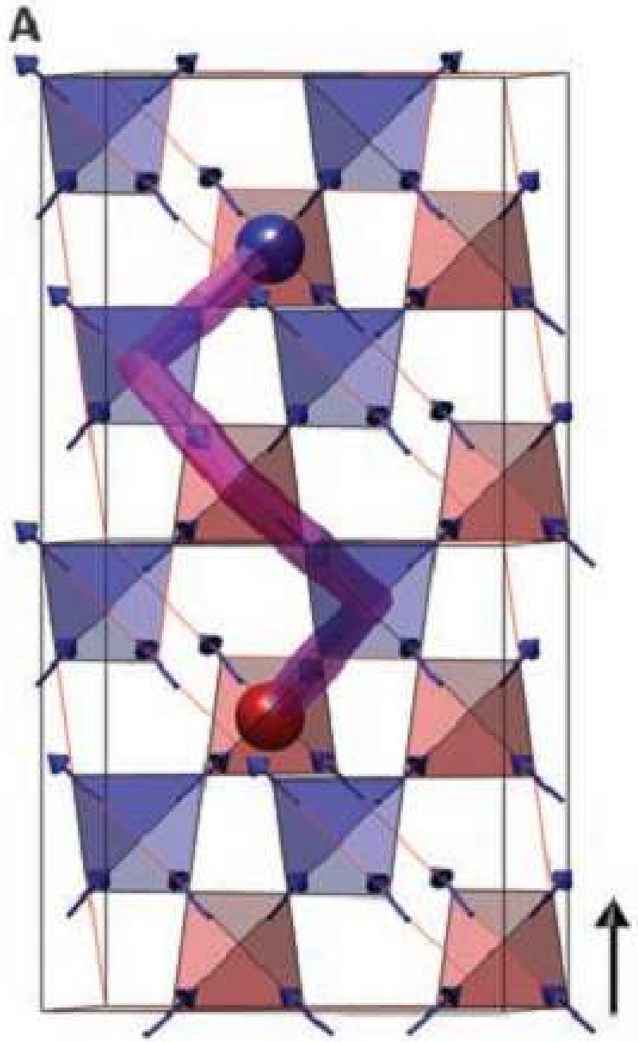




Spin

Spin Ice



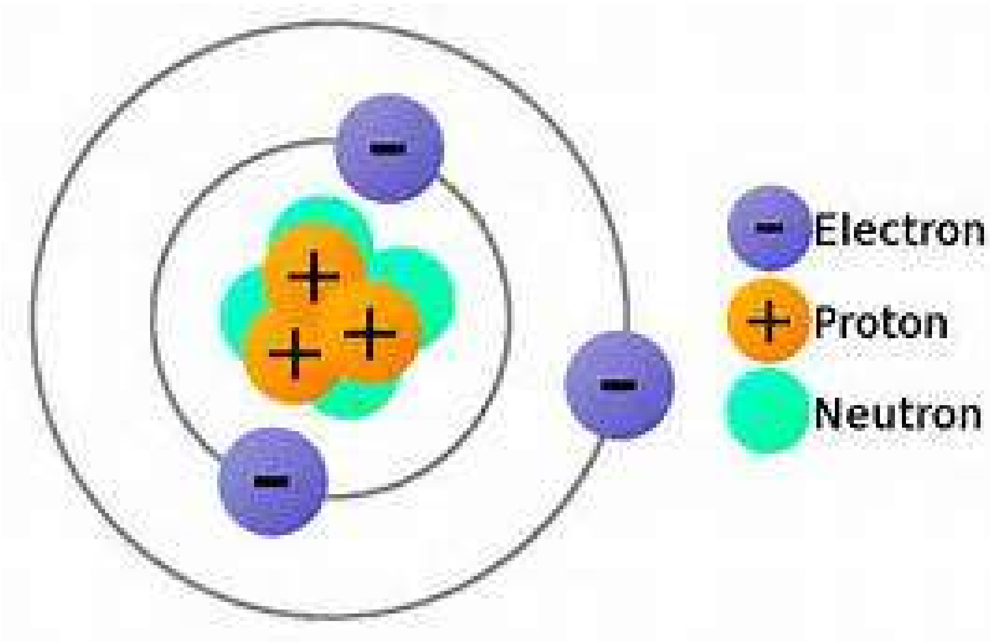


$Dy_2Ti_2O_7$

Morris, et al. Science (2009)

Spin

Atomic level



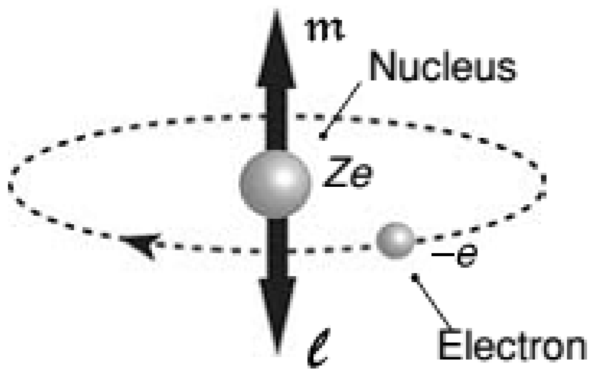
Intrinsic angular momentum

$$\frac{1}{2}\hbar$$

Coey, Book magnetism (2009)

Spin

Atomic—orbit moment



The Bohr atom. The electron moves in a circular orbit where its quantized angular momentum ℓ and magnetic moment m are oppositely directed.

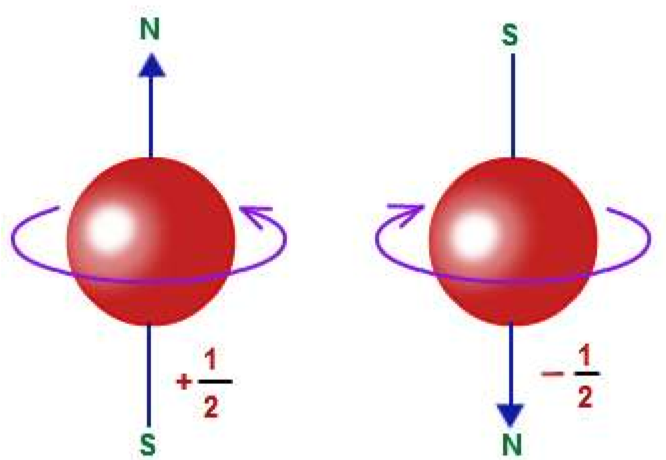
$$m_z = -\frac{e}{2m_e} m_l \hbar$$

$$m_l = 0, \pm 1, \pm 2, \ldots$$

Coey, Book magnetism (2009)

Spin

Atomic—Spin moment



$$m_z = -\frac{e}{m_e} m_s \hbar$$

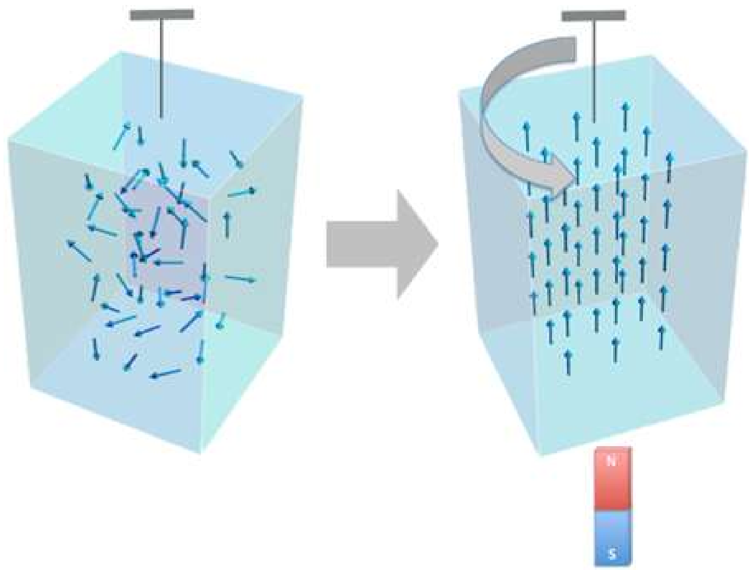
$$m_s = \pm\frac{1}{2}$$

$$\mu_B = \frac{e\hbar}{2m_e} = 9.274\times10^{-24}\,Am^2$$

Coey, Book magnetism (2009)

Spin

Atomic—Spin moment



Einstein–de Haas effect

Angular momentum

Magnetic moment $$m_z = -\frac{e}{m_e} m_s \hbar$$

[A. Einstein, W. J. de Haas,]

- *Experimental Proof of Ampère's Molecular Currents,* Deutsche Physikalische Gesellschaft, Verhandlungen 17 (1915): 152-170.
- *Experimental Proof of the Existence of Ampère's Molecular Currents* (in English), Koninklijke Akademie van Wetenschappen te Amsterdam, Proceedings 18 (1915-16).

Spin

从宏观（指南针）到微观（原子内部的电子自旋：Bohr Magneton）

自旋—量子数

自旋—利用自旋并操控自旋

自旋—物理机制

休息10分钟

Spin

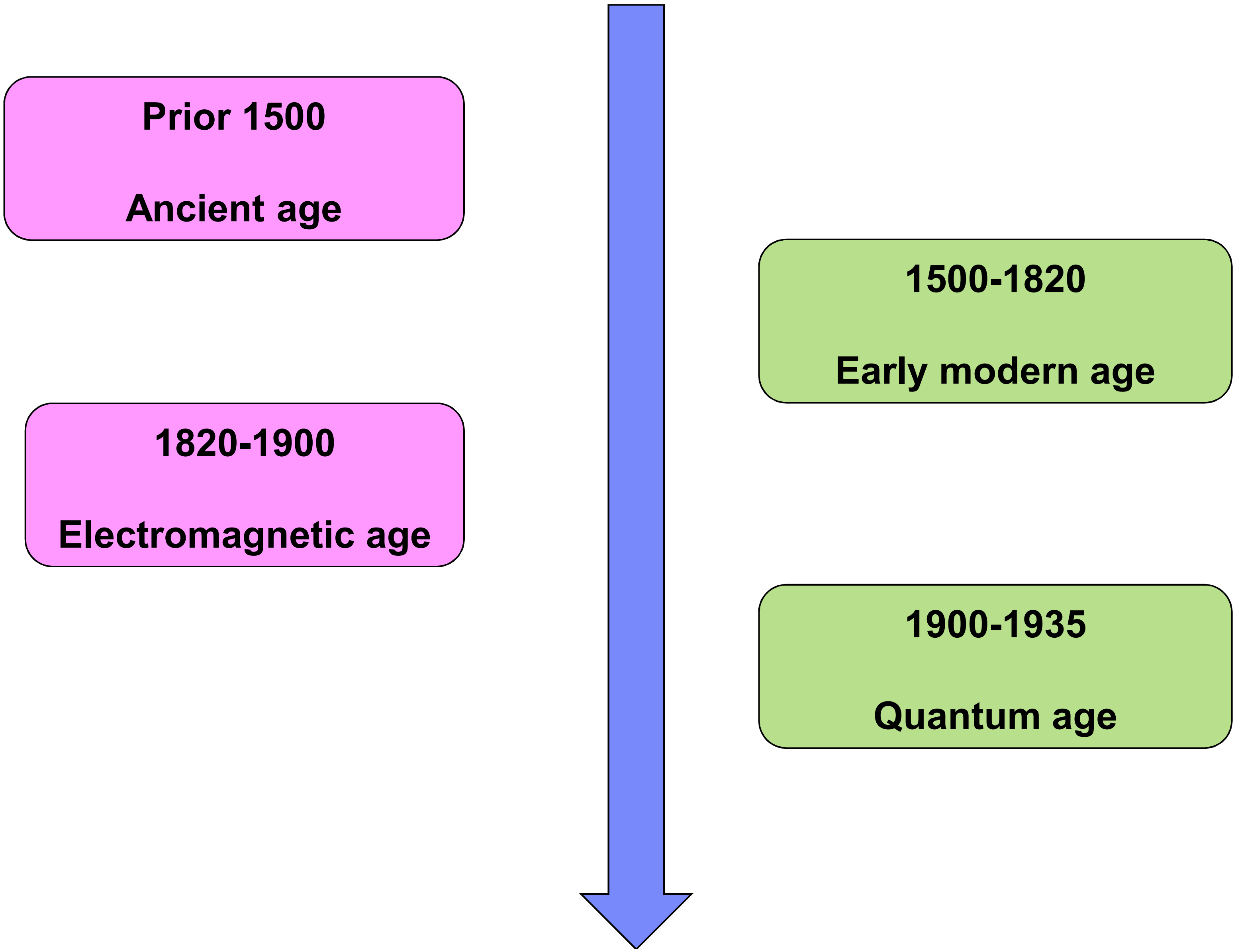
从宏观（指南针）到微观（原子内部的电子自旋：Bohr Magneton）

自旋—量子数

自旋—利用自旋并操控自旋

自旋—物理机制

Spin History



Spin History

1935 - Now

Age of magnetic applications

1995 - now

Age of Spin current and Nano Spin

Spin History

Prior 1500

Ancient age

Spin History

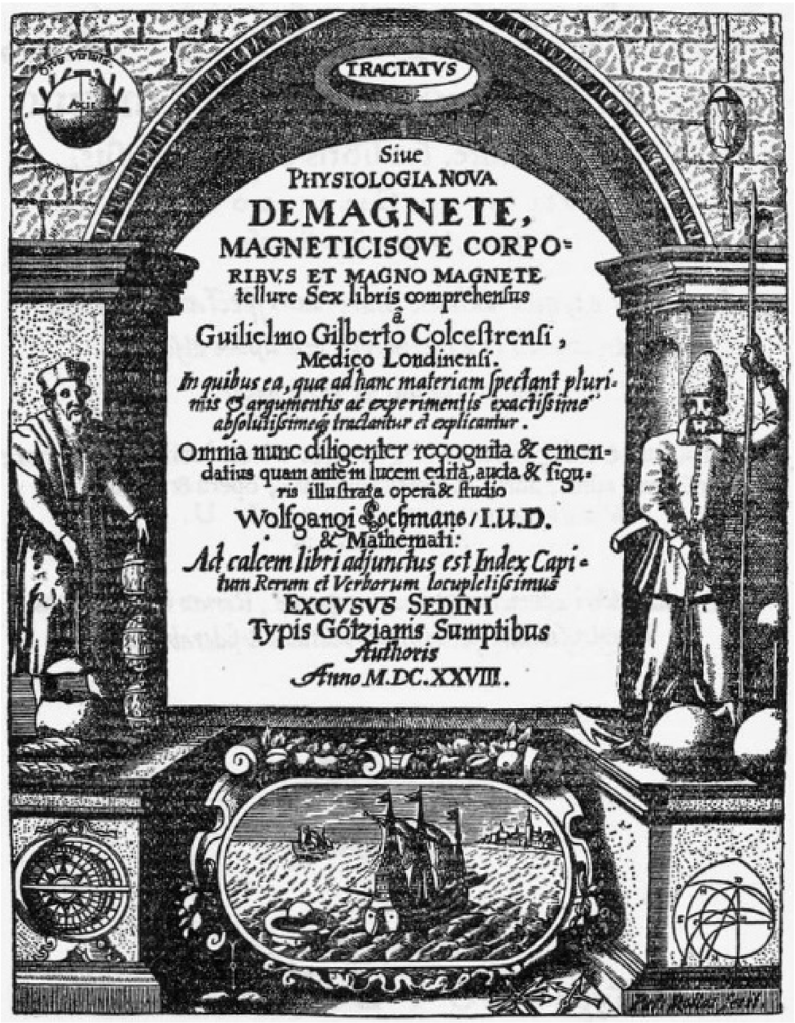
Prior 1500

Ancient age

史载，公元前227年，燕太子丹派刺客荆轲刺杀秦王，图穷匕现。为保安全，秦王愤怒之余采取措施，在前殿垒磁石为门，称**磁石门**，亦曰“却胡门”，以防行刺者再次入宫

《长安志》：“东西有阁道，垒磁石为之，著铁甲入者，磁石吸之，不得过。”

Spin History



TRACTATVS
Siue
PHYSIOLOGIA NOVA
DE MAGNETE,
MAGNETICISQVE CORPO-
RIBVS ET MAGNO MAGNETE
tellure Sex libris comprehensus
à
Guilielmo Gilberto Colcestrensi,
Medico Londinensi.
*In quibus ea, quæ ad hanc materiam spectant pluri-
mis & argumentis ac experimentis exactissime
absolutissimeq; tractantur et explicantur.*
Omnia nunc diligenter recognita & emen-
datius quam antè in lucem edita, aucta & figu-
ris illustrata operâ & studio
Wolfgangi Lochmans, I.U.D.
& Mathemati:
*Ad calcem libri adjunctus est Index Capi-
tum Rerum et Verborum locupletissimus*
EXCVSVS SEDINI
Typis Götzianis Sumptibus
Authoris
Anno M.DC.XXVIII.

1500-1820

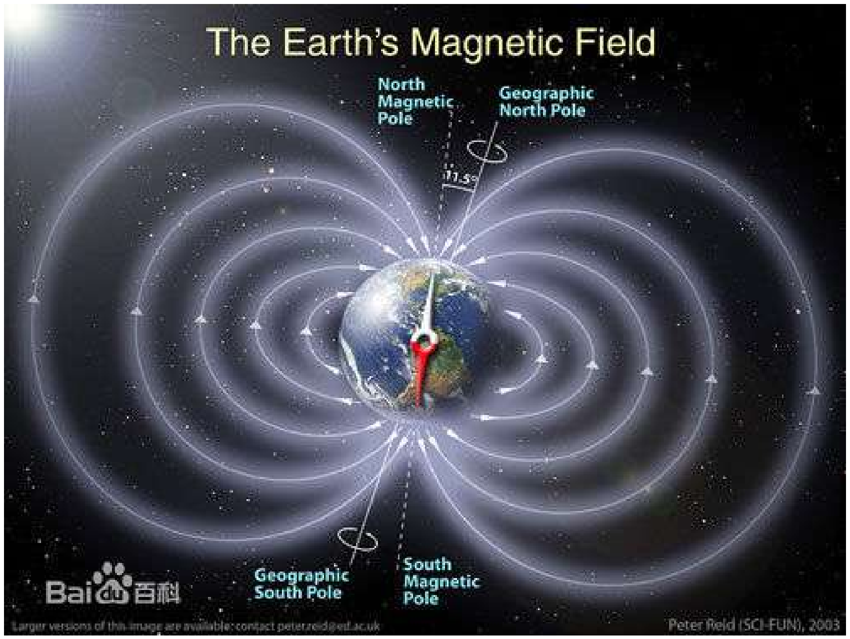
Early modern age

William Gilbert

(1544-1603)

Spin History

The earth's own magnetism



1500-1820

Early modern age

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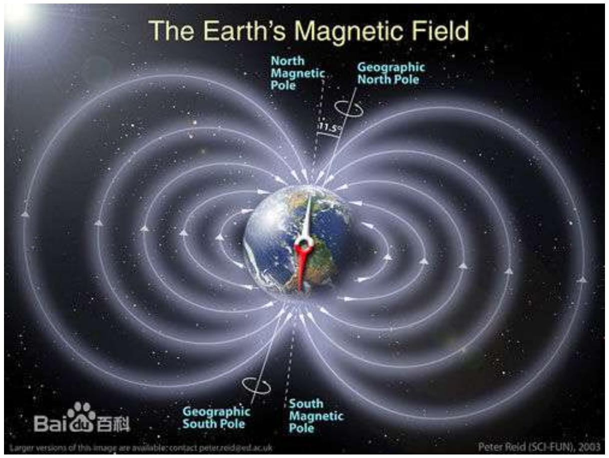
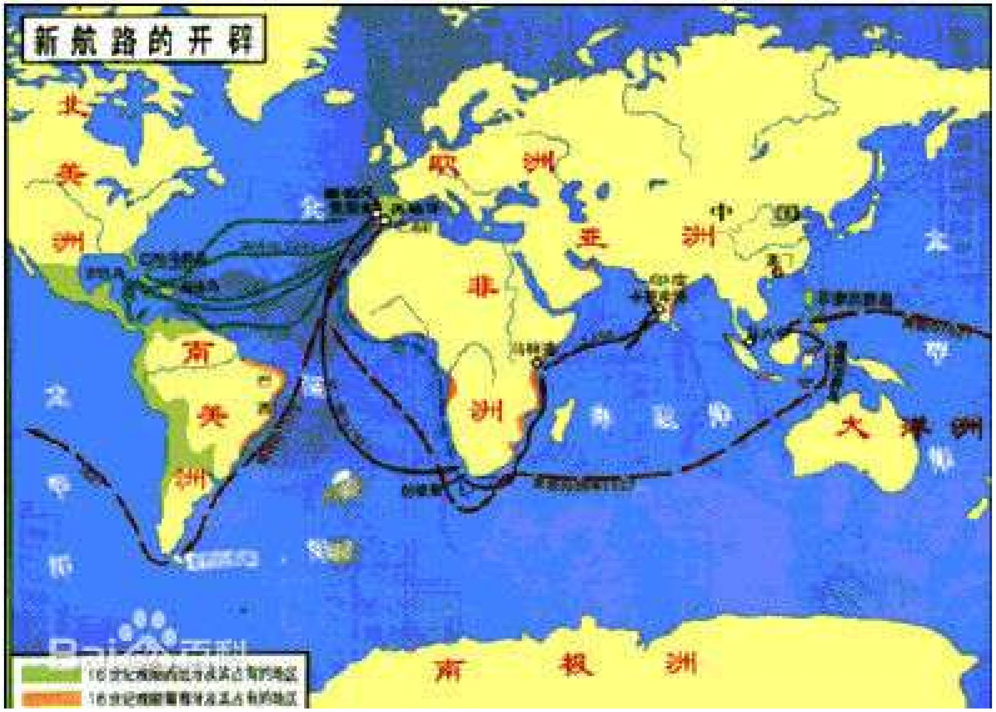
Spin History

The earth's own magnetism

1500-1820

Early modern age





Spin History

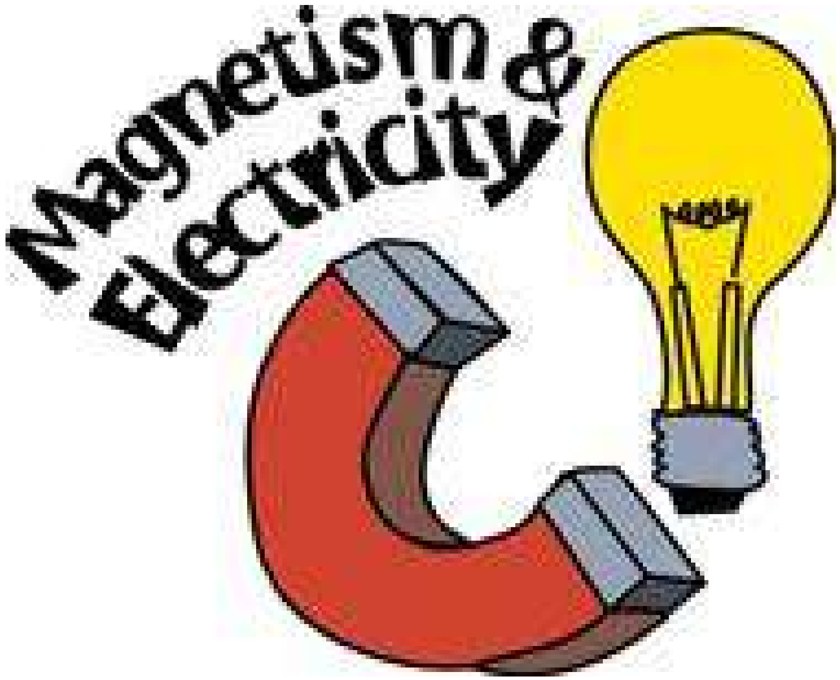
1500-1820

Early modern age

Spin History

1820-1900

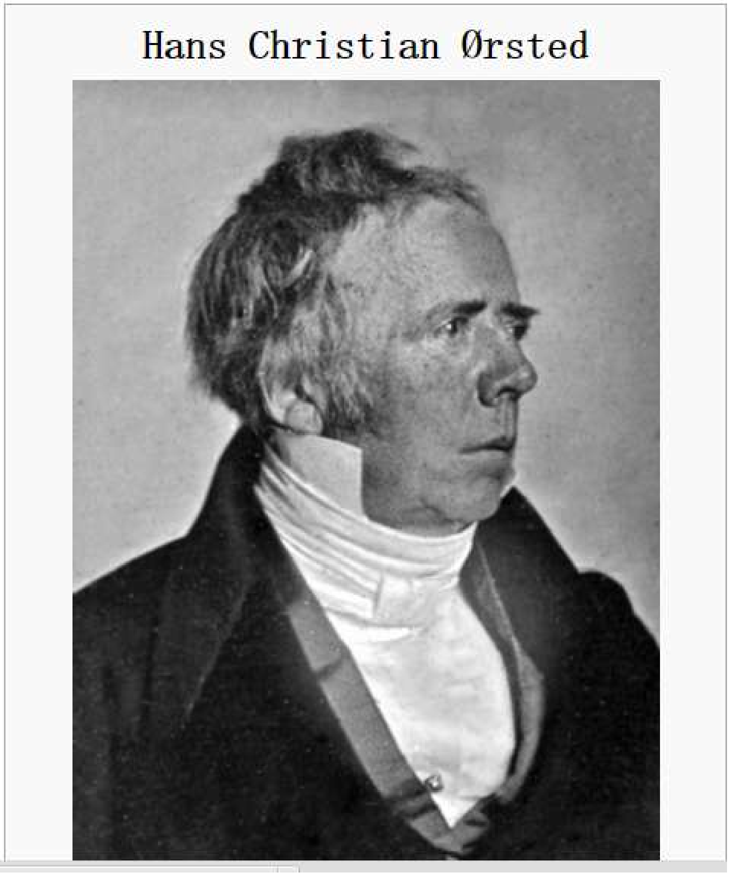
Electromagnetic age



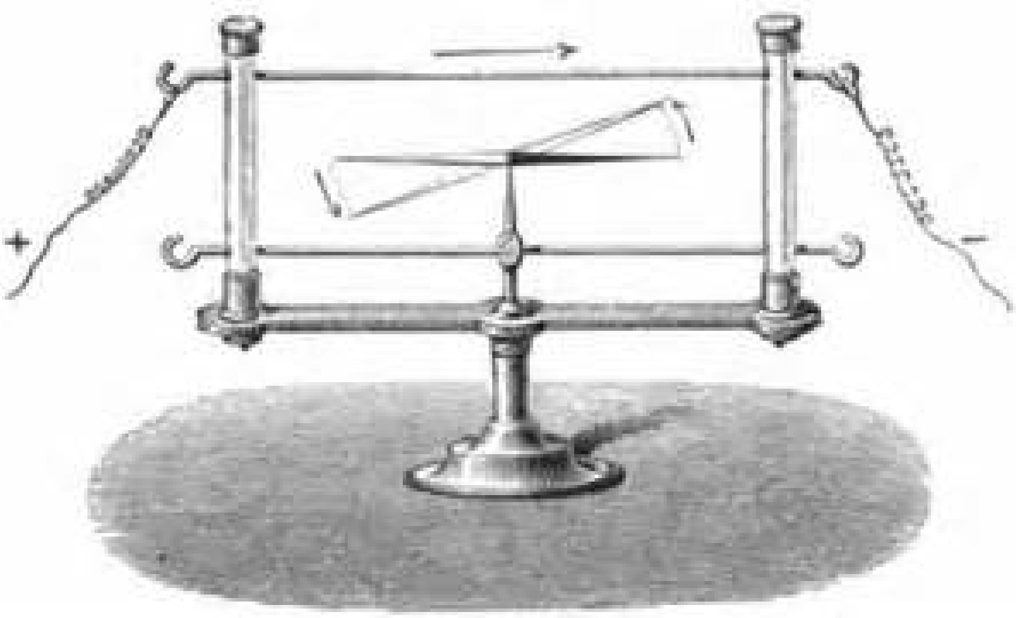
Spin History

1820-1900

Electromagnetic age



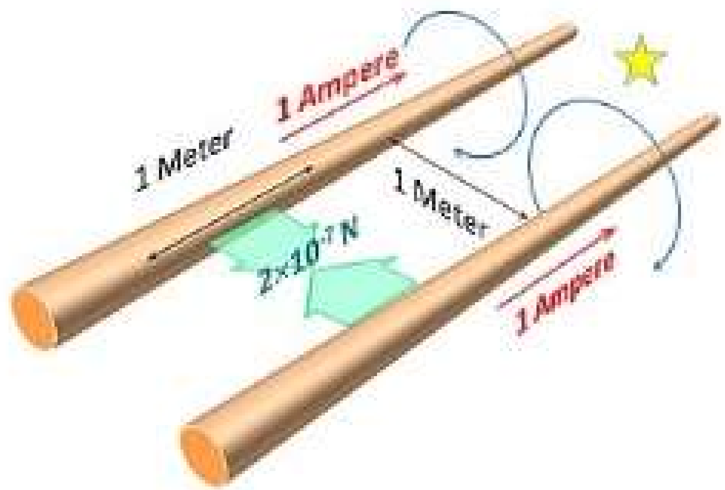
$$B = \frac{\mu_0 I}{2\pi r_0}$$



Spin History

1820-1900

Electromagnetic age



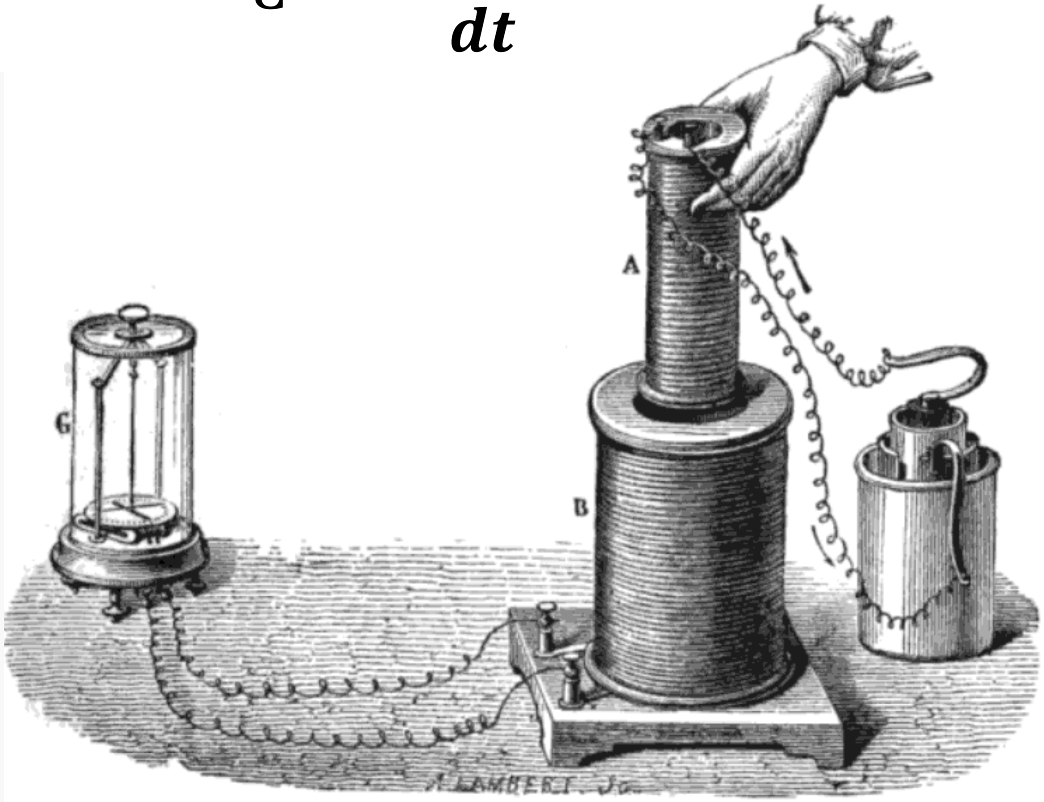
Spin History

1820-1900

Electromagnetic age

Michael Faraday

$$\mathcal{E} = -\frac{d\Phi}{dt}$$



Spin History

1820-1900

Electromagnetic age

James Clerk Maxwell

James Clerk Maxwell (1831 - 1879)

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

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

3. $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$

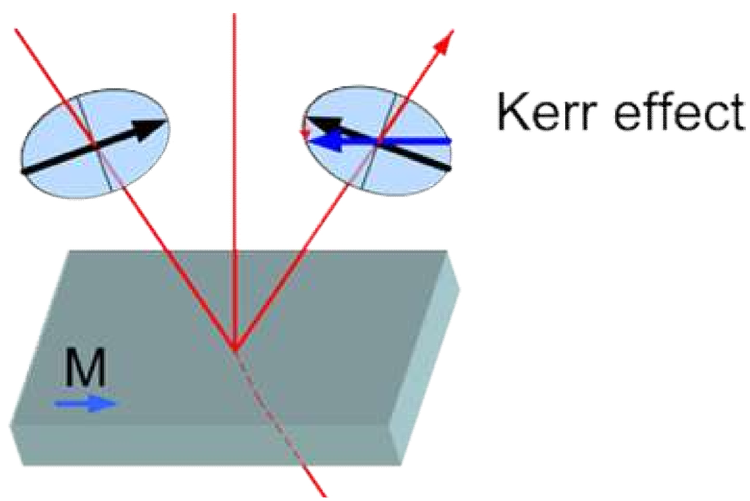
4. $\nabla \times \mathbf{H} = \dfrac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

Spin History

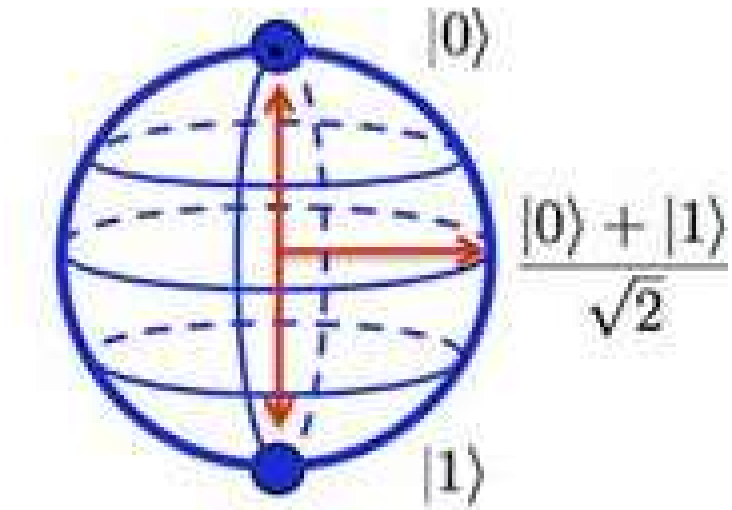
1820-1900

Electromagnetic age

1) A change in refractive index is proportional to the square of the **electric field**.
2) A change in refractive index is proportional to the square of the **magnetic field**. → Magneto optical Kerr effect (MOKE)



Spin History



1900-1935

Quantum age

Spin is Quantum!

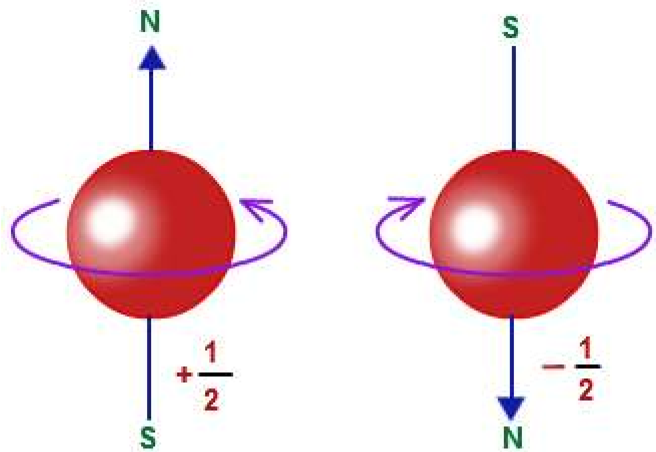
Spin History

Samuel Goudsmit

George Uhlenbeck

1900-1935

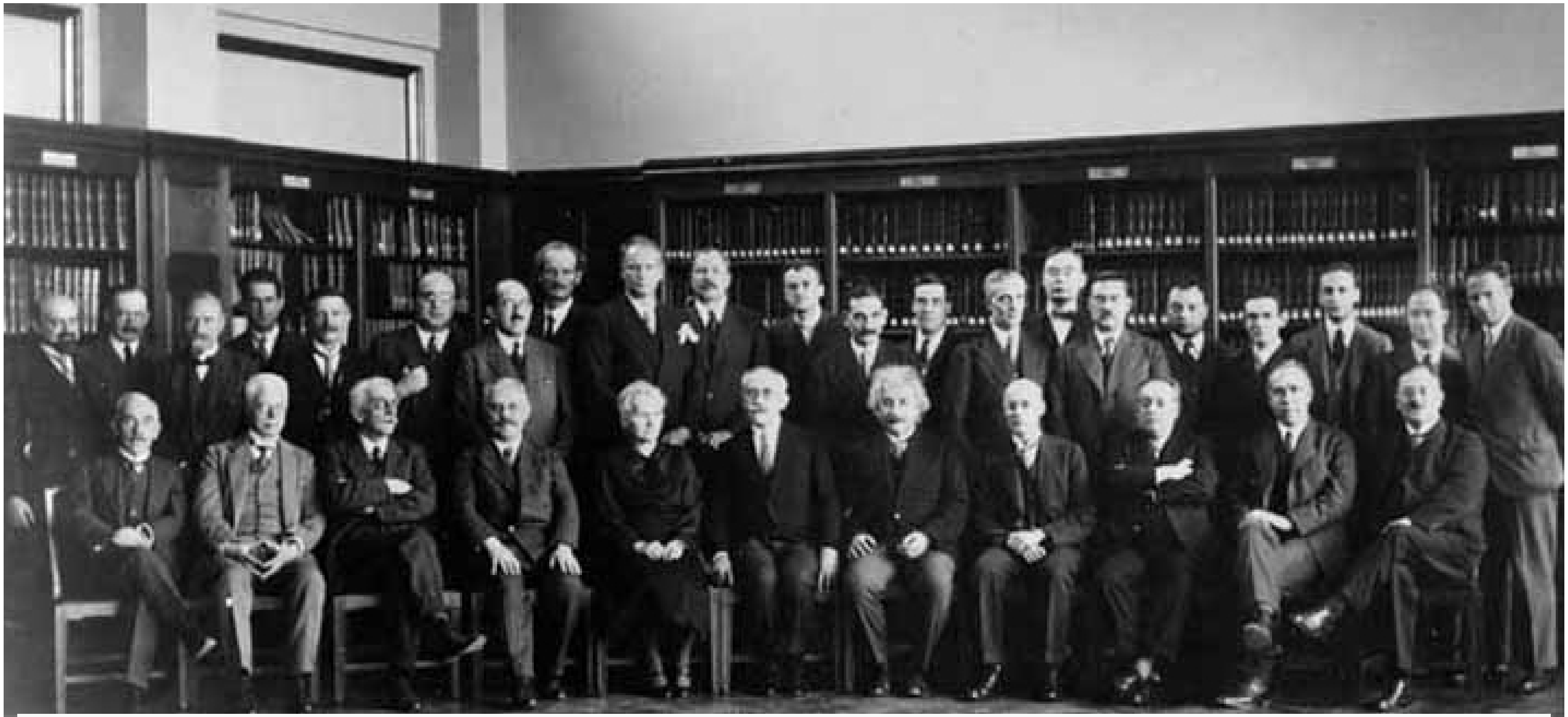
Quantum age



The spin is quantized in such a way that it can have just two possible orientations in a magnetic field, 'up' and 'down'.

Spin History

1930 Solvay Conferences on Physics Le magnétisme



Second row (standing):
E. Herzen, É. Henriot, J. Verschaffelt, C. Manneback, A. Cotton, J. Errera, O. Stern, A. Piccard, W. Gerlach, C. Darwin, P.A.M. Dirac, E. Bauer, P. Kapitsa, L. Brillouin, H. A. Kramers, P. Debye, W. Pauli, J. Dorfman, J. H. Van Vleck, E. Fermi, W. Heisenberg

Front role (sitting):
Th. De Donder, P. Zeeman, P. Weiss, A. Sommerfeld, M. Curie, P. Langevin, A. Einstein, O. Richardson, B. Cabrera, N. Bohr,W. J. De Haas

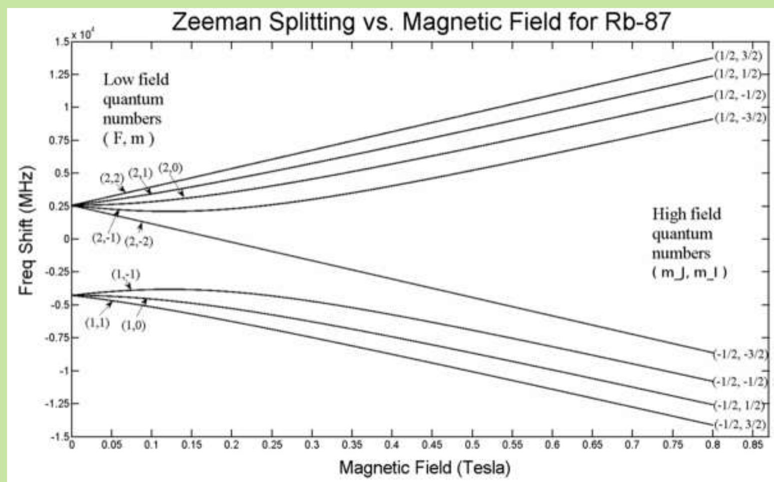
Spin History

1930 Solvay Conferences on Physics Le magnétisme

P. Zeeman:

Zeeman effect

Discovered that a spectral line is split into several components in the presence of a magnetic field.

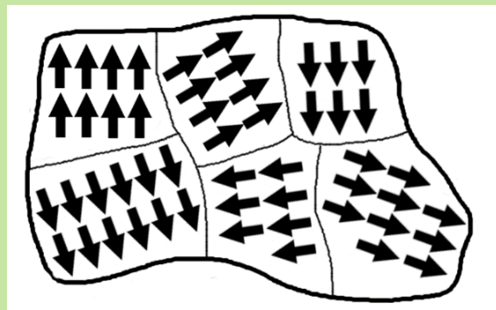


Spin History

1930 Solvay Conferences on Physics Le magnétisme

P. Weiss:

1) **Weiss domains**



2) **Curie-Weiss law**

$$\chi = \frac{C}{T - T_c}$$

Spin History

1930 Solvay Conferences on Physics Le magnétisme

A. Sommerfeld

Introduced spin quantum number: m_s

n: the principal quantum number,

ℓ: the angular momentum quantum number,

m_ℓ, the magnetic quantum number

m_s, the spin quantum number.

Spin History

1930 Solvay Conferences on Physics Le magnétisme

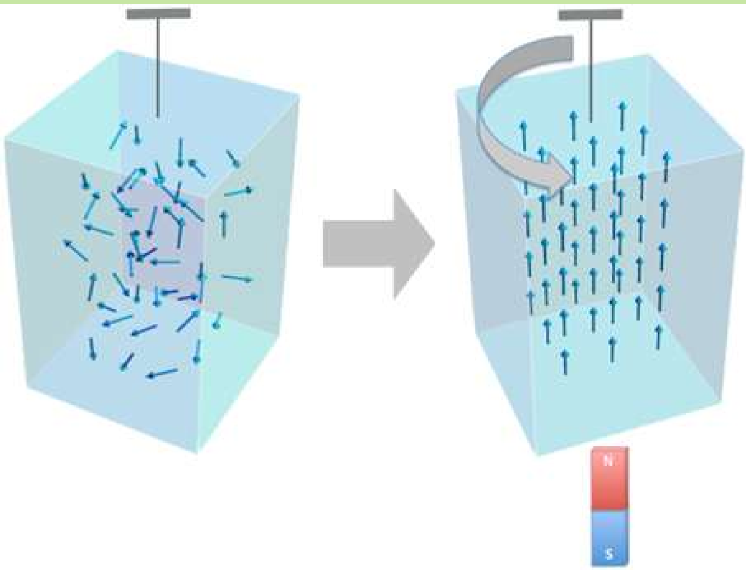
P. Langevin

Noted for his work on paramagnetism and diamagnetism

Spin History

1930 Solvay Conferences on Physics Le magnétisme

A. Einstein



The Einstein–de Haas effect

Spin History

1930 Solvay Conferences on Physics Le magnétisme

N. Bohr

Bohr Magneton

$$\mu_B = \frac{e\hbar}{2m_e} = 9.274 \times 10^{-24}\, Am^2$$

Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. J. de Haas

de Haas–van Alphen effect
(magnetic moment of a pure metal oscillation)

$$\Delta\left(\frac{1}{B}\right) = \frac{2\pi e}{S * h}$$

S: The area of the Fermi Surface

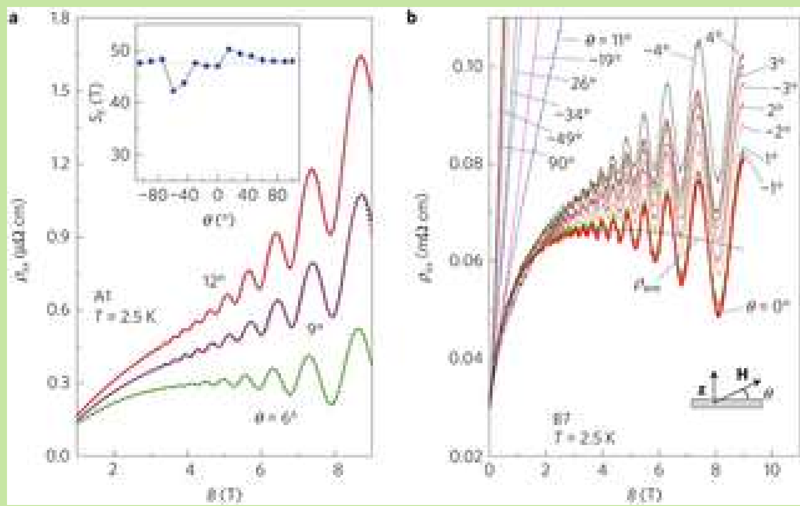
Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. J. de Haas

Shubnikov–de Haas effect (resistivity)

$$\Delta\left(\frac{1}{B}\right)=\frac{2e}{n^{*}h}$$



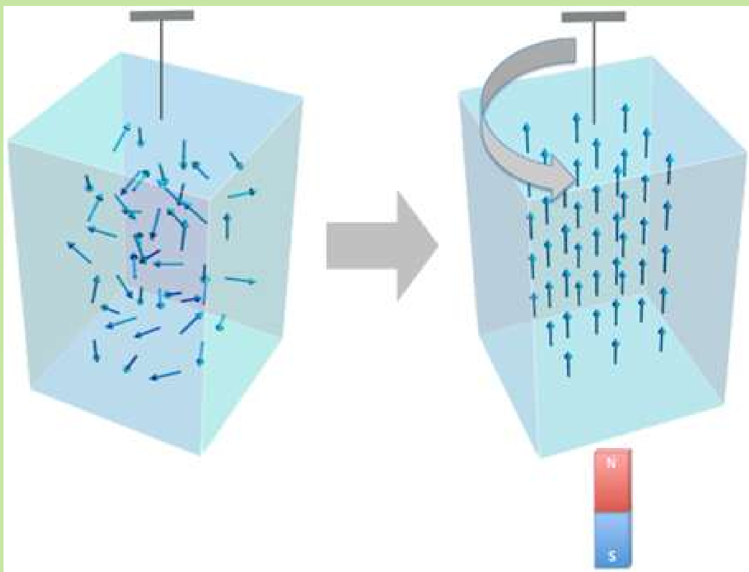
Dirac semimetal
Cd_3As_2

Liang, et al, Nature Materials (2014)

Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. J. de Haas



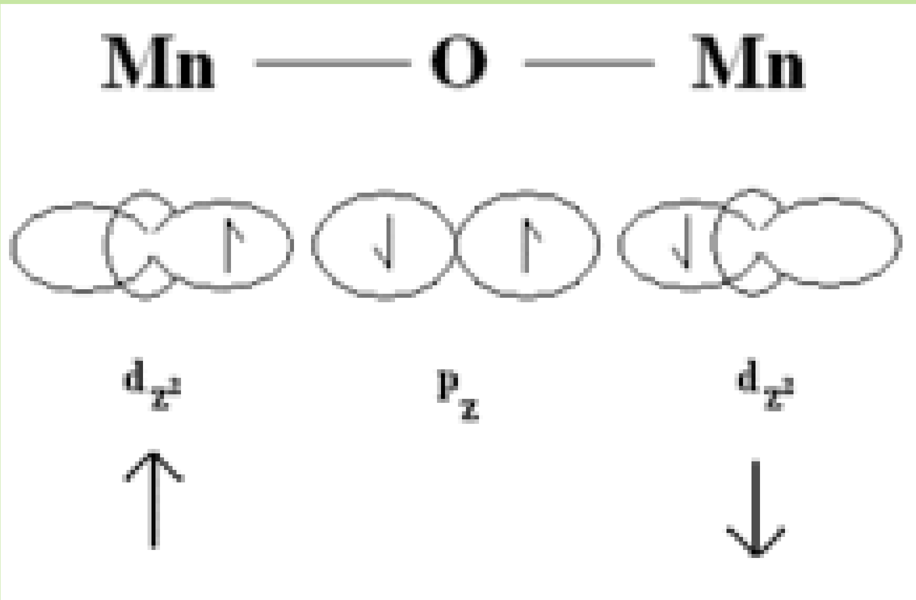
The Einstein–de Haas effect

Spin History

1930 Solvay Conferences on Physics Le magnétisme

H. A. Kramers

Kramers–Anderson superexchange



Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. Pauli

Pauli exclusion principle

It is impossible for two electrons of a poly-electron atom to have the same values of the four quantum numbers:
n, the principal quantum number,
ℓ, the angular momentum quantum number,
m_ℓ, the magnetic quantum number,
m_s, the spin quantum number.

Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. Paulі

Pauli Matrix

$$\sigma_1 = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_2 = \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_3 = \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. Pauli

Pauli effect

The apparently mysterious, anecdotal failure of technical equipment in the presence of Austrian theoretical physicist Wolfgang Pauli.

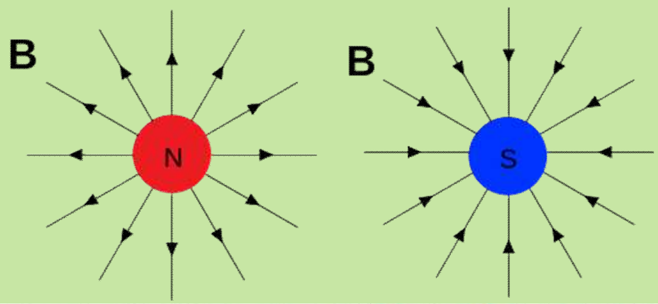
“*A functioning device and Wolfgang Pauli may not occupy the same room*”

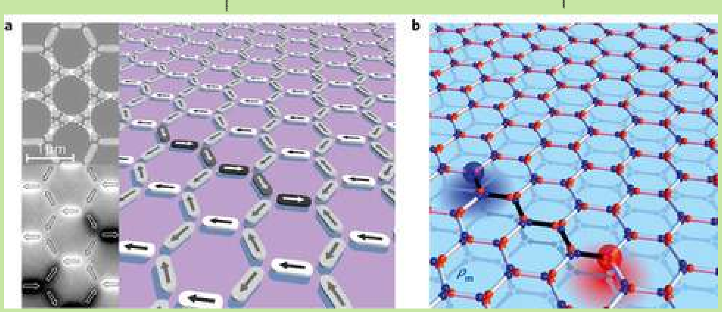
Spin History

1930 Solvay Conferences on Physics Le magnétisme

P. Dirac

Monopole and Dirac string





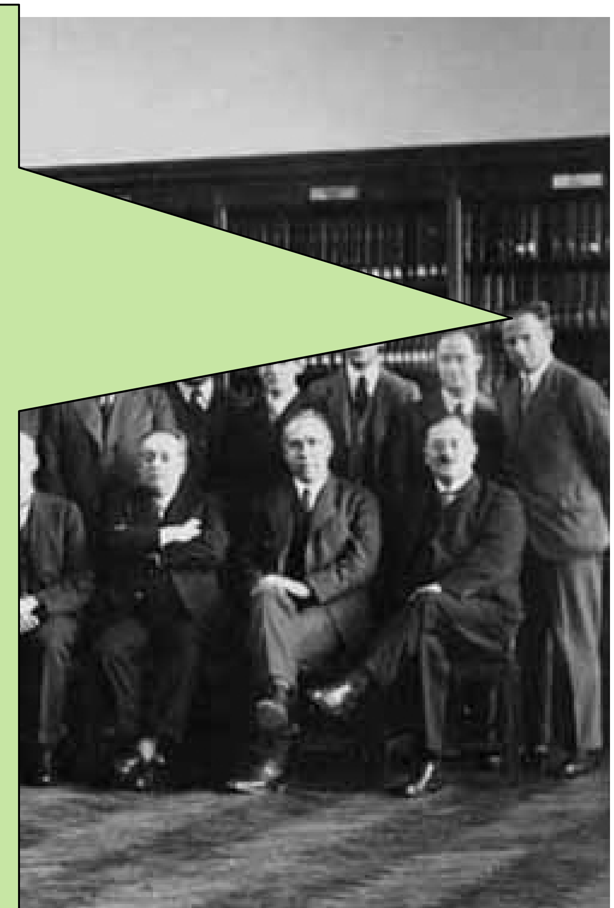
Spin History

1930 Solvay Conferences on Physics Le magnétisme

W. Heisenberg

Heisenberg exchange Hamiltonian

$$H_{\text{exchange}} = -J(|\mathbf{R}_1 - \mathbf{R}_2|)[(1/2) + 2\mathbf{S}_1.\mathbf{S}_2],$$



Spin History

1935 - Now

Age of magnetic applications

Electric Screwdriver

Spin History

1935 - Now

Age of magnetic applications

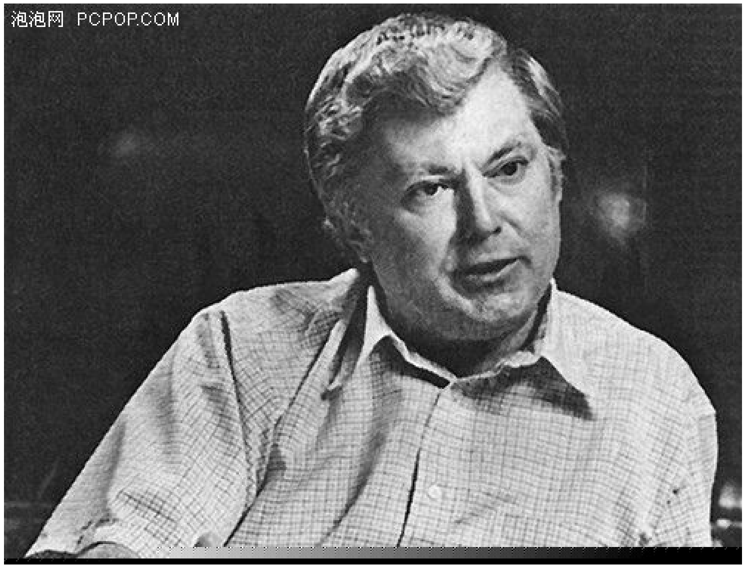
Magnetic tape for storage

Spin History

1935 - Now

Age of magnetic applications

Floppy disk

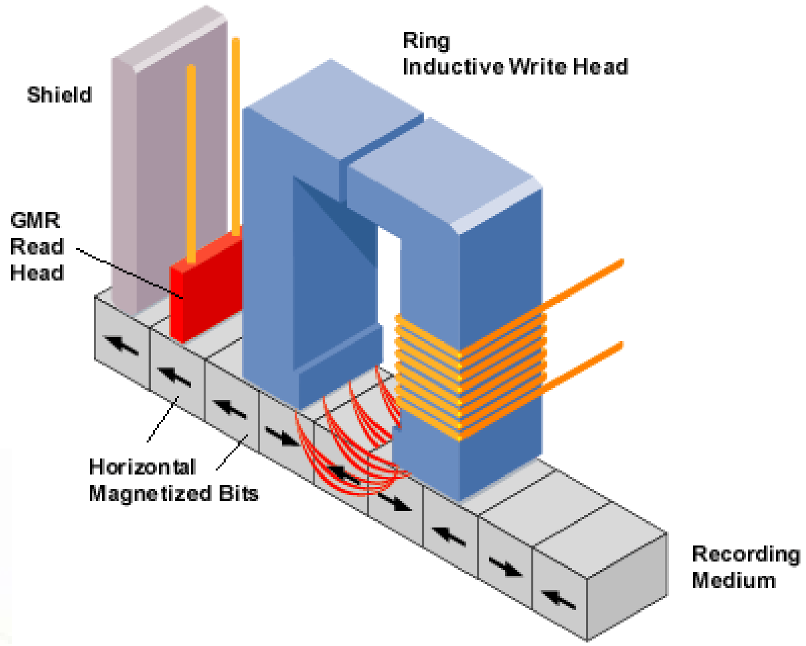


Alan Shugart

Spin

1935 - Now

Age of magnetic applications

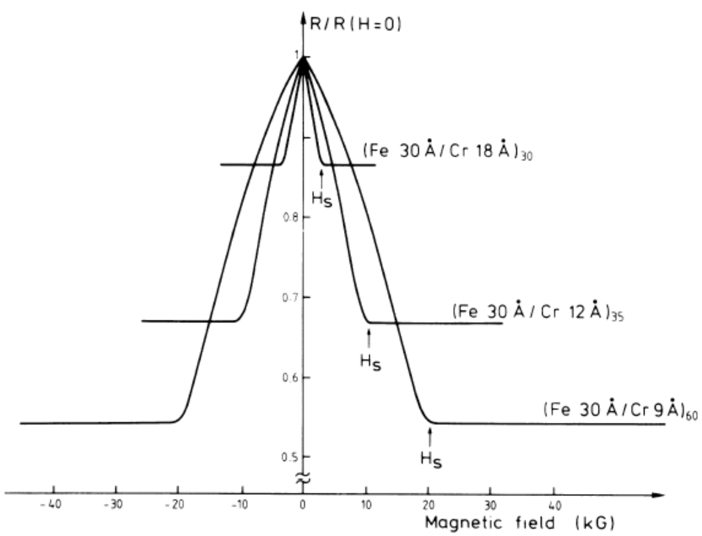


Spin

1935 - Now

Age of magnetic applications

GMR



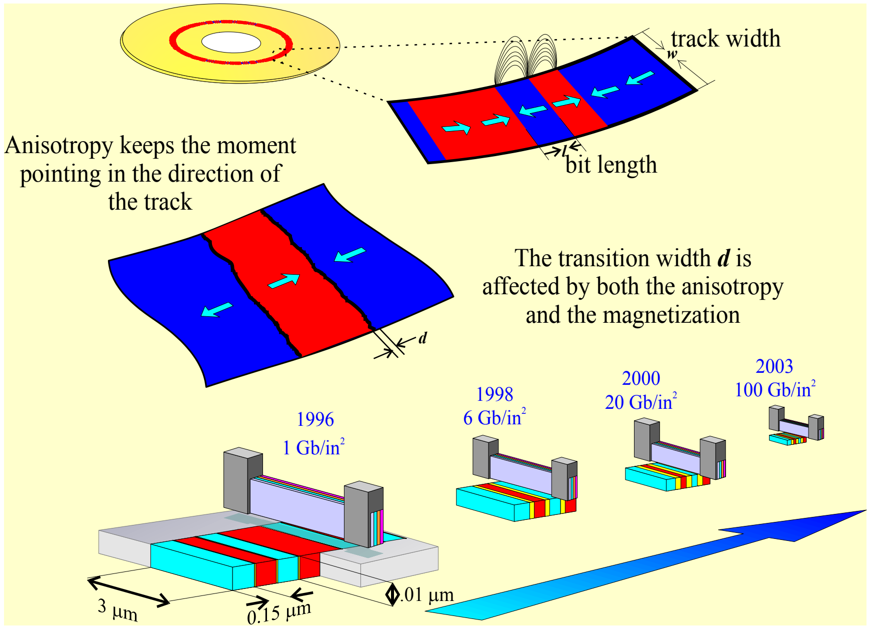
The Nobel Prize in Physics 2007 was awarded ***"for the discovery of Giant Magnetoresistance"***

Spin

1935 - Now

Age of magnetic applications

2014 Millennium Technology Prize
“in recognition of his discoveries, which have enabled a thousand-fold increase in the storage capacity of magnetic disk drives”



Spin Current

1995 - now

Age of Spin current

1) Generation of Spin Current

- **Spin injection from a Ferromagnet (Spin valves)**
- **Thermal gradient (spin Seebeck effect)**
- **Spin Hall effect**
- **Edelstein effect**
- **Spin pumping**

Spin Current

1995 - now

Age of Spin current

2) The use of Spin Current

- **Spin current torque**
- **Pure spin current torque**

Spin Current

1995 - now

Age of Spin current

3) The manipulation of Spin Current

- **Electrical tuning of the magnetism**
- **Magnetic field effect on the spins (Hanle)**
- **Zeeman effect on the spins**

Spintronics

Recent developments and

the focus of this class

- ➢ Generation of spin current
- ➢ Use of spin current
- ➢ Manipulation of spin current

下一节课: Sept. 22th

Chapter 2: Magnetism and Magnetic Materials

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html

谢谢！