In This Lecture:

- **An Overview of Spintronics**

Some of the material is complied from the following sources:

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Shun-Qing Shen, University of Hong Kong
David Awschalom, and Nitin Samarth

Spintronics:

- Conventional electronics has ignored the spin of electrons!
- In addition to their mass and electric charge, electrons have an intrinsic quantity of angular momentum called spin, almost as if they were tiny spinning balls.
- Associated with the spin is a magnetic field like that of a tiny bar magnet lined up with the spin axis.

Objective:

To create a revolutionary new class of electronics based on the spin degree of freedom in additional to, or in the place of, the charge degree of freedom.

Advantages of Spin

- Information is stored into spin as one of two possible orientations [classical bit]
- Electron spin lifetime is relatively long, on the order of nanoseconds; nuclei have milliseconds or more
- Spins can be injected/detected optically as well
- Spin devices may combine logic and storage functionality eliminating the need for separate components
- Magnetic storage is nonvolatile
- Superposition of spin states paves the way to quantum computers [quantum bit]

Early History of Spin

- Pauli's fourth quantum number
- Goudsmit and Uhlenbeck's proposal of spin encouraged by Ehrenfest
- Stern-Gerlach experiment
- Dirac's equation and Exclusion Principle

Wolfgang Pauli

- Born 1900 in Vienna, died 1958 in Zurich
- Wolfgang Pauli's fourth quantum number

  Principle quantum number, n, size of the orbital in an atom

  Orbital quantum number, l, shape of the orbital in an atom

  Magnetic quantum number, m, orientation in space of the orbital

  To distinguish between the two electrons in an orbital, we need a fourth quantum number!!!

- In January 1925 Pauli had proposed that the electron should be given an additional fourth quantum number which was a half integer

Wolfgang Pauli

- This was one of the clues which led Uhlenbeck to arrive at the idea of electron spin. He wrote

  ... *it occurred to me that , since (I had learned) each quantum number corresponds to a degree of freedom of the electron, Pauli's fourth quantum number must mean that the electron had an additional degree of freedom -- in other words the electron must be rotating.*

- Pauli (eventually) realized the importance of the extra angular momentum and postulated his exclusion principle (1945 Nobel Prize), which led to the quantum statistics of Fermi-Dirac distribution.

Wolfgang Pauli

- Pauli is infamous for a number of scathing remarks directed at his colleagues. Of one colleague's paper, he is purported to have said *"This isn't right. This isn't even wrong."*
- Pauli Effect: It was a standing joke among Wolfgang Pauli's colleagues that the famed theoretical physicist should be kept as far away from experimental equipment as humanly possible. His mere presence in a laboratory, it was said, would cause something to go wrong: the power would fail, vacuum tubes would suddenly leak, instruments would break or malfunction... Indeed, such was the frequency of Pauli-related incidents that the strange phenomenon came to be known as the 'Pauli Effect'.

Uhlenbeck- Goudsmit Contribution

- Samuel Abraham Goudsmit and George Eugene Uhlenbeck, two graduate students of Ehrenfest (later assistants) at the University of Leiden in Netherlands
- In 1925 Uhlenbeck and Goudsmit postulated the existence of

a new intrinsic property of particles that behaved like an angular momentum.

Uhlenbeck- Goudsmit Contribution

- This intrinsic property was later termed spin by Pauli, however, the image of a spinning sphere is not likely an accurate one. This new property needs to be viewed as an intrinsic property like mass and charge that is particular to a given type of particle. Note that, unlike mass and charge, there is no classical analog to spin!
- Spin angular momentum measurement yields only 2 possible values, $\pm \frac{\hbar}{2}$, therefore, should have an associated magnetic moment

$$\vec{\mathrm{M}} = \frac{g\mu_B}{\hbar}\vec{\mathrm{S}}, \qquad \mu_B = \frac{e\hbar}{2m}$$

Uhlenbeck- Goudsmit Contribution

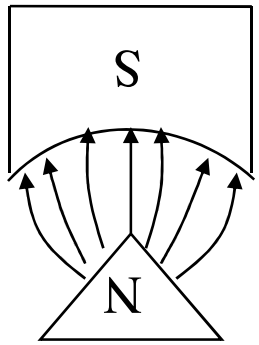
- It is found that good fits to experimental data are obtained when g=2, which means that the *spin gyromagnetic ratio*, defined to be $g\mu_B/\hbar$ is twice as large as the *orbital gyromagnetic ratio* $\mu_B/\hbar$.

"This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything by making a stupid mistake."

P. Ehrenfest, upon receiving the paper by G. Uhlenbeck and S. Goudsmit, from "The story of spin", S. Tomonaga

The Stern-Gerlach experiment

In an inhomogeneous magnetic field there is a force on the atoms which depends on *m*



$$\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B}) = -m\mu_B \frac{dB_z}{dz}$$

Direction of force tends to decrease the magnetic potential energy

$$E = E_0 + m\mu_B B_z \quad -l \le m \le l$$

So atoms in different internal angular momentum states will experience different forces and will move apart. So if we pass a beam of atoms through an inhomogeneous B field we should see the beam separate into parts corresponding to the distinct values of *m*.

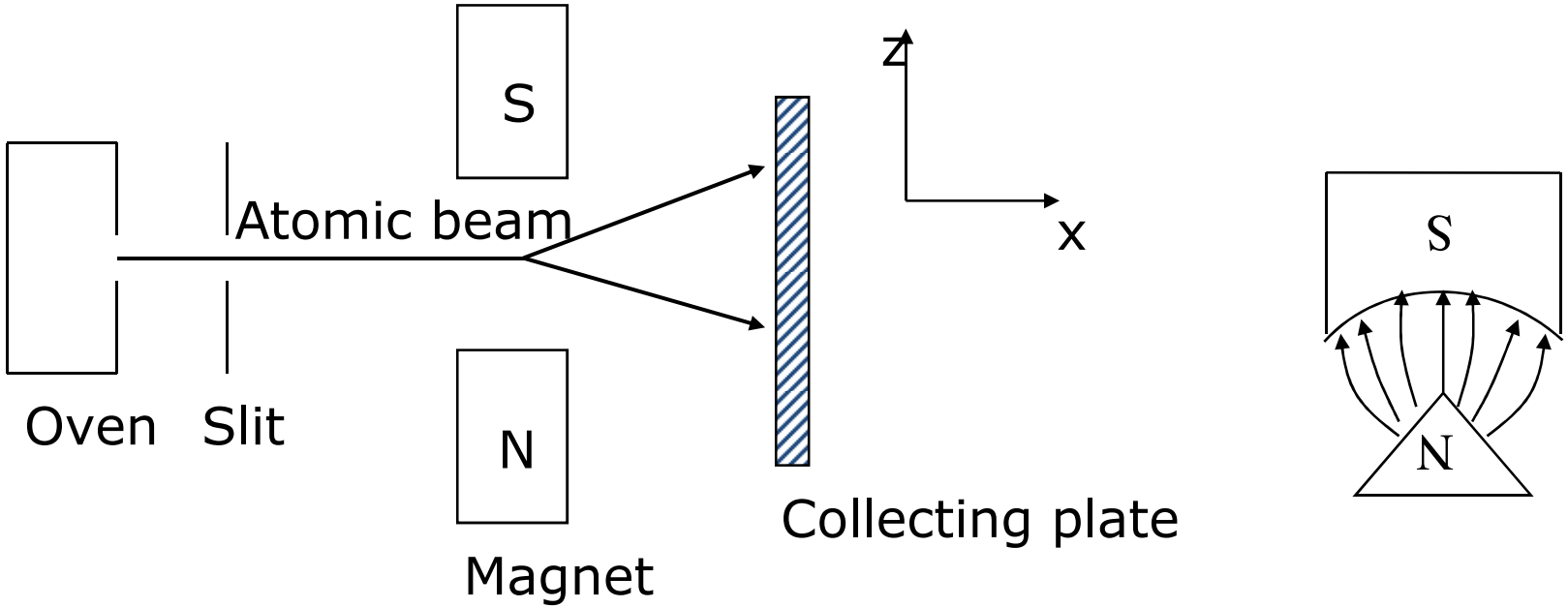
Predictions:

1. Beam should split into an odd number of parts ($2\ell+1$)
2. A beam of atoms in an s state (e.g. the ground state of hydrogen, $n = 1$, $\ell = 0$, $m = 0$) should not be split.

The Stern-Gerlach experiment (2)

Beam of atoms with a single electron in an s state (e.g. silver, hydrogen)

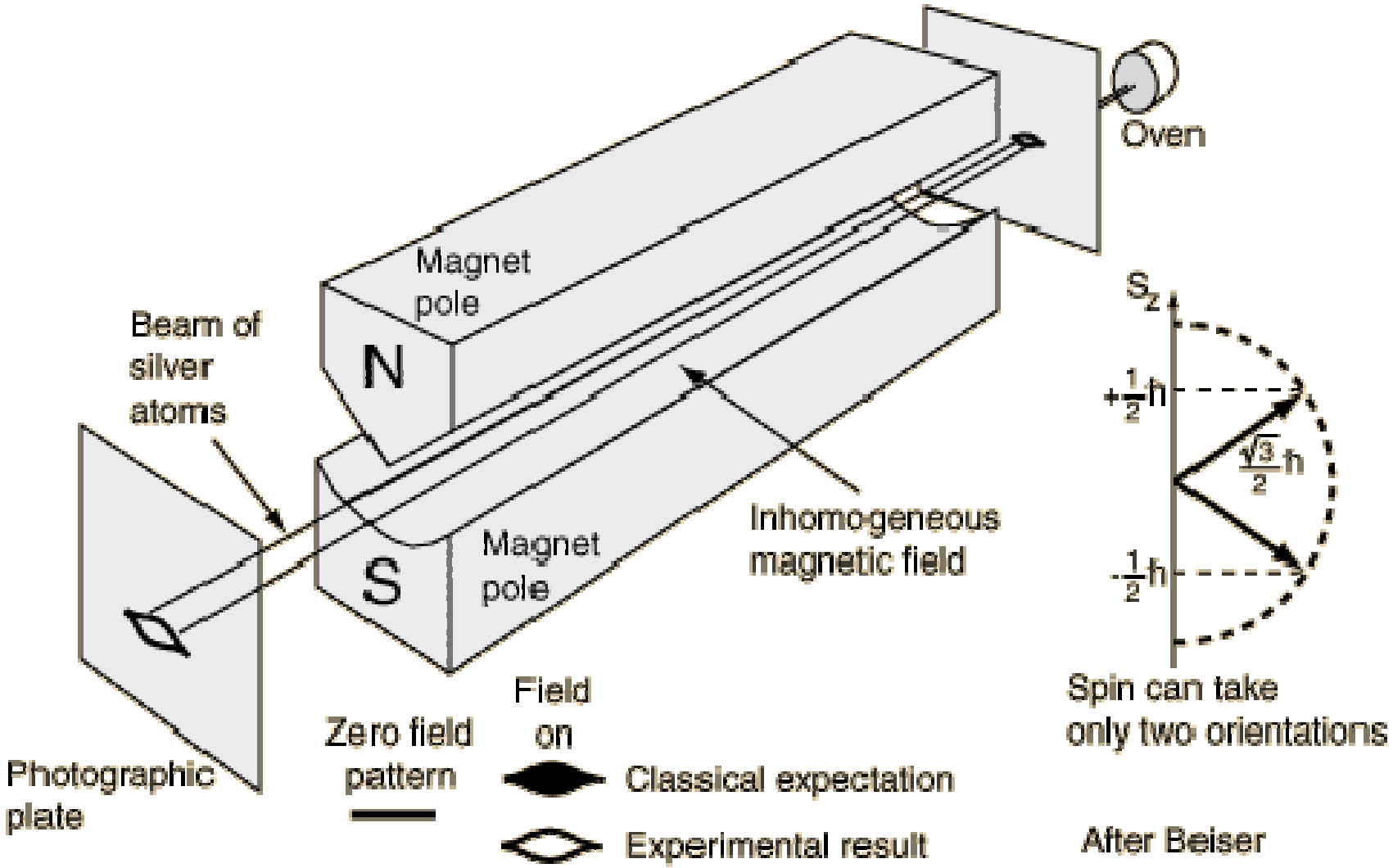
Study deflection in inhomogeneous magnetic field. Force on atoms is $\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B})$



Results show **two** groups of atoms, deflected in opposite directions, with magnetic moments $\mu = \pm\mu_B$

Consistent neither with classical physics (which would predict a continuous distribution of μ) nor with our quantum mechanics so far (which always predicts an odd number of groups and just one for an s state).

The Stern-Gerlach experiment (3)



A complete set of quantum numbers

Hence the **complete** set of quantum numbers for the electron in the H atom is: n,l,m,s,m_s with s = ½ and m_s = +/- ½. These correspond to a full wavefunction

$$\psi_{nlmsm_s}(\mathbf{r}) = R_{nl}(r)Y_{lm}(\theta,\phi)\chi_{s,m_s}$$

$$\chi_{1/2,1/2} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \chi_{1/2,-1/2} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Note that the spin functions χ do not depend on the electron spatial coordinates r,θ,φ; they represent a purely internal degree of freedom.

H atom in magnetic field, with spin included:

$$\hat{H} = H_0 + \frac{\mu_B}{\hbar}\mathsf{B}\cdot(\hat{\mathsf{L}} + g\hat{\mathsf{S}})$$

$g = 2$(Dirac's relativistic theory)

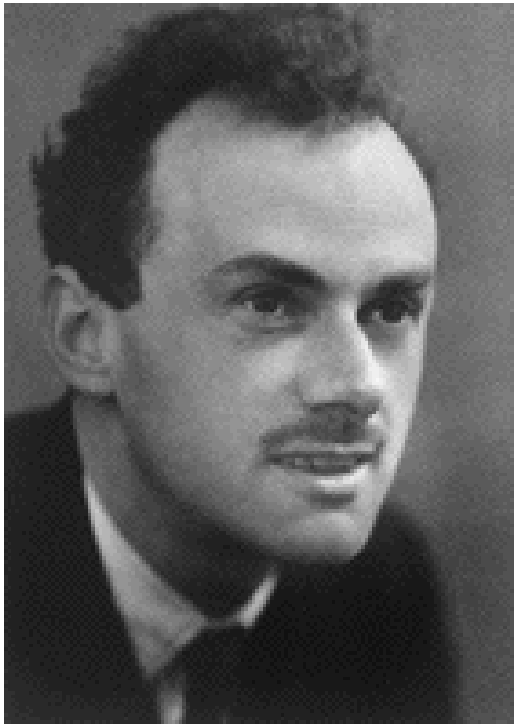
$g = 2.00231930437$(Quantum Electrodynamics)

Relativistic Quantum mechanics

The Dirac equation in the form originally proposed by Dirac is:

$$\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k\, c\right) \psi(\mathbf{x}, t) = i\hbar \frac{\partial \psi(\mathbf{x}, t)}{\partial t}$$

where m is the rest mass of the electron,
c is the speed of light,
p is the momentum operator,
$\mathbf{x}$ and t are the space and time coordinates,
$\hbar = h/2\pi$ is the reduced Planck constant

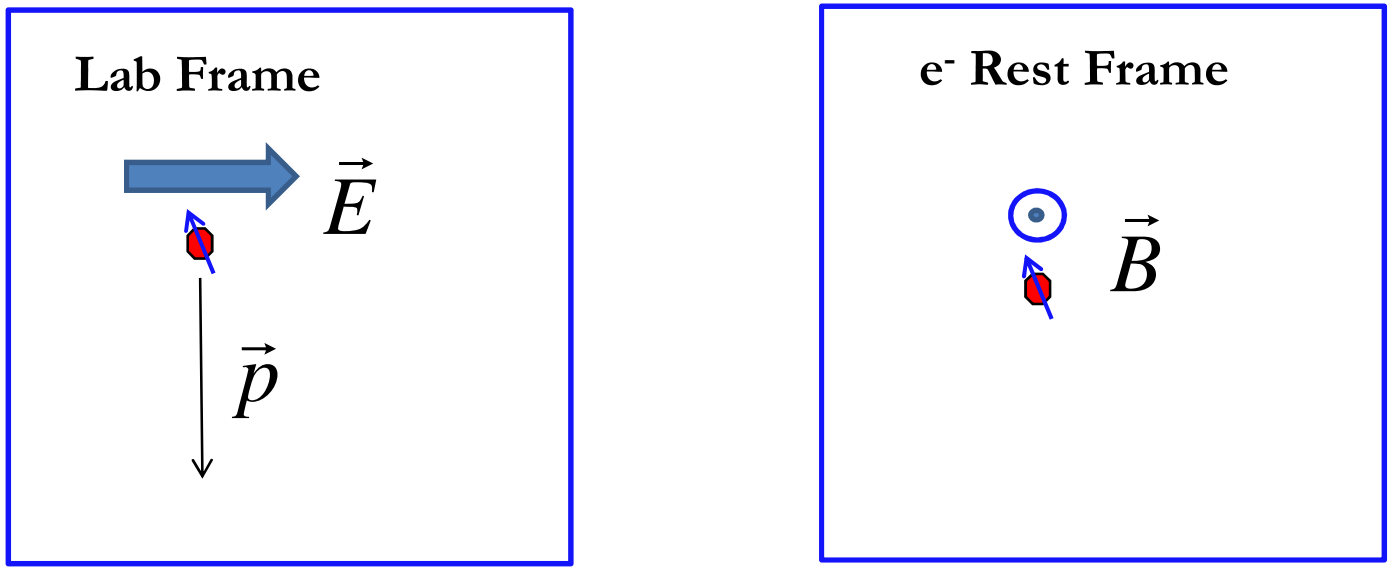


Paul A. M. Dirac

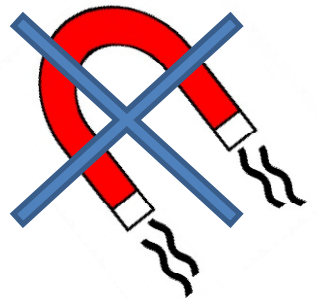
Relativistic Quantum Mechanics Effect:

Spin-Orbit Interaction: A relativistic effect of transformation of electric field to a magnetic field in the rest frame of the electron

$$H_{SO} = \frac{\hbar}{4m^2c^2}(\nabla V \times \vec{p}) \cdot \vec{\sigma} \qquad H_{SO} = -g\vec{\sigma} \cdot \vec{B}$$



Magnetism without magnets



Categories of Spintronics

Metal-based:

- Ferromagnetic metal based devices: read head (GMR), MRAM,…

Semiconductor-based:

- Spin transport in semiconductors: ultrafast switches, fully programmable all-spintronics microprocessors,…
- Manipulation of quantum spin states of individual electrons, nuclear spin and magnetic clusters: quantum logic gates,…
- Devices based on spin current in semiconductor

VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices

~10,000 citations

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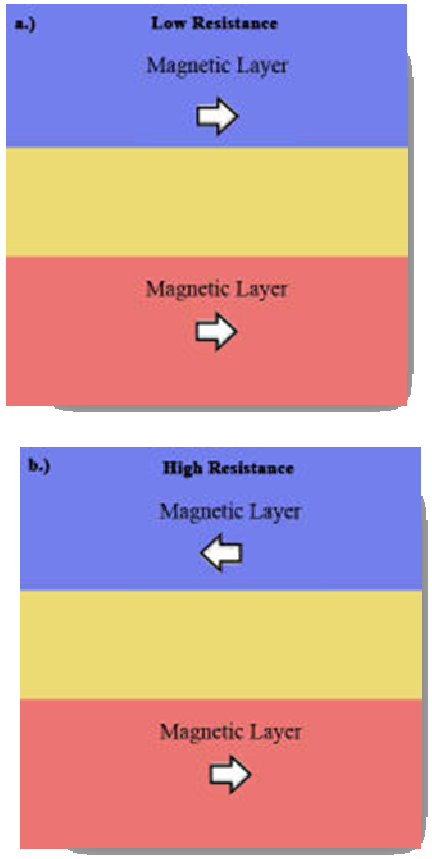
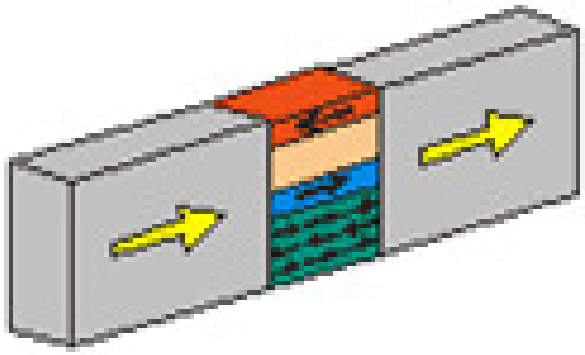
(Received 24 August 1988)

- 1988 France, GMR discovery is accepted as birth of spintronics
- A giant magnetoresistive device is made of at least two ferromagnetic layers separated by a spacer layer
- When the magnetization of the two outside layers is aligned, lowest resistance
- Conversely when magnetization vectors are antiparallel, high R
- Small fields can produce big effects
- parallel and perpendicular current



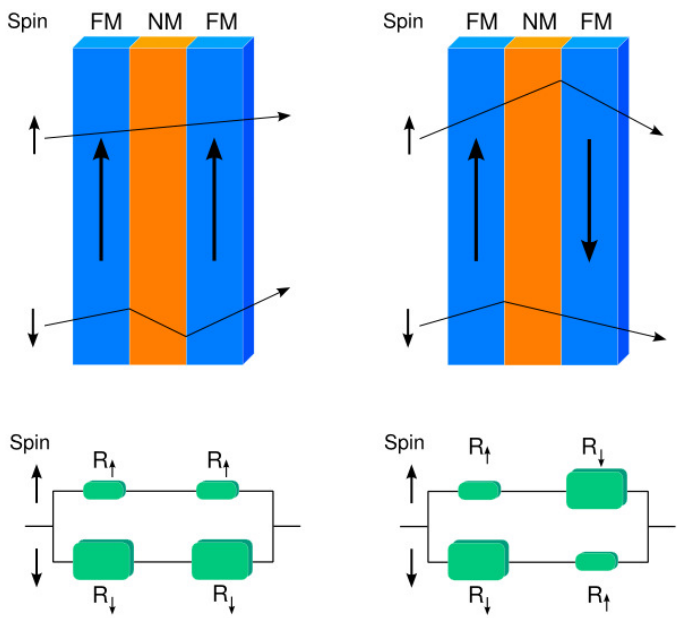
Parallel Current GMR

- Current runs parallel between the ferromagnetic layers
- Most commonly used in magnetic read heads
- Has shown 200% resistance difference between zero point and antiparallel states



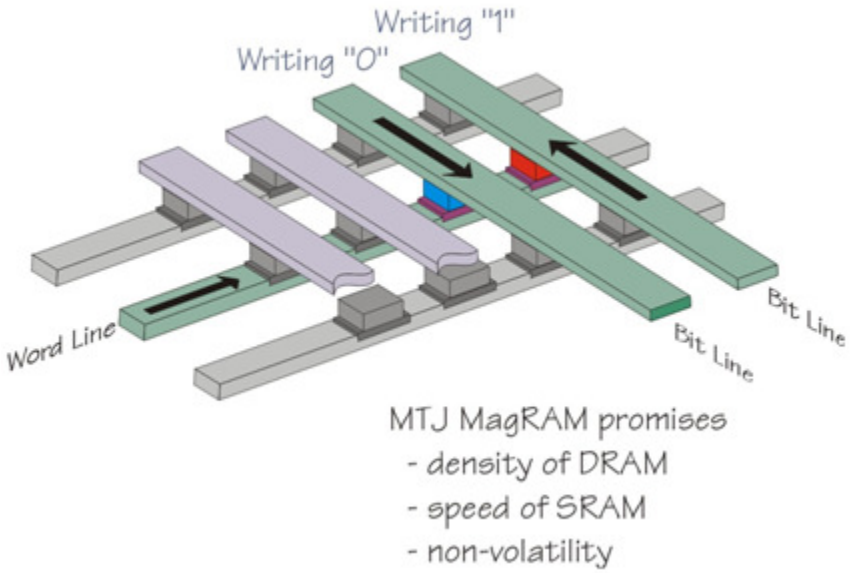
Spin Valve

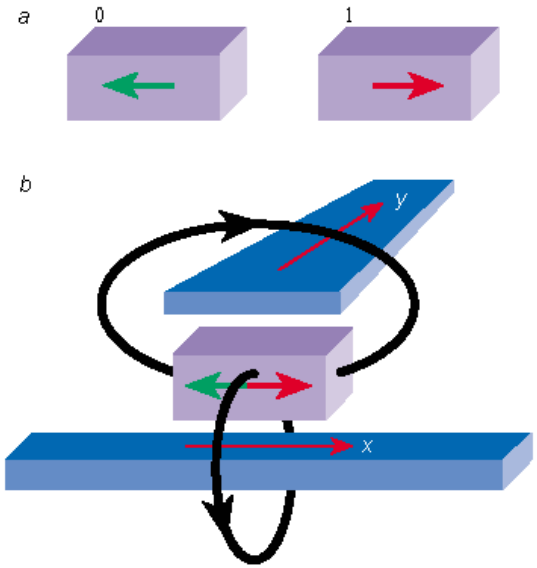
- Simplest and most successful spintronic device
- Used in HDD to read information in the form of small magnetic fields above the disk surface



MRAM

- The spin transfer mechanism can be used to write to the magnetic memory cells
- Currents are about the same as read currents, requiring much less energy





Semiconductor-based Spintronics

Advantages:

- Unparalled storage capacity of magnetic memories
- Computing power of semiconductor logic
- Relatively long-lived quantum coherence of spin states in semiconductors

Breakthrough: Spintronics without magnetism !

- Relies on our ability to manipulate carrier spins via spin-orbit interaction

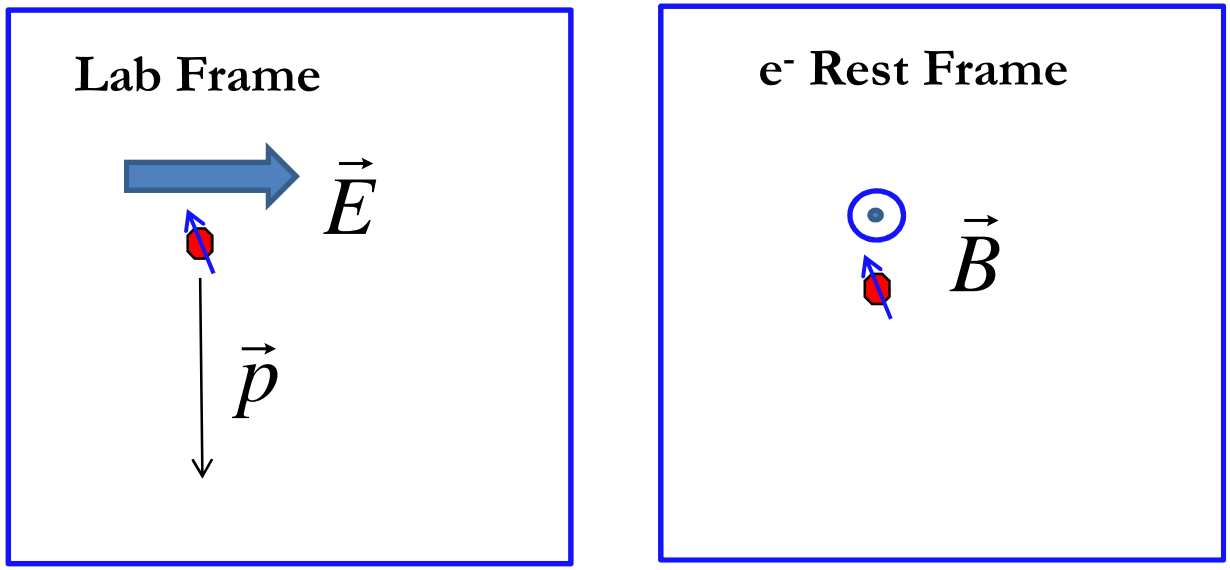
Two conceptually different processes:

- Spin-dependent scattering of relativistic electrons by Coulomb potential (Mott 1929)
- Acuisition of a geometric phase

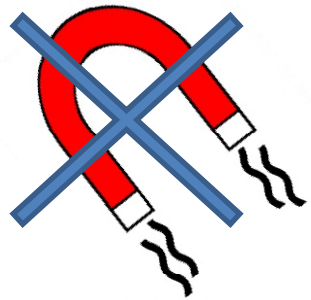
Magnetism via Spin-orbit coupling

Rashba Effect: Electric field via structural inversion asymmetry

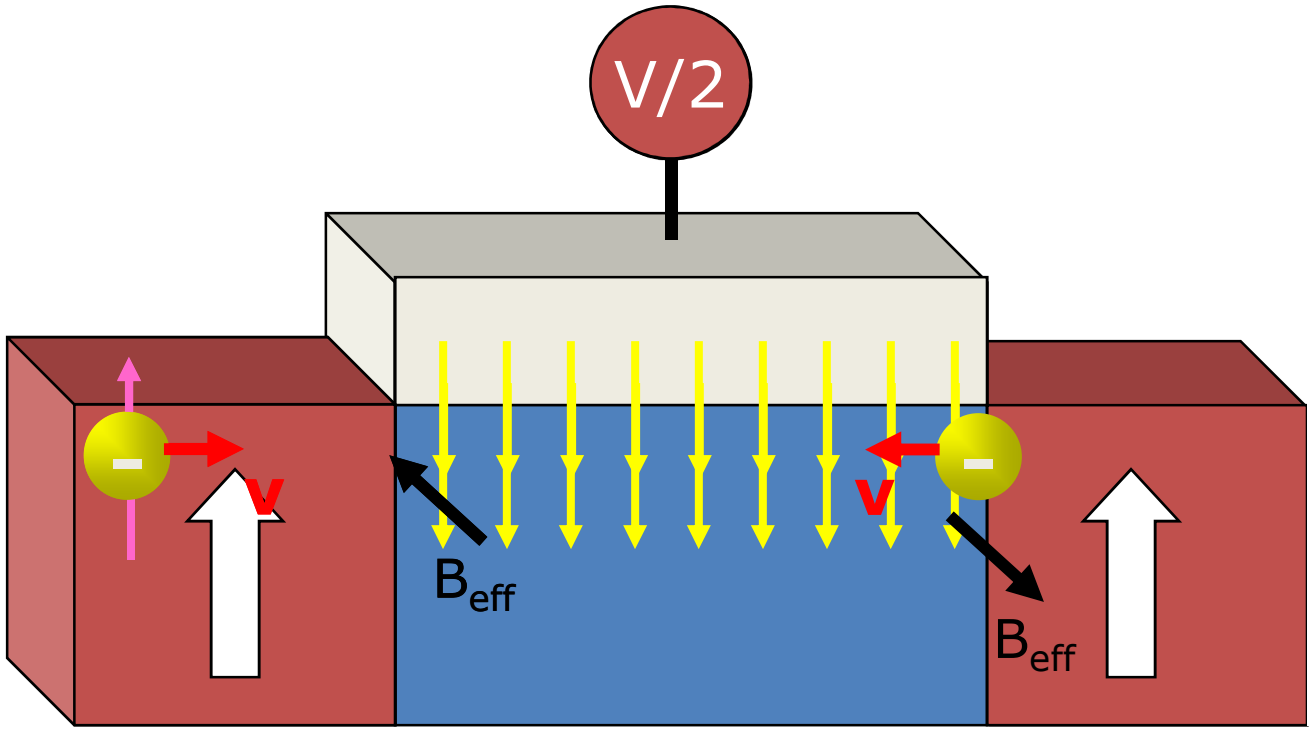
$$H_{so} = \frac{\hbar}{4m^2c^2}(\nabla V \times \vec{p}) \cdot \vec{\sigma}$$



Magnetism without magnets

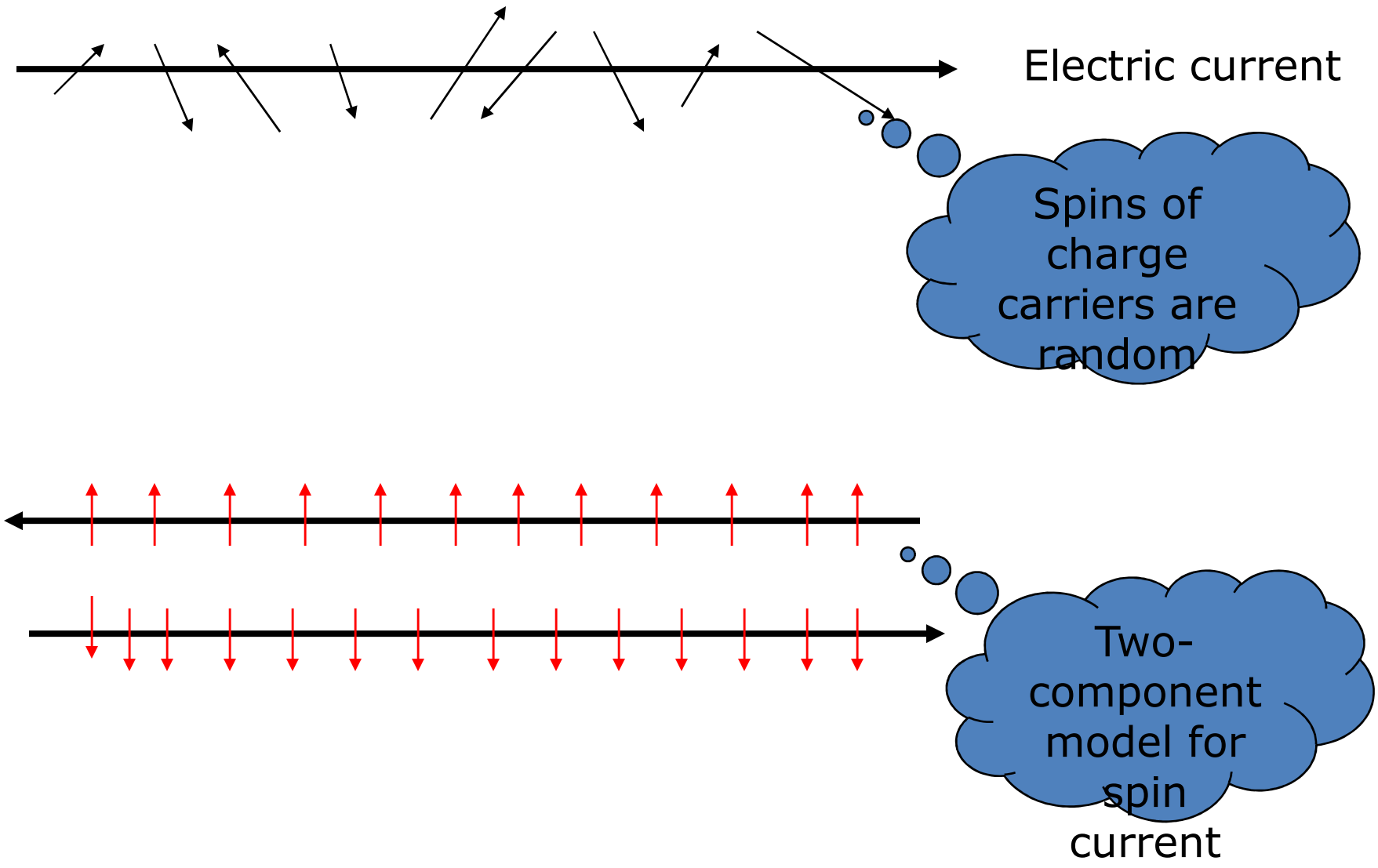


Datta-Das Field Effect Transistor



$$V_R = \lambda(p_x\sigma_y - p_y\sigma_x)$$

Electric current and spin current



What is the spin current?

Electrons carry both charge and spin which may have two components: up and down.

If the currents of electrons for different spins are not equal,

$$j_{\uparrow} = -j_{\downarrow}$$

The electric current

$$J_c = -e\left(j_{\uparrow} + j_{\downarrow}\right) = 0$$

The spin current

$$J_s = \frac{\hbar}{2}\left(j_{\uparrow} - j_{\downarrow}\right) \neq 0$$

Spin Hall Effect

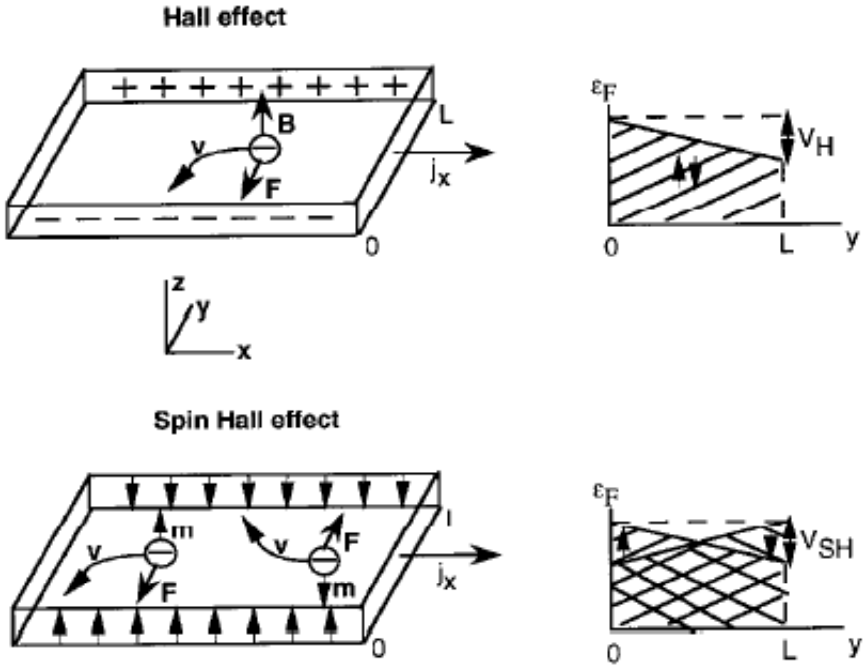


FIG. 1. The charge carriers are assumed to be electronlike. In the Hall effect, the Lorentz force on the moving charges causes charge imbalance; in the spin Hall effect skew scattering of the moving magnetic moments causes spin imbalance, in a direction perpendicular to the current flow. In the Hall effect the Fermi levels for up and down electrons are the same, and the difference in the Fermi levels at both edges of the sample is the Hall voltage V_H. In the spin Hall effect the difference in the Fermi levels for each spin at both edges of the sample is V_{SH}, but it is of opposite sign for spin up and down electrons.

D'yakonov and Perel, 1971, Hirsch, 1999, Hu et al 2003
Murakami et al, 2003, Sinova et al, 2004, Shen, 2004

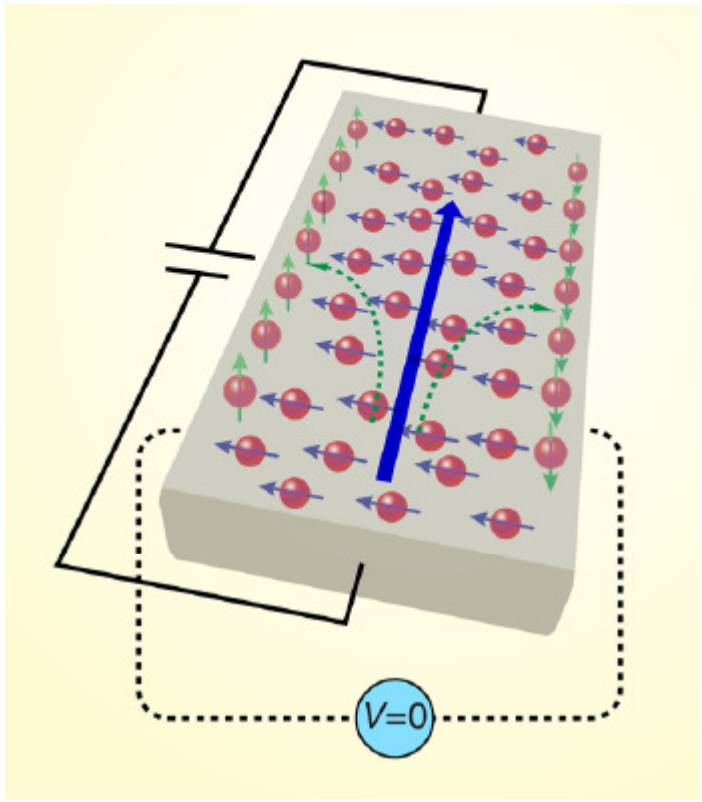


FIG. 1: Electrically-injected electrons become spin polarized through two different mechanisms during nominally "simple" transport in semiconductors. Electrons can experience anisotropic spin scattering from impurities in the presence of spin-orbit coupling, producing the spin Hall effect where "up" and "down" spins (green arrows) accumulate at opposite edges of the channel. In addition, symmetry-related spin-orbit fields can produce a homogeneous electron spin polarization throughout the channel (blue arrows). (Illustration: Alan Stonebraker)

Detecting Spins: Kerr Rotation

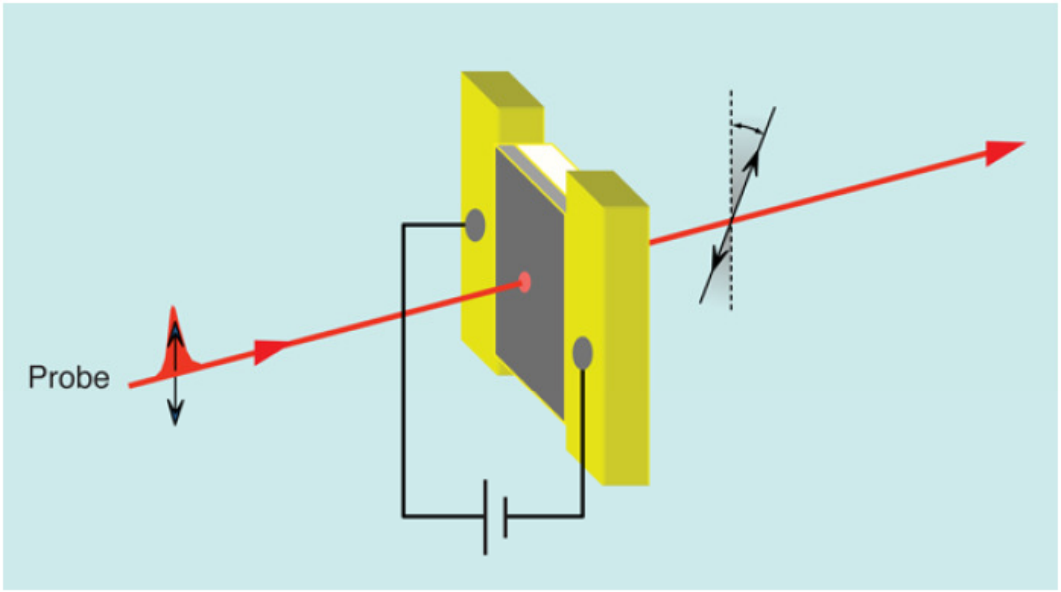
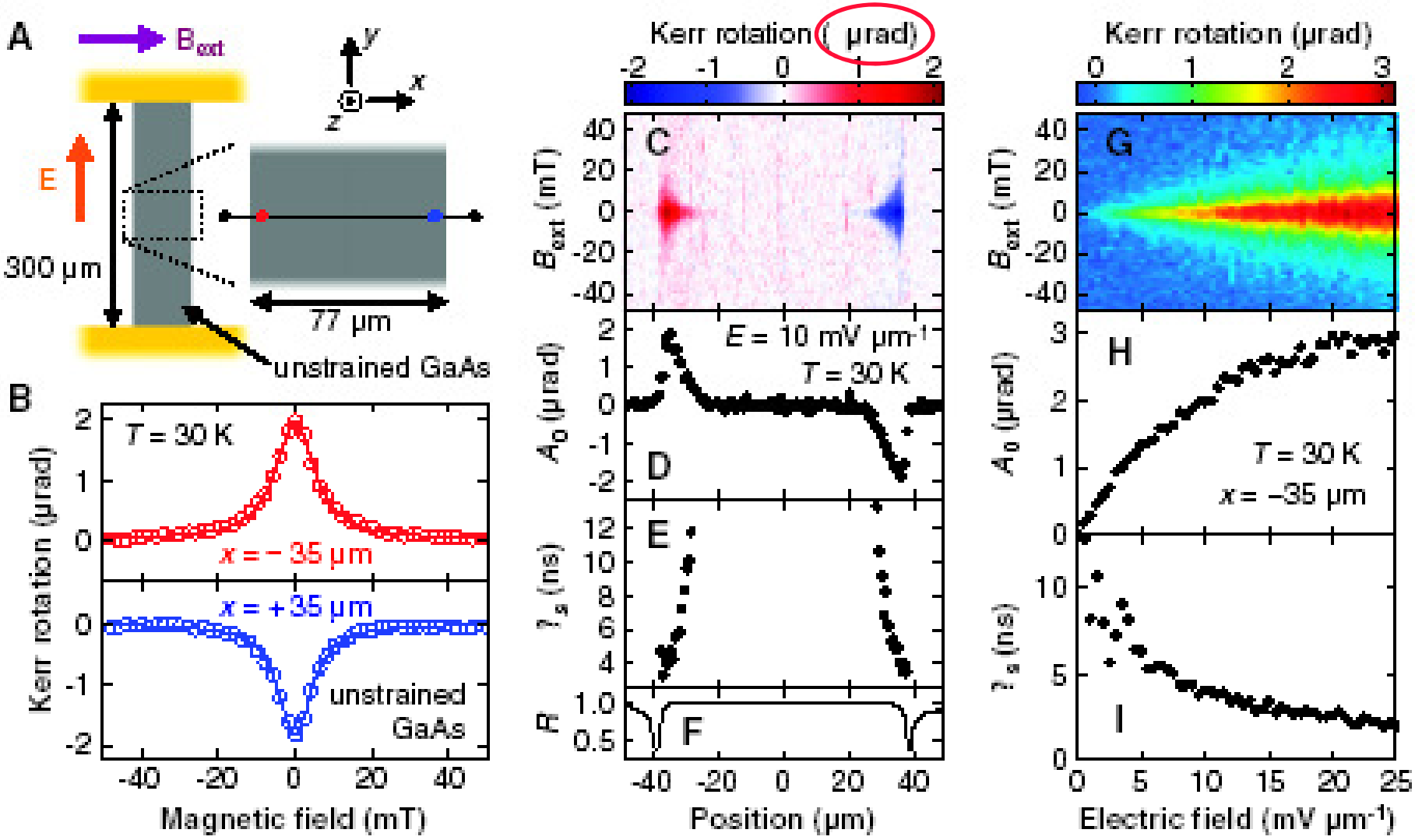


FIG. 2: Polarized electron spins in semiconductors may be probed through their interaction with optical fields. The polarization of light incident on the semiconductor will rotate in proportion to the strength of the magnetic field produced by this spin polarization. The rotation is known as the Faraday (Kerr) effect in transmission (reflection). (Illustration: Alan Stonebraker)

Kato, Myers, Gossard, and Awschalom, Science (2004)

Kerr Rotation Microscopy



Kato, Myers, Gossard, and Awschalom, Science (2004)

Detecting Single Electronic Spin

Magnetic resonance of a single molecular spin

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THE introduction of optical detection methods for observing magnetic resonance transitions in metastable paramagnetic states[1–4] has contributed enormously to our understanding of the properties of photoexcited molecules in condensed phases. In such experiments the luminescence intensity is recorded as a function of the frequency of an applied microwave field. At resonance with transitions between sublevels of a metastable paramagnetic state, the lifetime of the metastable state is altered and a consequent change in the luminescence intensity is observed. Here we report the observation of such optically detected magnetic resonance transitions for the triplet state of a single pentacene molecule embedded in a *p*-terphenyl host crystal. This result has been obtained by combining the conventional optical detection technique for observing magnetic resonance transitions[1–4] with the new single-molecule optical detection methods developed recently[5,6]. This observation opens the way for magnetic resonance studies in condensed phases with single-molecule sensitivity.

Sublimation-grown single crystals of *p*-terphenyl containing

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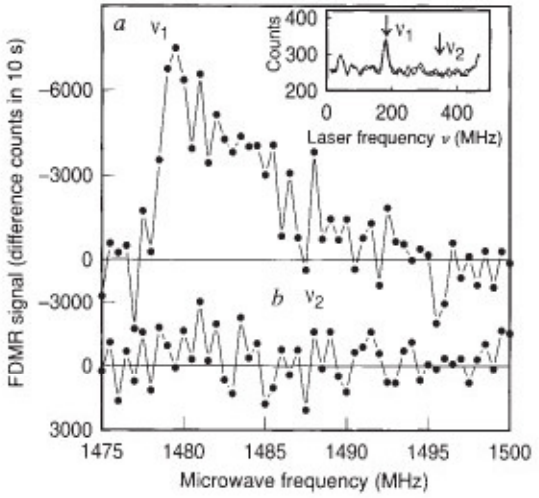

FIG. 1 *a*, FDMR signal of a single pentacene molecule in a *p*-terphenyl host crystal. The molecule was excited at the fixed laser frequency ν_1 (equivalent to 592.404 nm). This is indicated in the inset, where two consecutive fluorescence excitation spectra obtained by scanning the laser are shown. *b*, No FDMR signal is visible when the laser frequency is held at ν_2. The dots give the measured values, and the lines serve as a guide to the eye. The average photon-count rate during acquisition of trace *a* was $\sim 2 \times 10^4\ s^{-1}$, and the laser intensity was $\sim 200\ mW\ cm^{-2}$. The spectra in the inset were recorded with a lower laser intensity than that used for the FDMR signals.

Detecting Single Electronic Spin

Optical detection of magnetic resonance in a single molecule

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MAGNETIC resonance spectroscopy[1] is a powerful tool for molecular characterization and structure determination. The sensitivity of conventional approaches is limited to about 10^{10} electron spins or 10^{16} nuclear spins; this sensitivity can be improved to about 10^5 spins by polarizing the spins via optical pumping and detecting optical rather than microwave photons[2]. Recently, fluorescence from single molecules was detected by tuning a single-frequency laser in the inhomogeneously broadened fluorescence excitation band of a dilute dispersion of pentacene in a host crystal of *p*-terphenyl[3,4]. Here we report that, by combining single-molecule fluorescence spectroscopy with optically detected magnetic resonance for the pentacene-doped *p*-terphenyl system, we can detect magnetic resonance in a single pentacene molecule. We observe two of the three possible transitions between sublevels of the metastable triplet state. The spectral lineshapes indicate that the proton nuclear spin states change during the measurement, leading to spectral diffusion within the magnetic resonance line.

Single-molecule spectroscopy is usually done by observing fluorescence from a molecule driven several million times per second through the excitation–emission cycle. Occasionally, the molecule crosses over to the triplet manifold, and stays there for the average triplet lifetime. Consequently, fluorescence photons are emitted in packets separated by dark intervals when the molecule is in the triplet manifold[5]. As the different triplet sublevels generally have different population rates and different

to those for pentacene in *p*-terphenyl at room temperature[9] and in naphthalene crystal at 1.2K (ref. 8). Neither line was shifted by more than 3 MHz for the ~10 molecules in the red wing that we have investigated. The maximum intensity of the ODMR effect was ~25% for x–z and 15% for y–z. Below the saturation laser power, the lineshape of both transitions is very asymmetrical (Fig. 1 inset). There is a steep rise (in about 200 kHz) on one side and a slow fall (over about 5 MHz for x–z, 3 MHz for y–z) on the other side. The microwave transitions became broader and more symmetrical on saturation.

The fact that the two transitions show up indicates that the x and y sublevels are comparably populated. The ODMR effect calculated for a single transition from known intersystem crossing rates[5,10] would be 40%. This amount could be roughly shared in 25% on x–z and 15% on y–z. The ODMR lineshapes and widths resemble those of an ensemble average for naphthalene

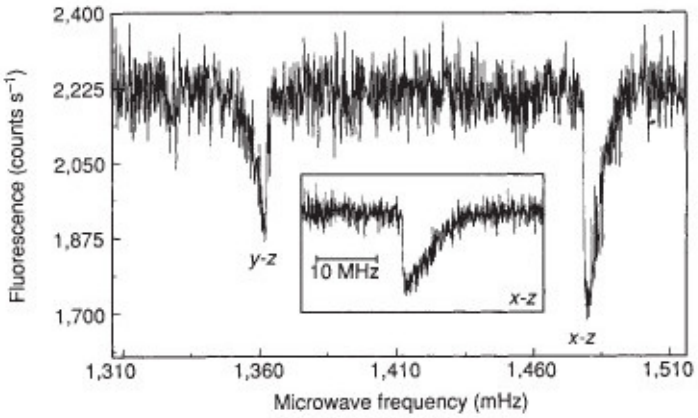

FIG. 1 Decrease of the fluorescence intensity of a single pentacene molecule when the microwave field is resonant with the y–z or the x–z transition. The inset shows the x–z transition on an enlarged frequency scale, on reducing the microwave power by a factor of ~30.

Detecting Single Nuclear Spin

Challenge:

Magneton: $\frac{e\hbar}{2m}$

Bohr (electron) magneton: 58 μeV/T
Nuclear magneton: 32 neV/T

Chemical Physics Letters 267 (1997) 179–185

Magnetic resonance on single nuclei

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Received 5 August 1996; in final form 8 January 1997

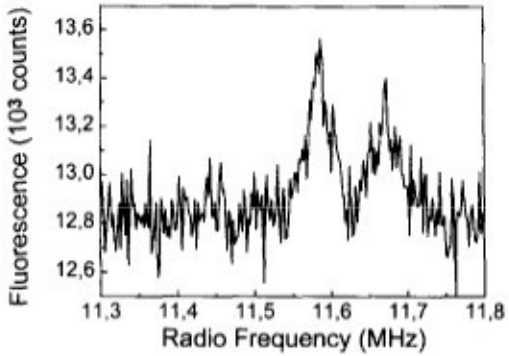

Fig. 3. ENDOR spectrum of a single molecule recorded with a microwave excitation at 1512 MHz, corresponding to the central peak in the ESR spectrum in Fig. 2. 3500 scans with a duration of 0.8 s have been accumulated.

Detecting Single Nuclear Spin

Observation of Coherent Oscillation of a Single Nuclear Spin and Realization of a Two-Qubit Conditional Quantum Gate

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(Received 12 February 2004; published 20 September 2004)

Rabi nutations of a single nuclear spin in a solid have been observed. The experiments were carried out on a single electron and a single ^{13}C nuclear spin of a single nitrogen-vacancy defect center in diamond. The system was used for implementation of quantum logical NOT and a conditional two-qubit gate (CROT). Density matrix tomography of the CROT gate shows that the gate fidelity achieved in our experiments is up to 0.9, good enough to be used in quantum algorithms.

DOI: 10.1103/PhysRevLett.93.130501 PACS numbers: 03.67.Lx, 03.65.Yz, 71.55.–i, 76.30.Mi

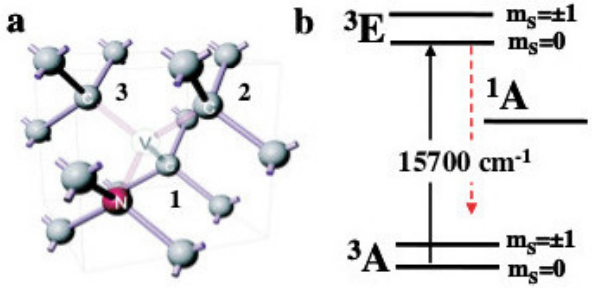

FIG. 1 (color online). (a) Atomic structure of the nitrogen-vacancy defect center. The numbers 1, 2, and 3 mark those carbon nuclei that have the largest hyperfine coupling to the electron spin of the defect center. (b) Scheme of electronic and spin energy levels of the nitrogen-vacancy center. Arrows indicate spin-selective excitation and fluorescence emission pathways.

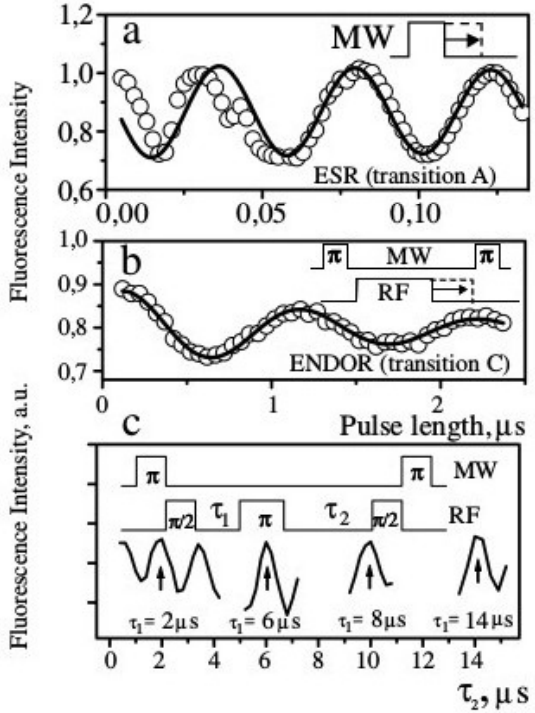

FIG. 3. Electron (a) and nuclear (b) spin transient nutations of a ^{13}C coupled nitrogen-vacancy defect. The fit function represents exponentially decaying harmonic oscillations. Deviation from the fit for short ESR pulses is related to pulse imperfections for short MW pulses. The insets show the applied pulse sequences. (c) Hahn echo of a single ^{13}C nuclear spin measured for different interpulse delays.

Single-shot Single Nucleus Measurement

Single-Shot Readout of a Single Nuclear Spin

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Projective measurement of single electron and nuclear spins has evolved from a gedanken experiment to a problem relevant for applications in atomic-scale technologies like quantum computing. Although several approaches allow for detection of a spin of single atoms and molecules, multiple repetitions of the experiment that are usually required for achieving a detectable signal obscure the intrinsic quantum nature of the spin's behavior. We demonstrated single-shot, projective measurement of a single nuclear spin in diamond using a quantum nondemolition measurement scheme, which allows real-time observation of an individual nuclear spin's state in a room-temperature solid. Such an ideal measurement is crucial for realization of, for example, quantum error correction protocols in a quantum register.

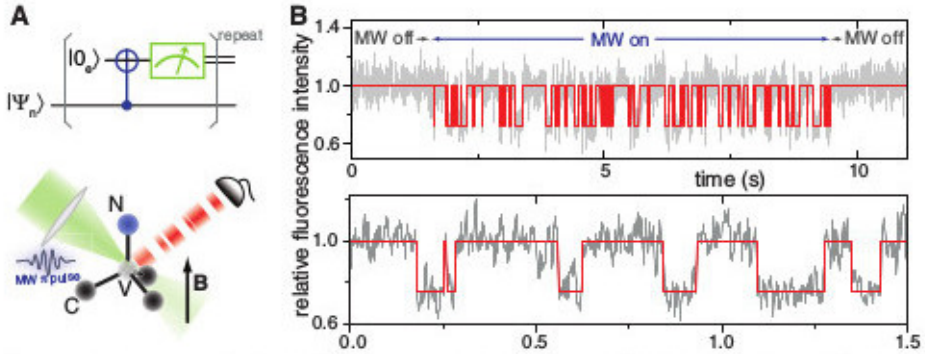

Fig. 1. Single-shot readout reveals quantum jumps of a single nuclear spin in real time. (**A**) Representation of the single-shot readout scheme. (**B**) Normalized fluorescence time traces (gray) showing quantum jumps of a single nuclear spin in real time. When MW pulses (controlled-NOT gates) are on, a telegraph-like signal appears, revealing the projective nature of this measurement. Low fluorescence intensity represents nuclear spin state $|-1_n\rangle$, and high fluorescence intensity indicates $|0_n\rangle$ or $|+1_n\rangle$. When MW pulses are off (upper trace), the fluorescence intensity remains high because it is not correlated with the nuclear spin state. Each data point was acquired by continuously repeating the readout scheme for 5 ms (2000 repetitions).

Neumann et al., Science **329**, 542 (2010)