

Quantum Mechanics

&

Quantum Materials

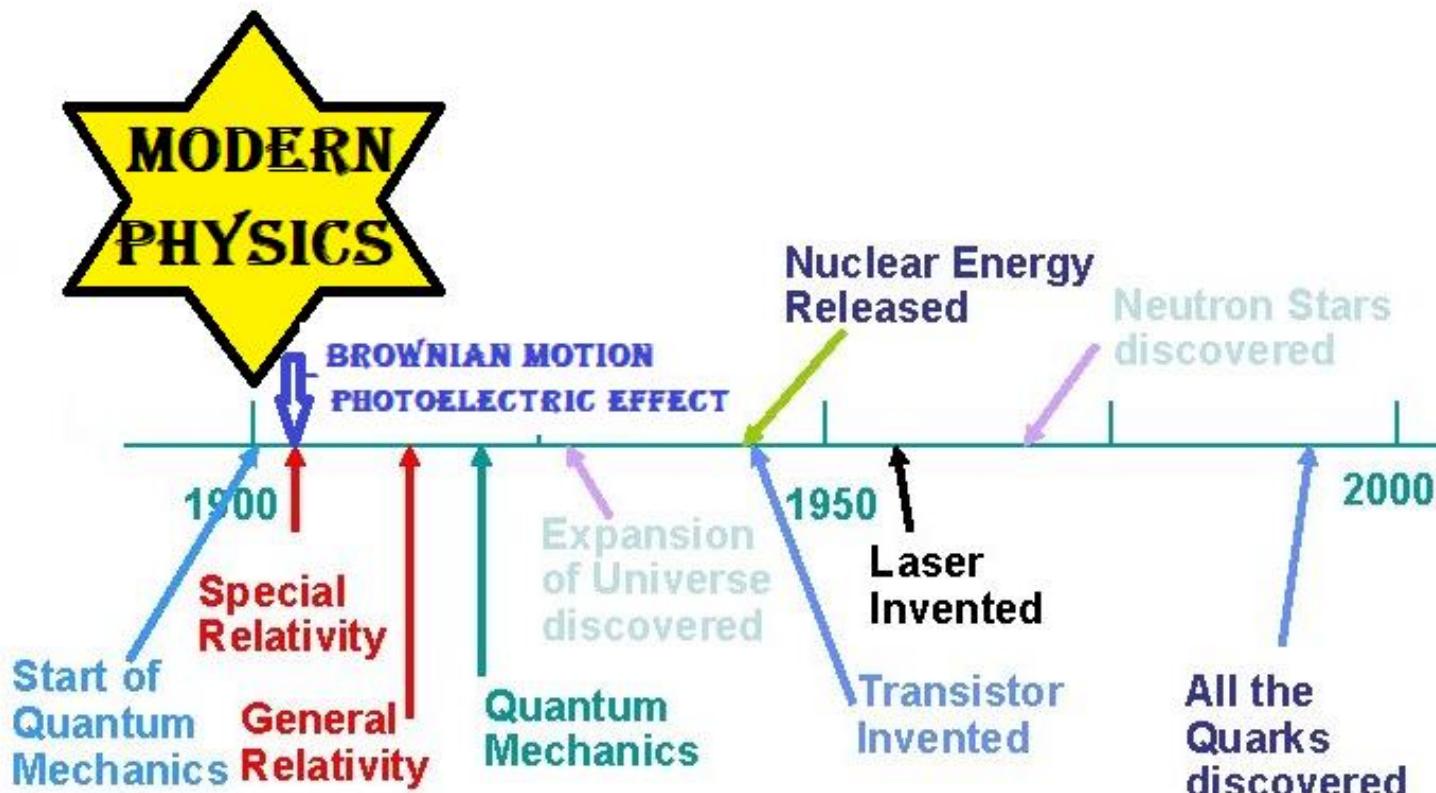
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Baltimore, Maryland, USA

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- **Quantum Mechanics Basics**
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 - **TMR (Tunneling Magnetoresistance)**
 - **Magnetostrictive Materials**
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Quantum Mechanics

- A branch of **modern physics** (20th century)



Modern physics was a sudden revolution that started in 1900

WHAT IS PHYSICS ?

A dense word cloud centered around the words "SPEED", "ENERGY", and "RADIO". Other prominent words include "frequency", "current", "power", "work", "acceleration", "wavelength", "sound", and "calculations". The words are in various colors and sizes, set against a white background.

Quantum Mechanics

- A **quantum** of energy is the amount of energy needed to move an electron from one energy level to another energy level.
(Refer to figure on the next page)
- **Mechanics** is the study of motion using the concept of space, time, mass and potential energy.
- **Quantum mechanics** is the mechanics of all types of particles.
- **Classical mechanics** is the mechanics of any type of particle with size \gg **atom**.

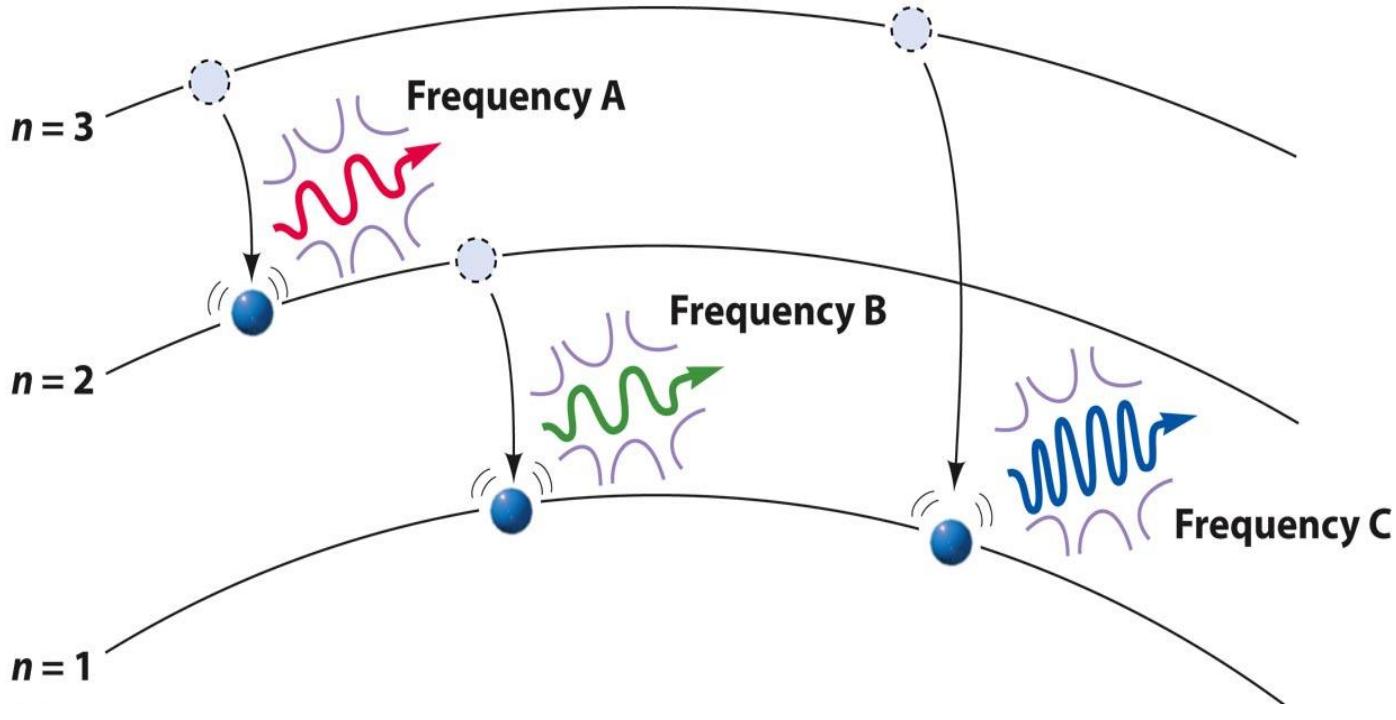


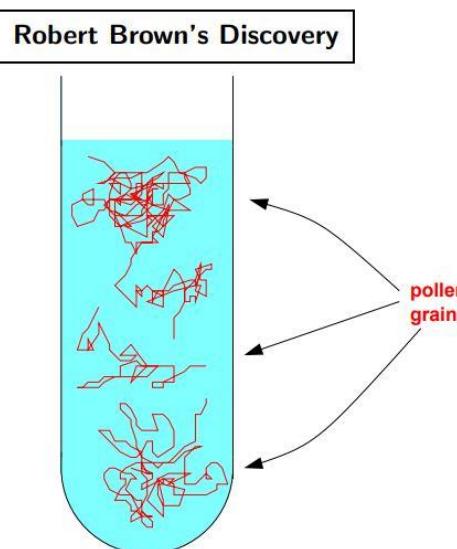
Figure: (Refer to figure on the next page)

A **quantum** of energy is the amount of energy needed to move an electron from one energy level to another energy level.

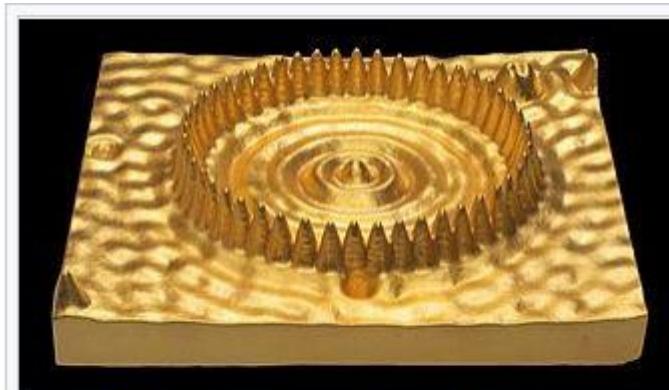
The degree to which they move from level to level determines the frequency of light they give off.

ATOM

- What is the universe made out of?
 - Prior to Democritu (450 BC) Earth, water, fire, wind, and void.
 - Democritus (450 BC) atoms & void
 - Indirect observation of atoms was through Brownian motion interpreted by A. Einstein (1905)



In 1827 Robert Brown, a Scottish botanist and curator of the British Museum, observed that pollen grains suspended in water, instead of remaining stationary or falling downwards, would trace out a random zig-zagging pattern. This process, which could be observed easily with a microscope, gained the name of **Brownian motion**.



The Well (Quantum Corral) (2009) by Julian Voss-Andreae. Created using the 1993 experimental data by Lutz *et al.*, the gilded sculpture was pictured in a 2009 review of the art exhibition "Quantum Objects" in the journal *Nature*.^[1]

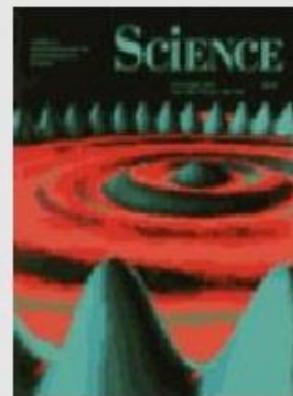
SHARE**REPORTS**

Confinement of Electrons to Quantum Corrals on a Metal Surface

M. F. Crommie¹, C. P. Lutz¹, D. M. Eigler¹

[+ See all authors and affiliations](#)

Science 08 Oct 1993;
Vol. 262, Issue 5131, pp. 218-220
DOI: 10.1126/science.262.5131.218

[Article](#)[Info & Metrics](#)**Science**

Vol 262, Issue 5131
08 October 1993

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Abstract

A method for confining electrons to artificial structures at the nanometer lengthscale is presented. Surface state electrons on a copper(111) surface were confined to closed structures (corrals) defined by barriers built from iron adatoms. The barriers were assembled by individually positioning iron adatoms with the tip of a 4-kelvin scanning tunneling microscope (STM). A circular corral of radius 71.3 Å was constructed in this way out of 48 iron adatoms. Tunneling spectroscopy performed inside of the corral revealed a series of discrete resonances, providing evidence for size quantization. STM images show that the corral's interior local density of states is dominated by the eigenstate density expected for an electron trapped in a round two-dimensional box.

An element can be identified by its emission spectra

When atoms absorb energy, electrons move into higher energy levels. These electrons then lose energy by emitting light when they return to lower energy levels.

Mercury



Nitrogen



The atomic theory of matter

HISTORY OF THE ATOM TIMELINE

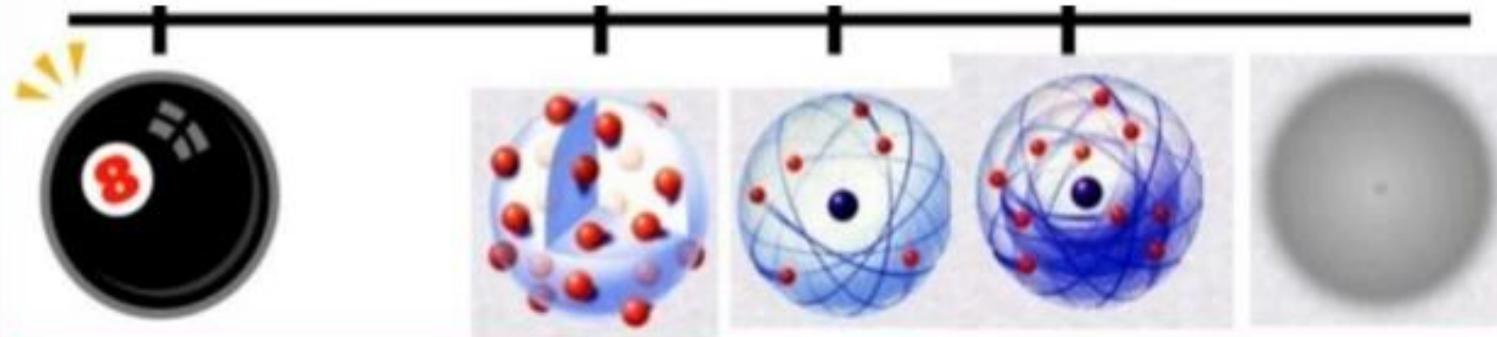
Democritus 460 BC
and Dalton 1803 AD

Thomson
1897

Rutherford
1912

Bohr
1913

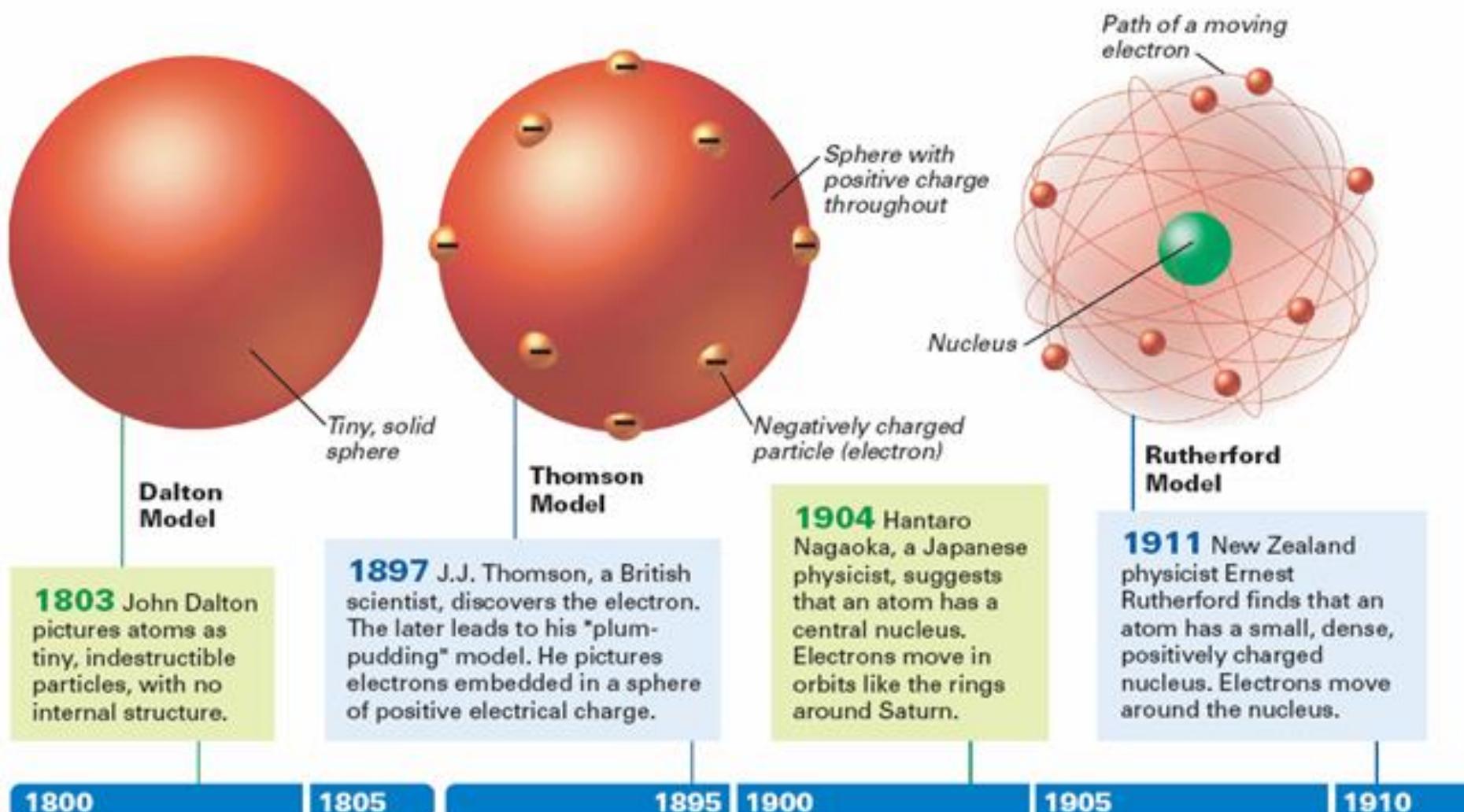
Modern
Quantum
Cloud Model
post 1930



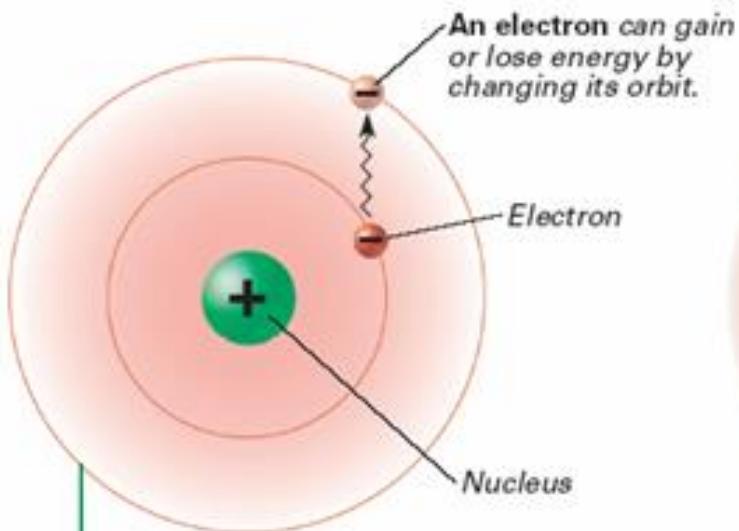
Democritus : the word atom, was coined by the ancient Greek philosopher in 460 B.C., the proposed Greek word atom, means **uncuttable**.

All **matter** in our **universe** is made of **atoms**.
Solids, liquids, and gasses are made up of **atoms**.

Atomic Model Timeline

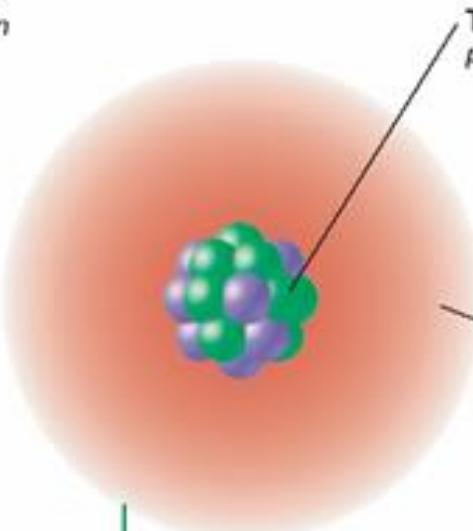


Atomic Model Timeline



Bohr Model

1913 In Niels Bohr's model, the electron moves in a circular orbit at fixed distances from the nucleus.



Electron Cloud Model

1923 French physicist Louis de Broglie proposes that moving particles like electrons have some properties of waves. Within a few years, experimental evidence supports the idea.

1926 Erwin Schrödinger develops mathematical equations to describe the motion of electrons in atoms. His work leads to the electron cloud model.

1932 James Chadwick, an English physicist, confirms the existence of neutrons, which have no charge. Atomic nuclei contain neutrons and positively charged protons.

1915

1920

1925

1930

1935

Applications

Classical Mechanics, Classical E&M, Thermodynamics & Statistical Mechanics, and Math Physics

Industrial revolution- engines, cars, planes, missiles, bridges, buildings, hydro-electric power, large ships, vacuum-valves electronics, radio, tv, ENIAC Computer, etc.

ENIAC (which meant "Electronic Numerical Integrator And **Computer**") was a **computer** built between 1943 and 1946 by a senior physicist with a young engineer helper. The machine was built out of nearly 17,500 vacuum tubes, 7,200 diodes and many miles of wire. It weighed about 27 tons, was 1 meter deep, 2.5 meters **tall**, and about 25 meters long. It covered 1,800 square feet (167 square meters) of floor space, weighed 30 tons, consumed 160 kilowatts of electrical **power**.

Quantum Mechanics and Relativistic Mechanics

Transistors, Microelectronics and photonics, digital technology, Information technology, world wide web (the internet), faster computers, smart phones, artificial satellites, faster and efficient (cars, planes, missiles, etc),

Applications

Future technologies that result directly from **Quantum Mechanics**

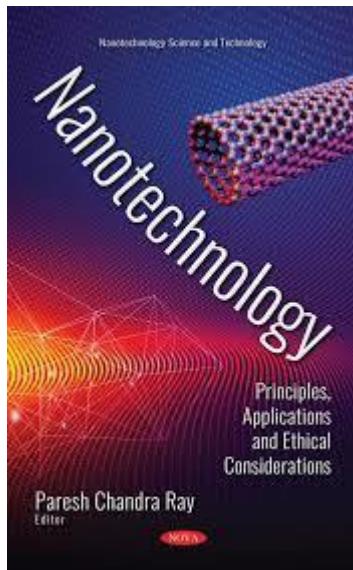
Quantum computer



Quantum teleportation



Nanotechnology



The wave-function

Wavefunction, $\Psi(x,t)$, which contain the information required to describe ALL of the dynamical properties of the particle.

$$|\Psi(x, t)|^2 dx = \left\{ \begin{array}{l} \text{probability of finding the particle} \\ \text{between } x \text{ and } (x + dx), \text{ at time } t. \end{array} \right\}$$

Where $|\Psi(x,t)|^2 = \Psi^*(x,t) \Psi(x,t)$

The wave-function

$$\langle x \rangle = \int_{-\infty}^{+\infty} x |\Psi(x, t)|^2 dx.$$

Expectation value of position of the particle

$$\langle p \rangle = m \frac{d \langle x \rangle}{dt} = -i\hbar \int \left(\Psi^* \frac{\partial \Psi}{\partial x} \right) dx.$$

Expectation value of momentum
of the particle

$$\langle T \rangle = \frac{-\hbar^2}{2m} \int \Psi^* \frac{\partial^2 \Psi}{\partial x^2} dx.$$

Expectation value of kinetic energy
of the particle

$$\langle Q(x, p) \rangle = \int \Psi^* Q(x, \frac{\hbar}{i} \frac{\partial}{\partial x}) \Psi dx.$$

Expectation value of any dynamical
Variable Q of the particle

$$\sigma_x \sigma_p \geq \frac{\hbar}{2},$$

The uncertainty principle

where $\sigma^2 \equiv \langle (\Delta x)^2 \rangle = \langle x^2 \rangle - \langle x \rangle^2$.

The Schrödinger Equation

- Rutherford's and Bohr's model focused on describing the path of the electron around the nucleus like a particle (like a small baseball).
- Austrian physicist **Erwin Schrödinger (1887–1961)** treated the electron as a wave.
 - The modern description of the electrons in atoms, the **quantum mechanical model**, comes from the mathematical solutions to the Schrödinger equation.

Schrödinger Equation

$$\hat{H} \psi = E \psi$$

1-D Schroedinger Equation

$$E \psi(x,t) = H \psi(x,t)$$

$$H = P^2/2m + V(x)$$

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi.$$

$\psi(x,t)$

Schroedinger: If electrons are waves, their position and motion in space must obey a wave equation.

Solutions of wave equations yield wave functions, Ψ , which contain the information required to describe ALL of the dynamical properties of the particle.

Provides a picture of the electronic distributions of the electrons about the nucleus of an atom and about the connected nuclei of a molecule.

The time independent Schrödinger Equation

If \mathbf{V} the potential energy only depends spatially (that is, ie, $\mathbf{V}(\mathbf{x})$), then separation of variables is possible:

$$\psi(x,t) = \phi(x)f(t)$$

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi.$$

Schrödinger Equation

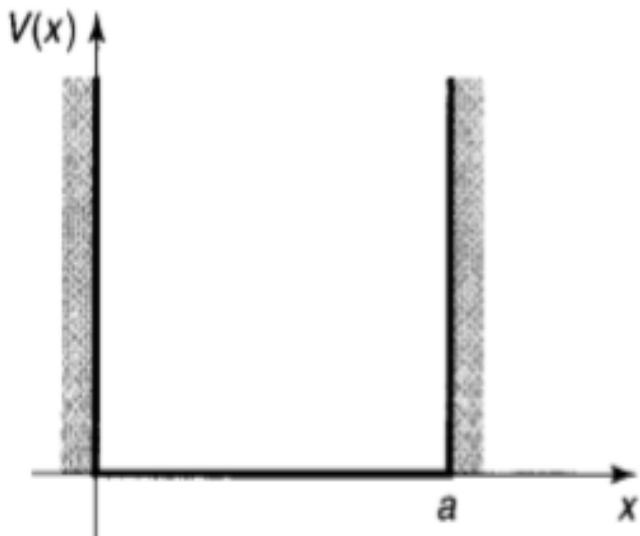
$$E \phi(x) = -\frac{\hbar^2}{2m} \frac{\partial^2 \phi(x)}{\partial x^2} + V\phi(x)$$

Time Independent
Schrödinger Equation

$$f(t) = e^{-iEt/\hbar}$$

A Particle in an Infinite Square Well Potential

$$V(x) = \begin{cases} 0, & \text{if } 0 \leq x \leq a, \\ \infty, & \text{otherwise} \end{cases}$$



$$-\frac{\hbar^2}{2m} \frac{d^2 \phi(x)}{dx^2} = E \phi(x)$$

$$\phi(x) = A \sin(kx) + B \cos(kx)$$

Boundary conditions

$$B=0 \text{ and } ka=n\pi$$

$$\phi_n(x) = A \sin\left(\frac{n\pi x}{a}\right)$$

Normalization

$$A = \sqrt{\left(\frac{2}{a}\right)}$$

$$\phi_n(x) = \sqrt{\left(\frac{2}{a}\right)} \sin\left(\frac{n\pi x}{a}\right)$$

From one of the boundary conditions, $ka=n\pi$

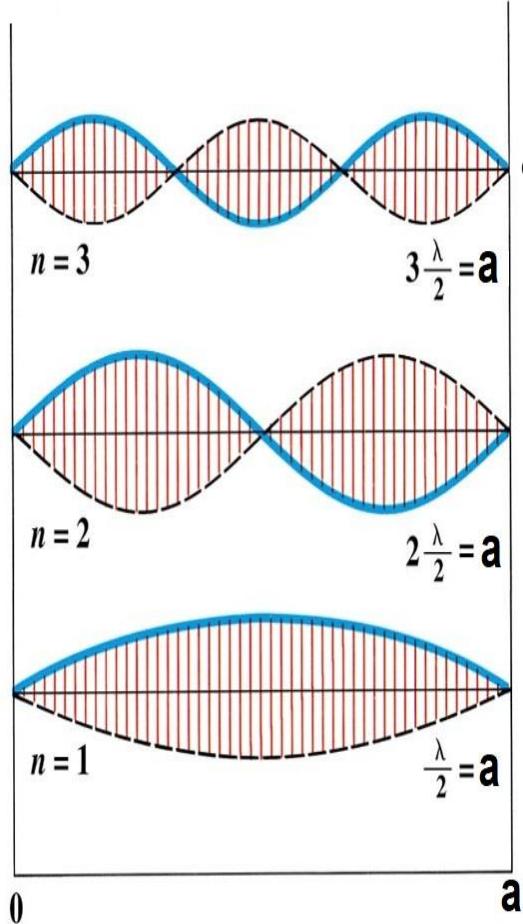
$$E_n = \left(\frac{n\pi\hbar}{a}\right)^2 \frac{1}{2m}$$

A Particle in an Infinite Square Well Potential

$$E_3 = \left(\frac{3\pi\hbar}{a}\right)^2 \frac{1}{2m} = 9E_1$$

$$E_2 = \left(\frac{2\pi\hbar}{a}\right)^2 \frac{1}{2m} = 4E_1$$

$$E_1 = \left(\frac{\pi\hbar}{a}\right)^2 \frac{1}{2m}$$



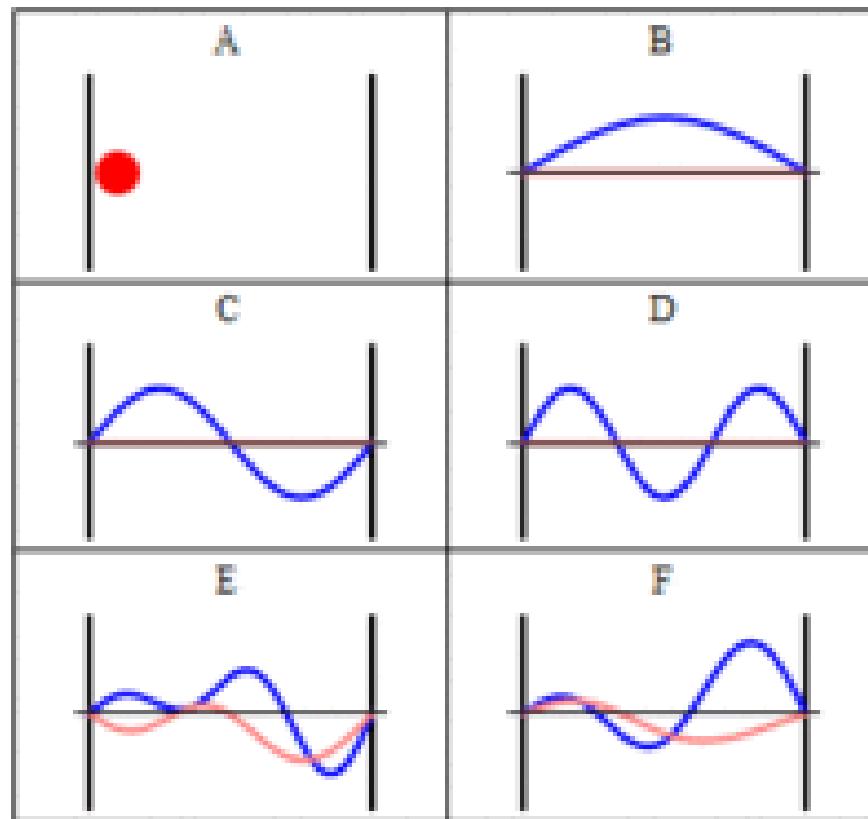
$$\phi_3(x) = \sqrt{\left(\frac{2}{a}\right)} \sin\left(\frac{3\pi x}{a}\right)$$

$$\phi_2(x) = \sqrt{\left(\frac{2}{a}\right)} \sin\left(\frac{2\pi x}{a}\right)$$

$$\phi_1(x) = \sqrt{\left(\frac{2}{a}\right)} \sin\left(\frac{\pi x}{a}\right)$$

- $\phi_1(x)$ is ground state and $n > 1$ is excited state
- $\phi_n(x)$ alternatively even or odd
- $\phi_n(x)$ each successive state has one more node
- $\phi_n(x)$ are mutually orthonormal (orthogonal and normalized)
- $\phi_n(x)$ are complete (any $\phi(x)$ can be expressed as a linear combination
 $\phi(x) = \sum_n c_n \phi_n(x)$)

A Particle in an Infinite Square Well Potential



The Harmonic Oscillator

Classical Harmonic Oscillator

The 2nd law of motion

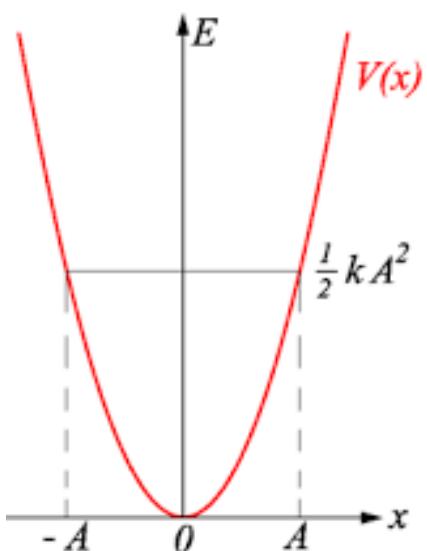
$$F = -kx = m \frac{d^2x}{dt^2}$$

$$X(t) = A \sin(\omega t) + B \cos(\omega t)$$

$$\omega = \sqrt{\left(\frac{k}{m}\right)}$$

$$V(x) = \frac{1}{2} kx^2$$

$$V(x) = \frac{1}{2} m\omega^2 x^2$$



Quantum Harmonic Oscillator

The Schrödinger Equation

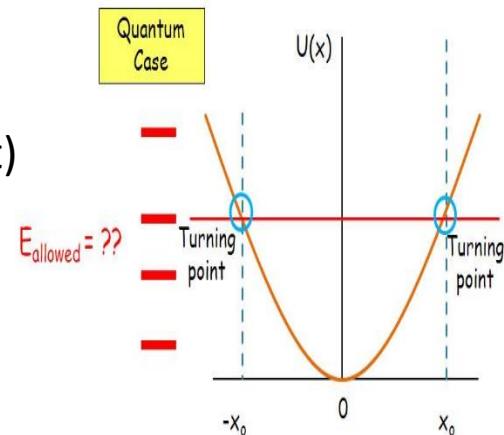
$$H\psi(x,t) = E\psi(x,t)$$

$$H = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2$$

$$-\frac{\hbar^2}{2m} \frac{d^2\phi(x)}{dx^2} + 0.5 m\omega^2 x^2 \phi(x) = E\phi(x)$$

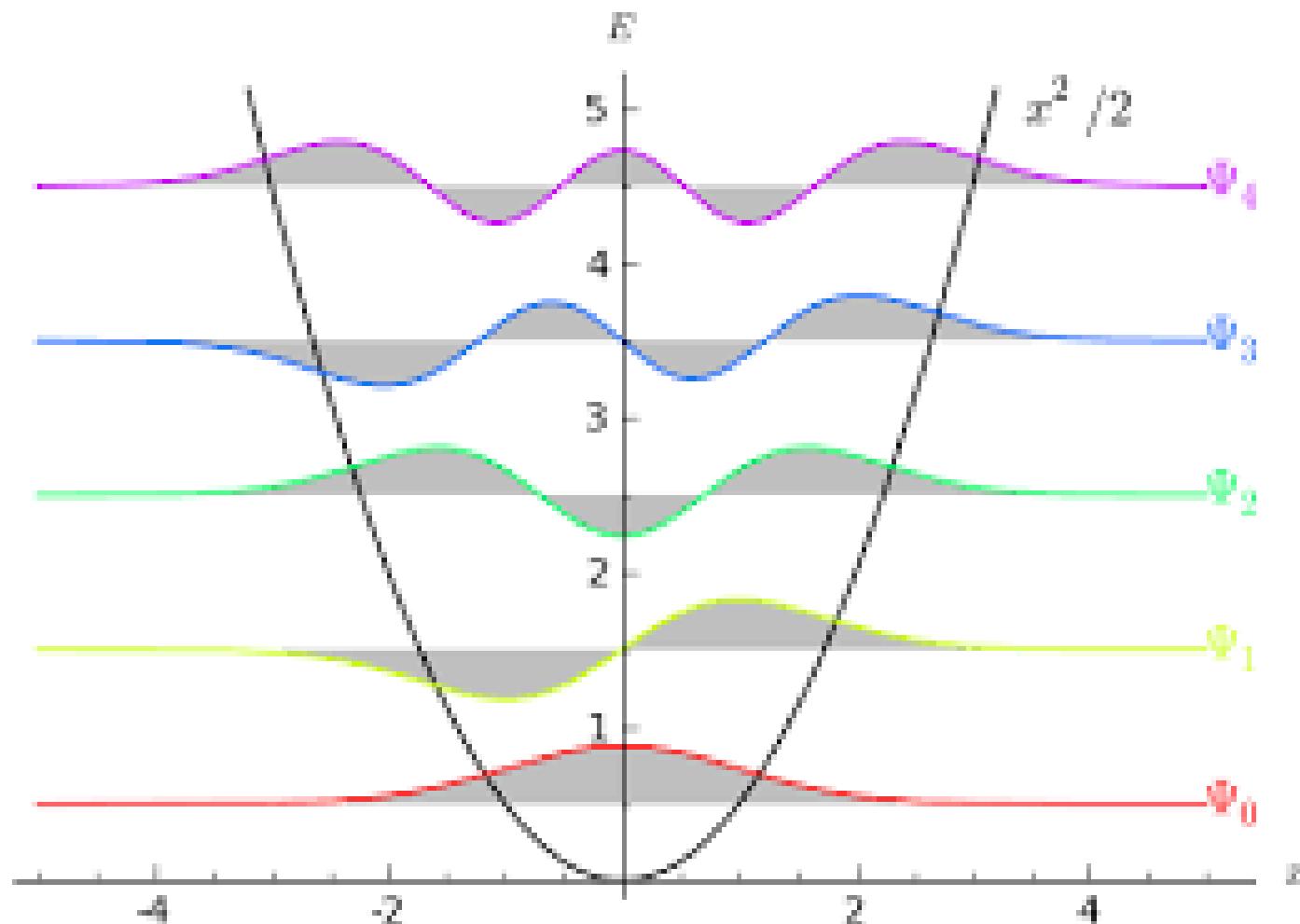
$$f(t) = e^{-iEt/\hbar}$$

$$\psi(x,t) = \phi(x)f(t)$$

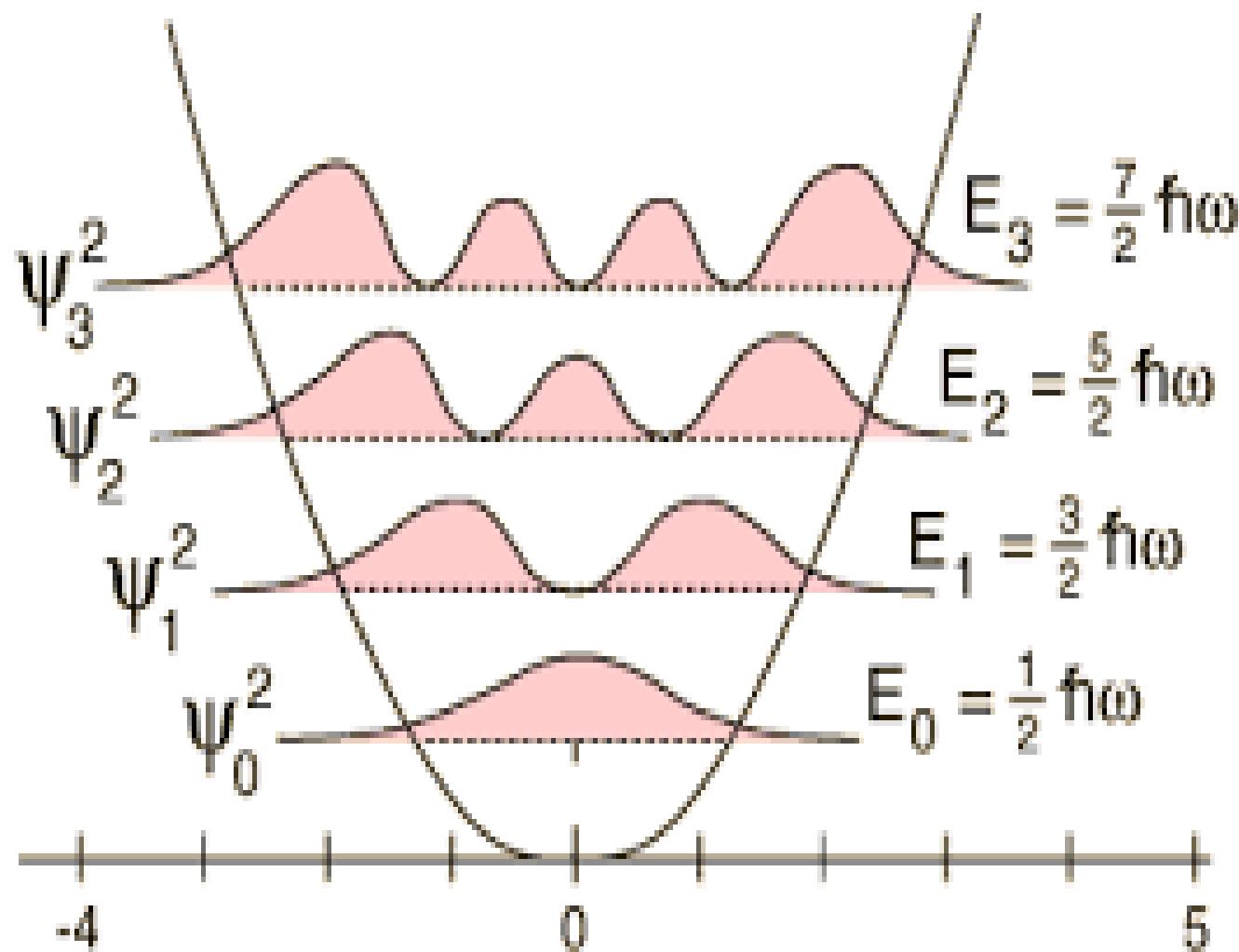


The Quantum Harmonic Oscillator (cont.)

$$E_n = (n + \frac{1}{2}) \hbar\omega$$

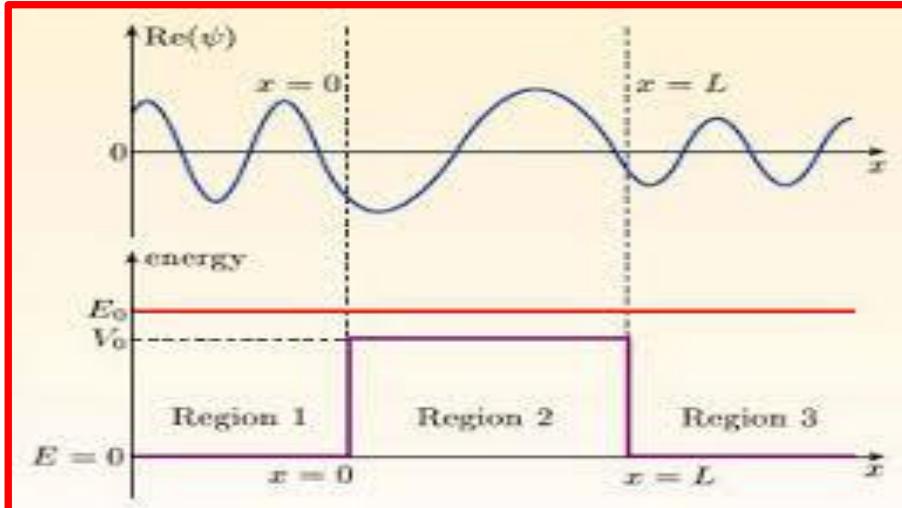


The Quantum Harmonic Oscillator (cont.)



The Scattering Matrix

The theory of scattering generalizes in a pretty obvious way to arbitrary localized potentials.



Scattering from an arbitrary localized potential ($V(x)$ except in Region II).

$$\phi(x) = \begin{cases} Ae^{ikx} + Be^{-ikx} & \text{Region 1} \\ Cf(x) + Dg(x) & \text{Region 2} \\ Fe^{ikx} + Ge^{-ikx} & \text{Region 3} \end{cases} \quad \begin{matrix} V=0 \\ V \neq 0 \\ V=0 \end{matrix} \quad \text{where } k = \sqrt{2mE/\hbar^2}$$

$$\begin{aligned} A + B &= Cf(0) + Dg(0) \\ iK(A - B) &= Cf'(0) + Dg'(0) \\ F + G &= Cf(a) + Dg(a) \\ iK(F - G) &= Cf'(a) + Dg'(a) \end{aligned}$$

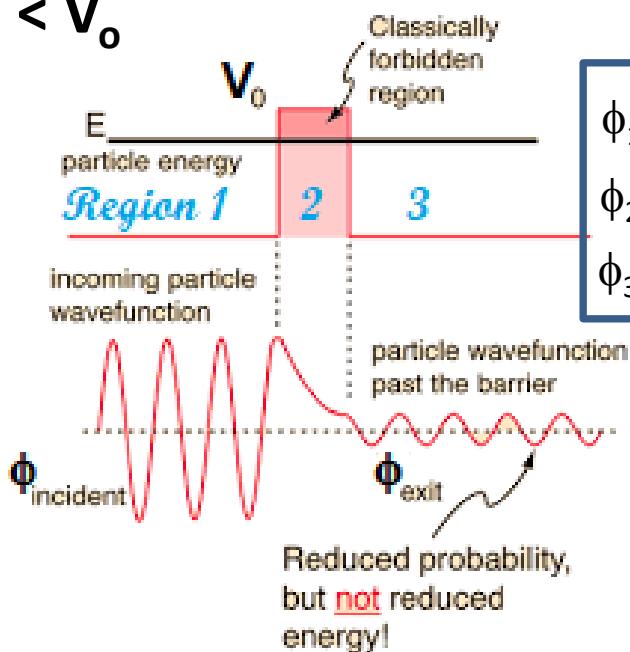
$$\Rightarrow \begin{aligned} B &= S_{11}A + S_{12}G \\ F &= S_{21}A + S_{22}G \end{aligned} \Rightarrow$$

$$\begin{pmatrix} B \\ F \end{pmatrix} = S \begin{pmatrix} A \\ G \end{pmatrix}$$

$$S = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}$$

The Scattering Matrix (Cont.)

$$0 < E < V_0$$



$\phi_1 = Ae^{ikx} + Be^{-ikx}$	<i>Region 1</i>	$V=0$	where $k=\sqrt{2mE/\hbar^2}$
$\phi_2 = Ce^{\gamma x} + De^{-\gamma x}$	<i>Region 2</i>	$V \neq 0$	where $\gamma=\sqrt{2m(V_0-E)/\hbar^2}$
$\phi_3 = Ee^{ikx}$	<i>Region 3</i>	$V=0$	where $k=\sqrt{2mE/\hbar^2}$

$$\phi_1|_{x=-a} = \phi_2|_{x=-a} \Rightarrow Ae^{-iKa} + Be^{iKa} = Ce^{-\gamma a} + De^{\gamma a}$$

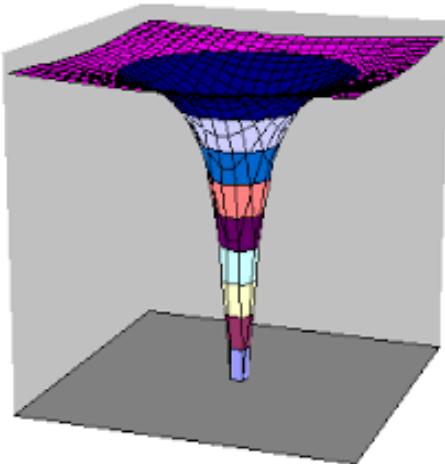
$$\phi'_1|_{x=-a} = \phi'_2|_{x=-a} \Rightarrow iK(Ae^{-iKa} - Be^{iKa}) = \gamma(Ce^{-\gamma a} - De^{\gamma a})$$

$$\phi_3|_{x=a} = \phi_2|_{x=a} \Rightarrow Ee^{iKa} = Ce^{\gamma a} + De^{-\gamma a}$$

$$\phi'_3|_{x=a} = \phi'_2|_{x=a} \Rightarrow iK(Ee^{iKa}) = \gamma(Ce^{\gamma a} - De^{-\gamma a})$$

$\phi_1 = Ae^{ikx} + Be^{-ikx}$	<i>Region 1</i>	$(x < -a)$	$V=0$	where $k=\sqrt{2mE/\hbar^2}$
$\phi_2 = C\sin(\gamma x) + D\cos(-\gamma x)$	<i>Region 2</i>	$(-a < x < a)$	$V \neq 0$	where $\gamma=\sqrt{2m(V_0-E)/\hbar^2}$
$\phi_3 = Fe^{ikx}$	<i>Region 3</i>	$(x > a)$	$V=0$	where $k=\sqrt{2mE/\hbar^2}$

WAVE EQUATION IN 3D



$$\mathbf{E}\Psi(\mathbf{r},t) = \mathbf{H}\Psi(\mathbf{r},t)$$

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V(r)\psi$$

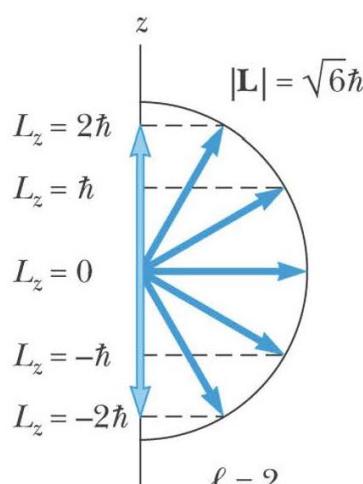
Normalization

$$\int \Psi^*(\mathbf{r},t) \Psi(\mathbf{r},t) dV = 1$$

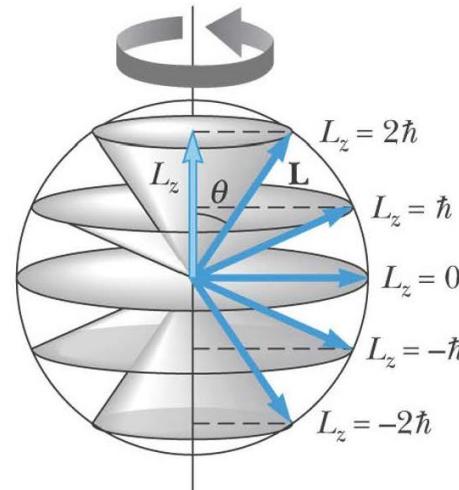
Angular momentum values

Angular momentum is quantized:

$$|\mathbf{L}| = \hbar \sqrt{l(l+1)} ; \quad l_z = \hbar m = -\hbar l, \dots, \hbar l$$



(a)



(b)

SPIN

Orbital $\mathbf{L} = \mathbf{r} \times \mathbf{P}$ motion of center of mass
 Spin $\mathbf{S} = I\omega$ **motion about center of mass**
 Quantum Mechanics intrinsic & extrinsic
 $[S_i, S_j] = i\hbar S_k$

$$\mathbf{S}^2 |sm\rangle = \hbar^2 s(s+1) |sm\rangle$$

$$S_z |sm\rangle = \hbar m |sm\rangle$$

$$S_{\pm} |sm\rangle = \hbar \sqrt{(s(s+1)-m(m\pm 1))} |s (m\pm 1)\rangle$$

$$S_{\pm} = S_x \pm iS_y$$

$$S=0, 1/2, 3/2, 5/2, \dots$$

$$m = -s, -s+1, \dots, s-1, s$$

Spin of π -meson is 0, electron (e) is $1/2$, photon (ν) is 1, δ -particle is $3/2$, and graviton (g) is 2

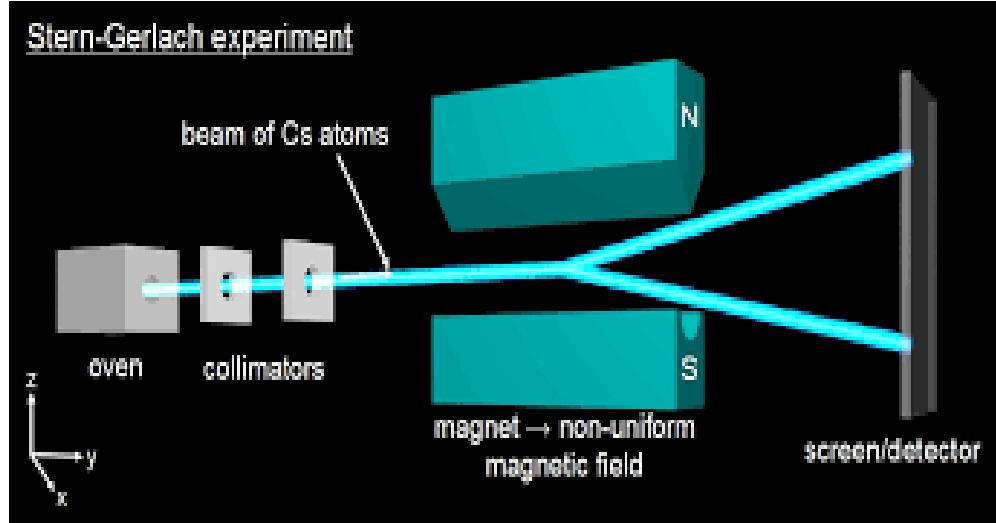
Spin $1/2$ particle

$S = 1/2$ (proton, neutron, electron, all quarks, and all leptons)

$|1/2 \ 1/2\rangle$ spin-up \uparrow

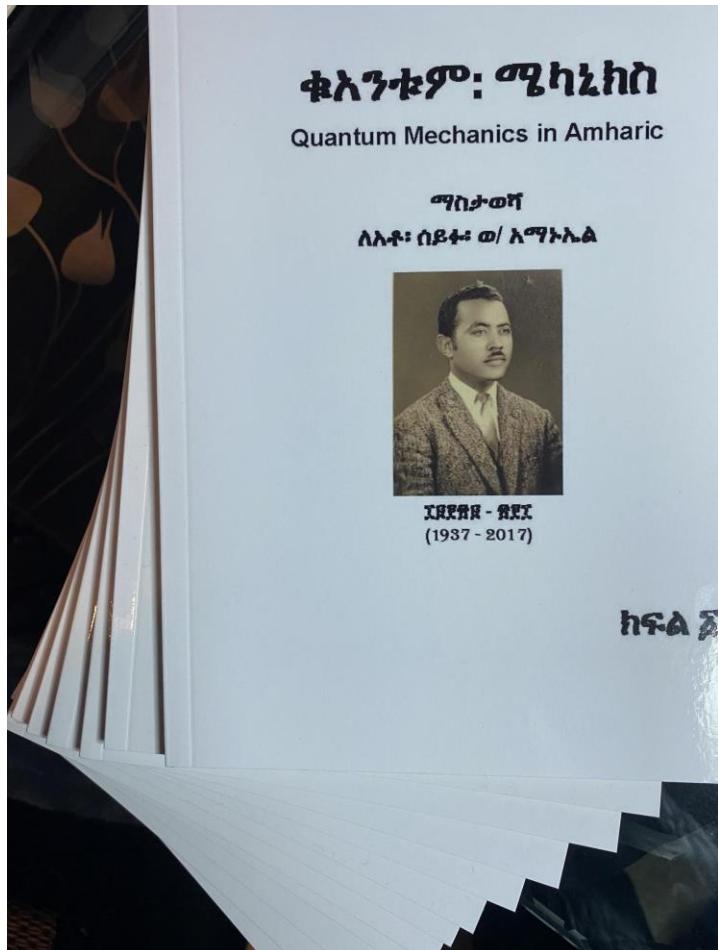
$|1/2 \ -1/2\rangle$ spin-down \downarrow

$$\text{Spinor } \chi = \begin{pmatrix} a \\ b \end{pmatrix} = a\chi_+ + b\chi_- \text{ where } \chi_+ = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \chi_- = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



Quantum Mechanics Book in Amharic

Einstein Project in Africa



Quantum Mechanics in Amharic Paperback – October 8, 2020

by Dereje Seifu (Author)

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Quantum Mechanics in Amharic, to my knowledge, is the first book on quantum mechanics to use the rich expressions of the Amharic language, which has a long history. Since the late twentieth century, Amharic has been the working language of Ethiopia's courts, military, trade, and daily communication, and it remains the country's official language. The recent census indicates that there are 22 million native Amharic speakers and 4 million secondary speakers in Ethiopia. There are also over 3 million Amharic-speaking emigrants outside Ethiopia. The Ethiopian Jewish communities in Ethiopia and Israel as well as the Ethiopian diaspora in and around Washington, D.C. speak Amharic. Amharic is one of the six non-English languages included in Washington's Language Access Act of 2004, thus ensuring citizens access to government services and education in Amharic. While Ethiopian Christians regard Ge'ez—Amharic's root language—as holy, Amharic is the holy language of the Rastafarian religion and is widely used by its followers worldwide. The script of the Amharic language is known as an abugida, and the graphemes of its writing system are called fidel. These graphemes are displayed on the last page of Quantum Mechanics in Amharic surrounded by the green, yellow, and red of the original Ethiopian flag, which remains an icon of freedom because Ethiopia is the only non-colonized nation in Africa. Each fidel, which represents a consonant and vowel sequence, has a shape determined by its consonant and modified by its vowel.

The primary language of quantum mechanics, one of the many branches of physics, is mathematics. However, everyday language is required to explain in depth the laws of physics that are presented using mathematical expressions. The book's introduction briefly describes the historical roots of quantum mechanics, starting with natural philosophy from 400 BG. Although some civilizations, such as Ethiopia's Aksumite civilization, date well before this to 3000 BC, there are some indications of knowledge transfer from earlier civilizations to more recent ones. The book then follows the historical timeline through the present state of quantum mechanics, describing several interesting phenomena that can only be explained using quantum mechanics, such as quantum tunneling, causality, the nature of reality, duality, entanglement, superposition, and quantum scattering. The first three of these are described in detail. The first chapter briefly explains the underlying physics essential to understanding quantum mechanics. It also explores some current quantum mechanics research and potential future applications, including quantum computers, quantum teleportation, and nano-science/technology. The second chapter presents the Schrödinger equation and the wave function, including wave-particle duality. The third chapter introduces readers to the time-independent Schrödinger equation and its applications in solving the state of a one-dimensional particle in five different potentials. The end of the book includes translations of over 130 words and lists a few useful references. Readers are given exercises to complete throughout the book, including proofs after example proofs are presented.

Books such as Quantum Mechanics in Amharic that are written in indigenous languages on advanced topics will be useful for the Einstein Project in Africa. It has been over a century since 1905, the so-called "Miracle Year" of Einstein, and the world has not since witnessed another scientist of his caliber. It is possible that his successor will be a child in Africa who does not have access to modern education. Science books in indigenous languages may help lift this barrier.

Quantum Mechanics
Phys 528

1- The wave function of an electron in an infinite potential well of width L is given by

$$\psi(x) = A \sin \frac{4\pi x}{L}$$

- a) Find the normalization constant A.
- b) What is the energy corresponding to this state?
- c) Sketch the above wave function.

2- A particle in the harmonic oscillator potential has an initial wave function, $\psi(x, 0)$, for some constant A.

$$\psi(x, 0) = A[\phi_1(x) + \phi_2(x) + 3 \phi_3(x)]$$

- a) Find A by normalizing $\psi(x, 0)$.
- b) Find the probability the particle is found in the ground state.
- c) Find the expectation value of the position of the particle, $\langle x \rangle$.

3- A one-dimensional harmonic oscillator wave function is

$$\psi(x) = Axe^{-bx^2}$$

- a) Find the total energy E.
- b) Find the constant b.
- c) Find the normalization constant A.

4- For the Hamiltonian matrix H :
$$H = \frac{\hbar}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

- a) Find its eigenvalues
- b) Find the corresponding eigenvectors

5- What is the up-to-date interpretation of the wave function $\psi(x, t)$, solution of the Schrödinger equation?

- 6- The complete set expansion of an initial wave function $\Psi(x,0)$ of a system in terms of energy eigenfunctions Y_n of the system has three terms: that is, $n=1, 2$, and 3 . The measurement of energy on the system represented by $\Psi(x,0)$ gives the values E_1 and E_2 with probability $\frac{1}{3}$ and E_3 with probability $\frac{1}{2}$. Write down the most general expansion of

a. $\Psi(x,0)$

b. $\Psi(x,t)$

- 7- A one-dimensional potential barrier is shown in Figure 1. Calculate the transmission coefficient for particles of mass m and energy E ($V_1 < E < V_0$) incident on the barrier from the left.

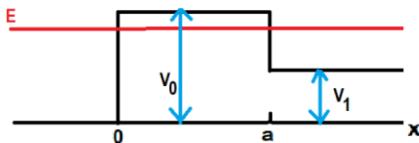


Figure 1

- 8- Consider a 3-D harmonic oscillator shown in Figure 2, with potential $V(r) = \frac{1}{2}m\omega^2r^2$.
Find the

a. Find the energy E_n

b. Find the corresponding degeneracy $d(n)$.

c. Find $\langle r \rangle$ and $\langle r^2 \rangle$.

d. Find $\langle x \rangle$ and $\langle x^2 \rangle$.

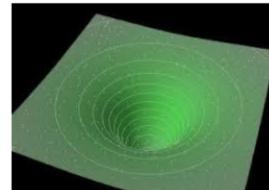


Figure 2

- 9- Why is the ground state energy of a harmonic oscillator non-zero.

10- Calculate the following commutator

a. $[H, t]$, where H is the Hamiltonian given by $H = \frac{P^2}{2m} + V$.

b. $[H, t]$, where H is the Hamiltonian given by $H = i\hbar \frac{\partial}{\partial t}$

- c. Explain the apparent contradiction as to why part a and b give two very different answers for the same commutator.

- 1- Consider a finite square barrier potential shown below, Figure A.
 For $a < x < b$, the space part of the electron wave function has the form:
 $k^2 = 2mE/\hbar^2$ and $g^2 = 2m(V_0 - E)/\hbar^2$
 (a) Ae^{ikx} (b) Ae^{-ikx} (c) $Ae^{ix} + Be^{ix}$ (d) $Ae^{ix} - Be^{-ix}$ (e) $Ae^{ikx} + Be^{-ikx}$
- 2- For the finite square barrier potential shown below, Figure A.
 For $x < a$, the space part of the electron wave function has the form:
 $k^2 = 2mE/\hbar^2$ and $g^2 = 2m(V_0 - E)/\hbar^2$
 (a) Ae^{ikx} (b) Ae^{-ikx} (c) $Ae^{ix} + Be^{ix}$ (d) $Ae^{ix} - Be^{-ix}$ (e) $Ae^{ikx} + Be^{-ikx}$
- 3- Consider a step potential shown in Figure B. Which of the following statement is correct for a particle with $E < 0$.
 (a) The form of the wave function to the left is e^{ikx} , where $k^2 = 2mE/\hbar^2$.
 (b) The form of the wave function to the left is e^{igx} where $g^2 = 2m(V_0 - E)/\hbar^2$.
 (c) There is no bound state.
 (d) All of the above.
 (e) None of the above.
- 4- If the particle energy E was $0 < E < V_0$ for the step potential shown in Figure B. Which of the following statement is correct.
 (a) The form of the wave function to the left is e^{ikx} , where $k^2 = 2mE/\hbar^2$.
 (b) The form of the wave function to the left is e^{igx} where $g^2 = 2m(V_0 - E)/\hbar^2$.
 (c) There is no bound state.
 (d) All of the above.
 (e) None of the above.
- 5- The wave function of a particle in a harmonic oscillator potential is given by $\Psi(x) = c_1 \Psi_1 + c_2 \Psi_2 + c_3 \Psi_3$, where Ψ_i are eigen-states of a harmonic oscillator Hamiltonian. What is the probability that measurement of the particle energy yields a value E_1 , eigen-value corresponding to the eigen-state Ψ_1
 (a) c_1 (b) c_1^2 (c) $c_1/(c_1+c_2+c_3)$ (d) $c_1 c_2 c_3$ (e) $c_1^2/(c_1+c_2+c_3)^2$
- 6- The accepted interpretation of a particles wave function $\Psi(x,t)$ is $|\Psi(x,t)|^2 dx$ is the probability the particle is between x and $x+dx$ at time t
 (a) True (b) False
- 7- $\partial/\partial t (\Psi^*(x,t) \Psi(x,t) dx) = 0$. This statement is
 (a) True (b) False
- 8- $\int (\Psi^*(x,t) \Psi(x,t) dx) = 1$. This statement is
 (a) True (b) False
- 9- If the ground state energy of a quantum harmonic oscillator was zero it would have violated
 (a) The Principle of Conservation of Energy
 (b) The Principle of Conservation of Angular Momentum
 (c) The Uncertainty Principle
 (d) All of the above
 (e) None of the above
- 10- If the commutator of two operators A and B is zero, that is $[A, B] = 0$, then one can conclude
 (a) The two operators can be measured simultaneously.
 (b) The two operators have mutual eigenvectors that will diagonalize them.
 (c) $AB = BA$
 (d) All of the above.
 (e) None of the above.

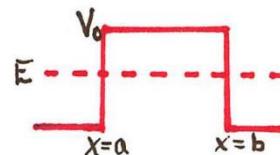


Figure A

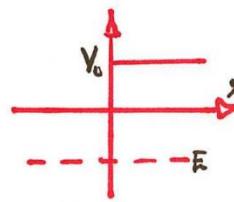


Figure B

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- **Quantum Mechanics Basics**
- **Quantum Materials**
 - **TMR (Tunneling Magnetoresistance)**
 - **MagnetostRICTIVE MATERIALS**
 - **Lower dimensional materials**



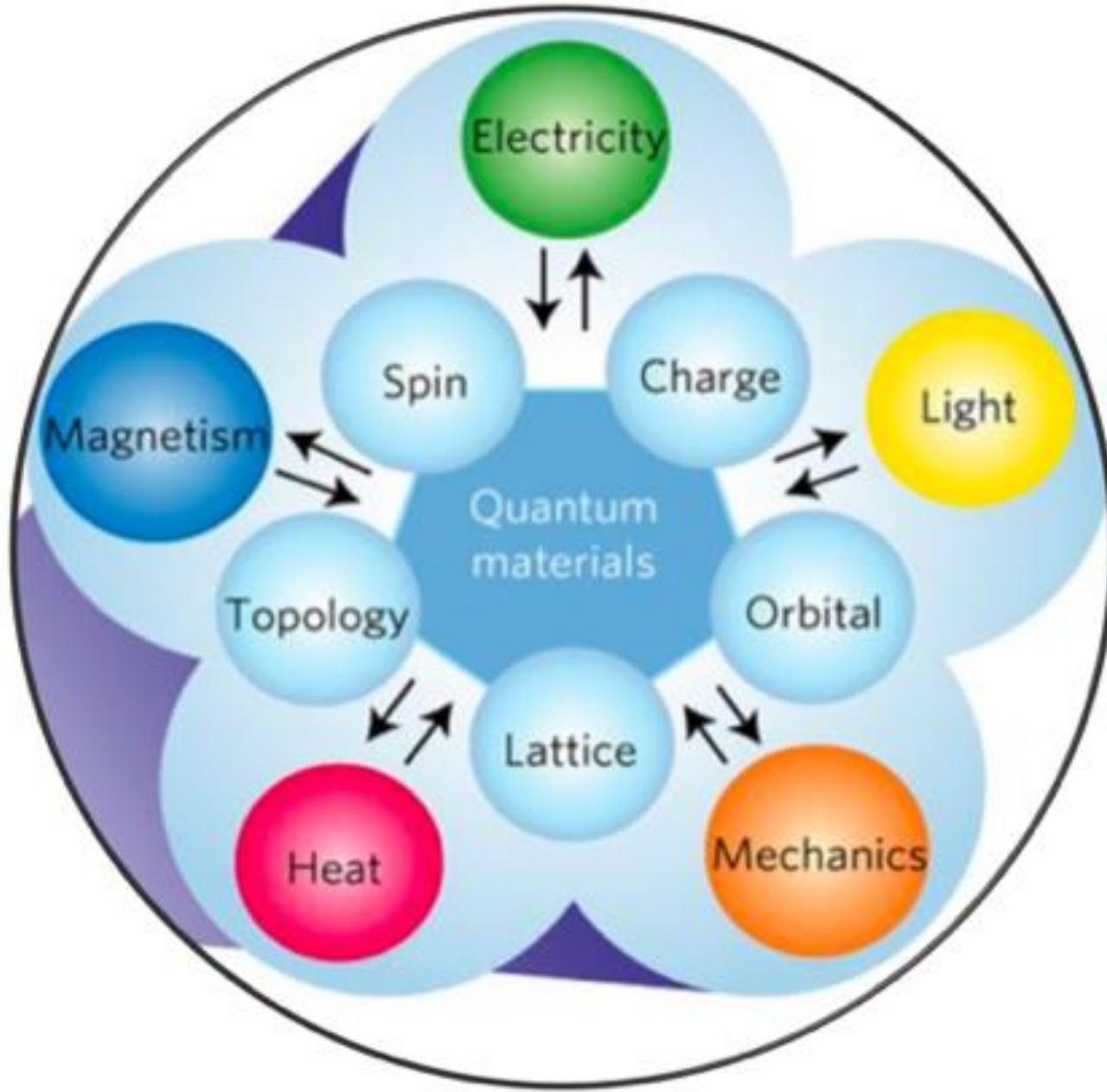
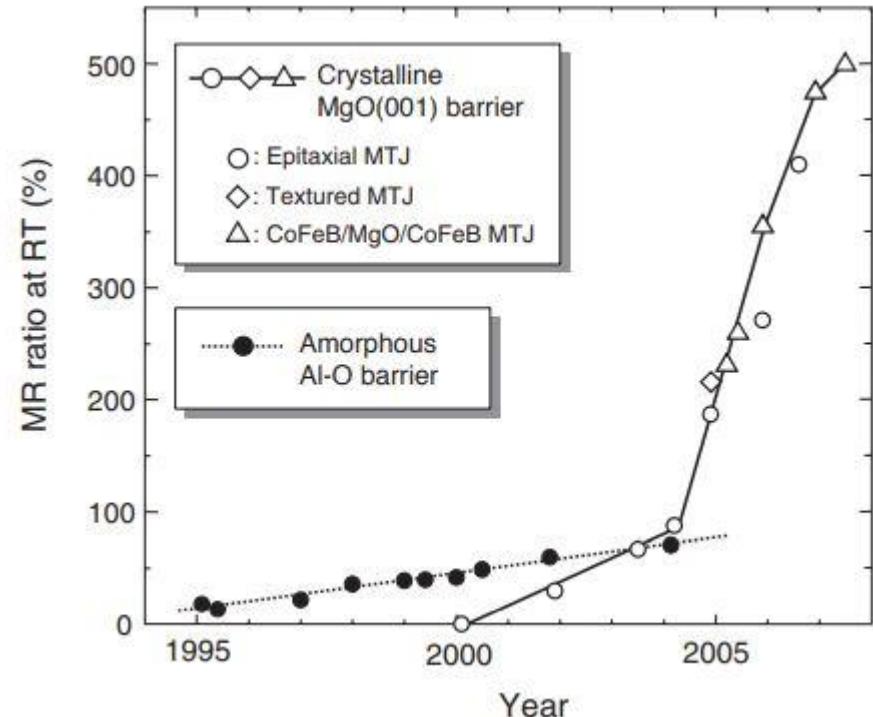
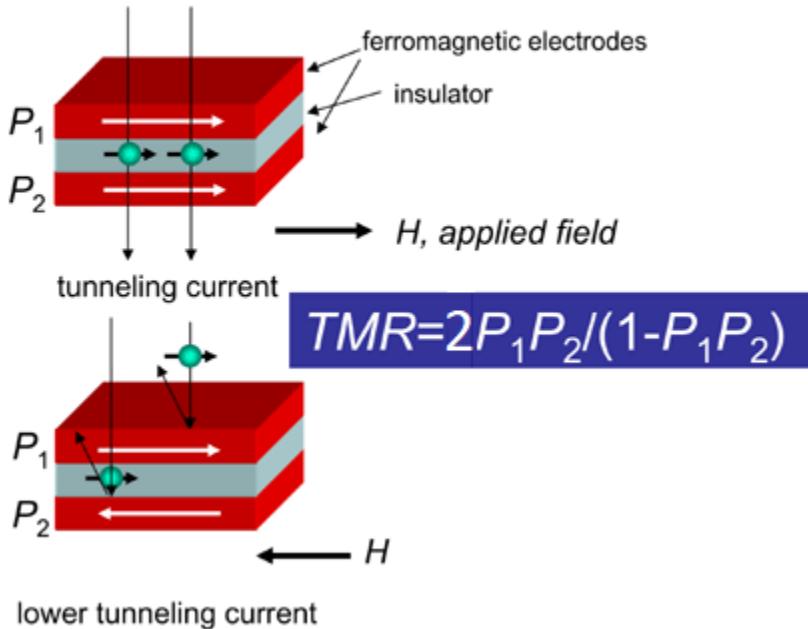


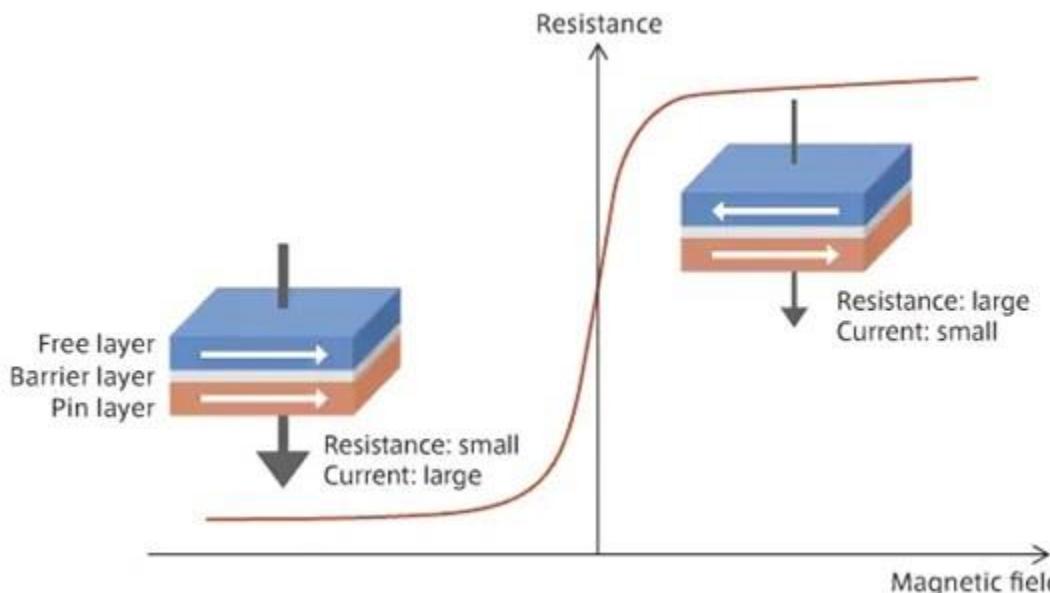
Table of Contents

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 - **MagnetostRICTive Materials**
 - **Lower dimensional materials**

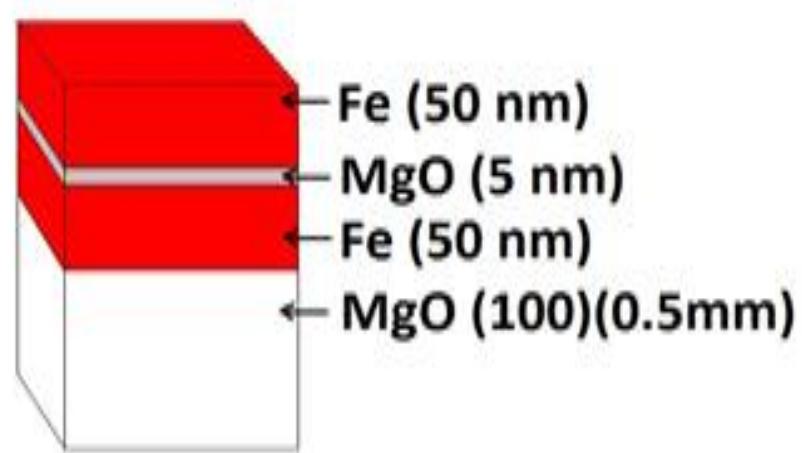
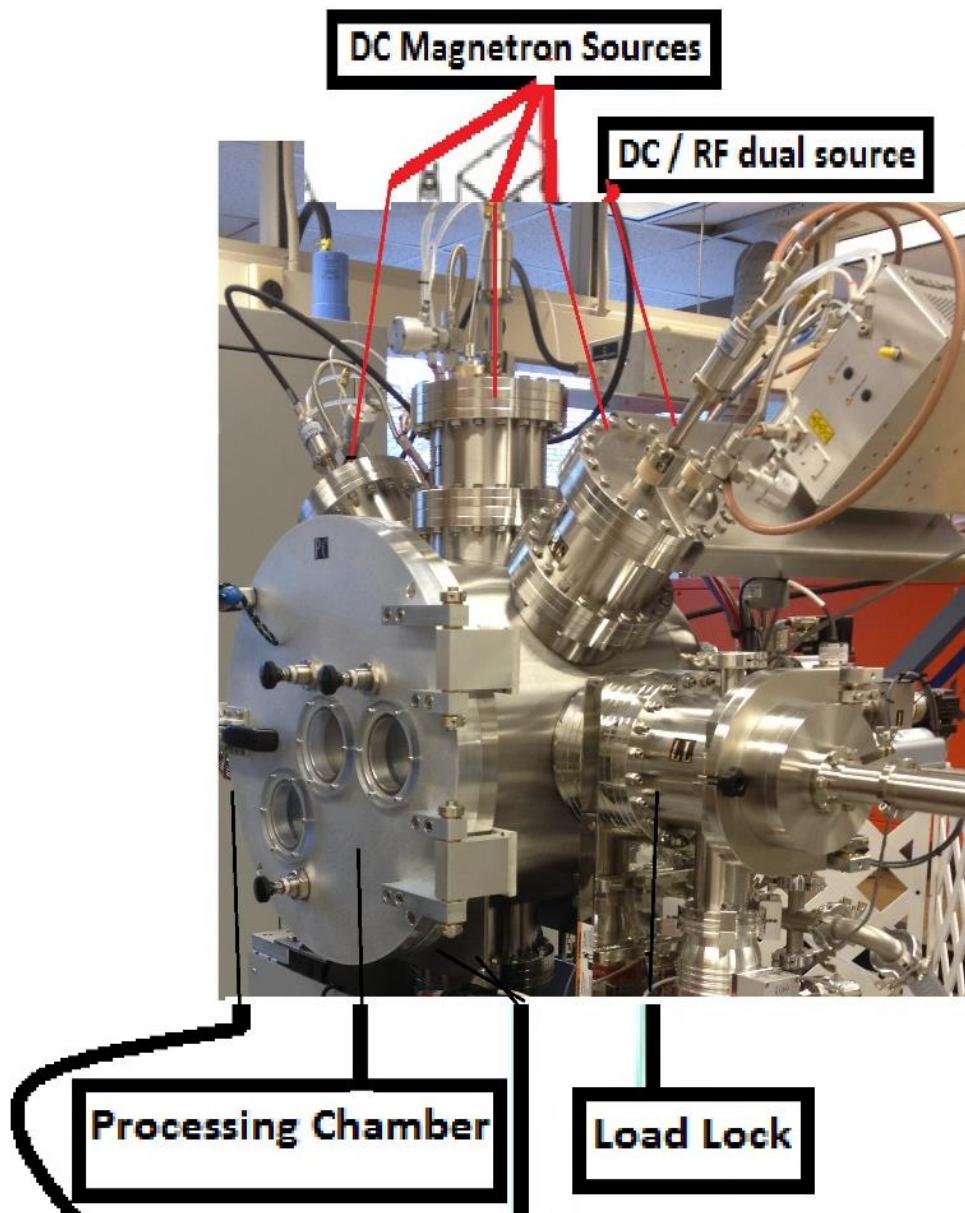
Tunneling Magnetoresistance (TMR)



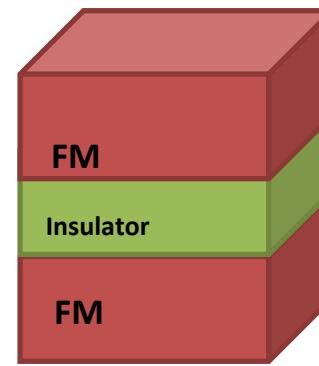
Mater. Today 9, 36 (2006)



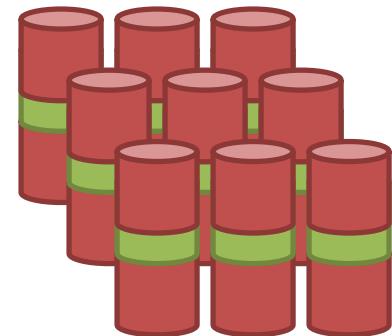
TMR synthesis



Planar Films



Arrays of
Filled CNTs



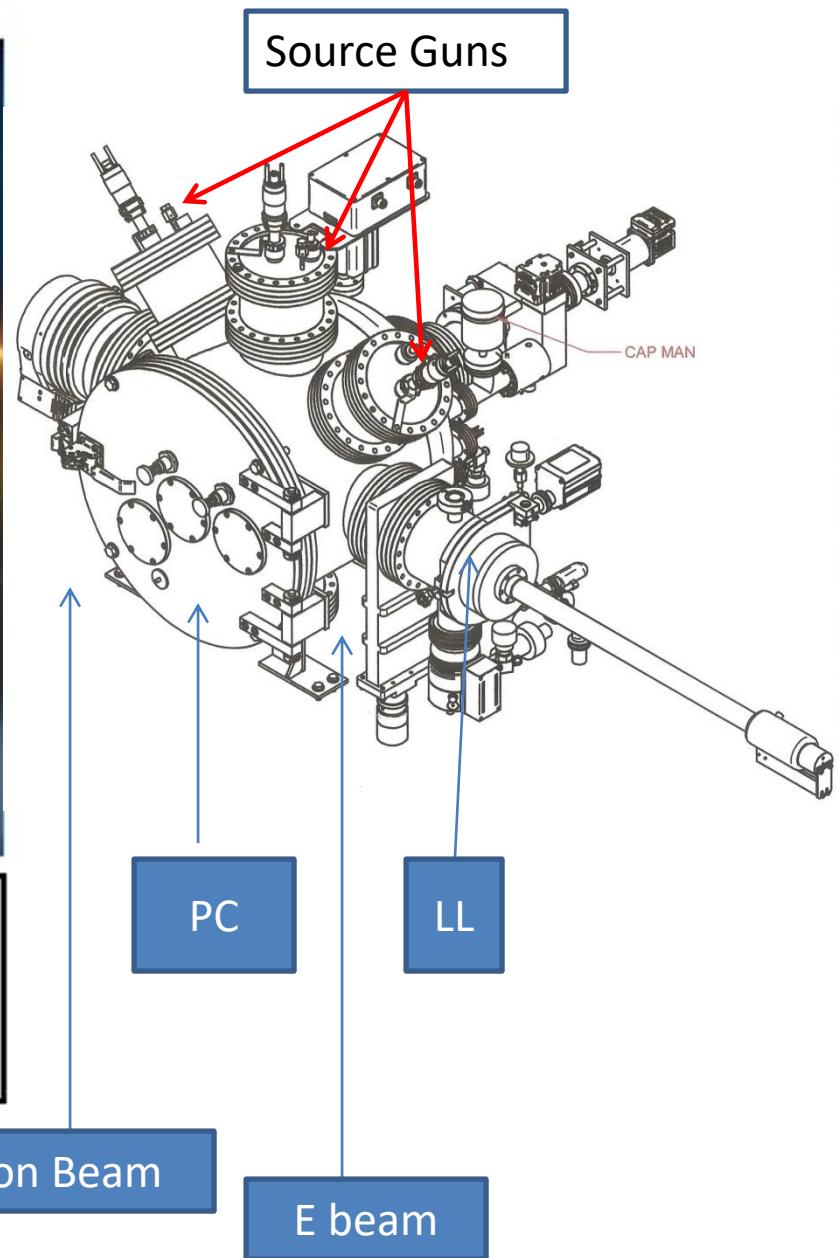
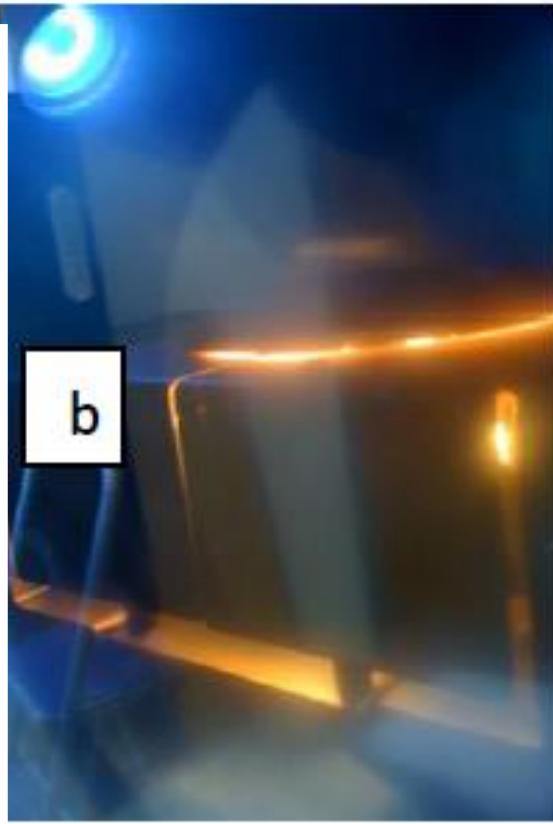
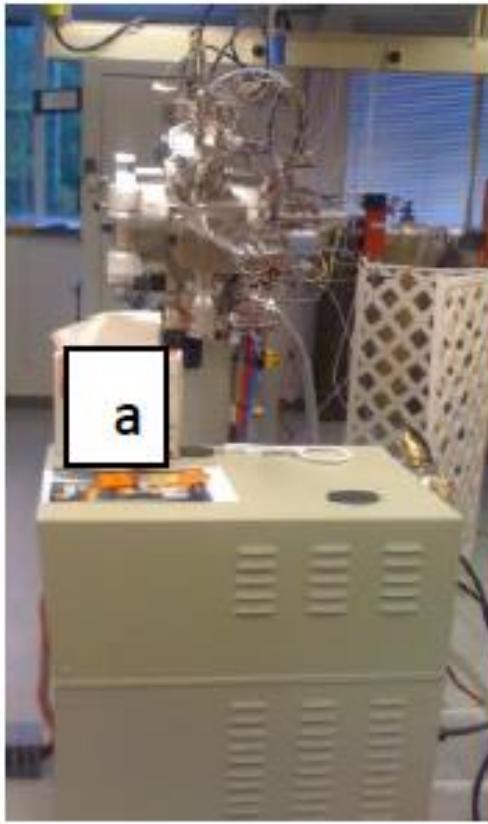
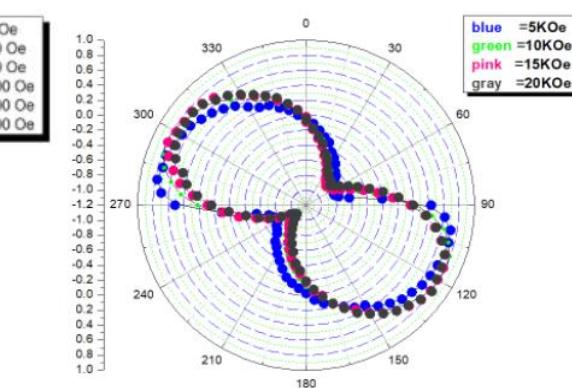
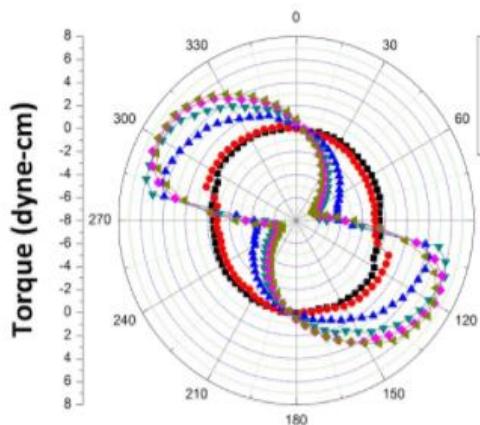
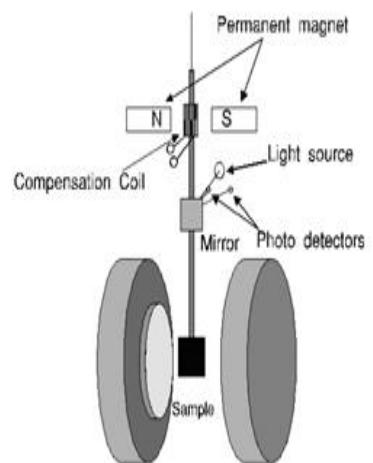
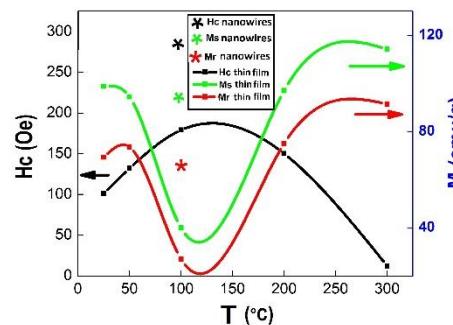
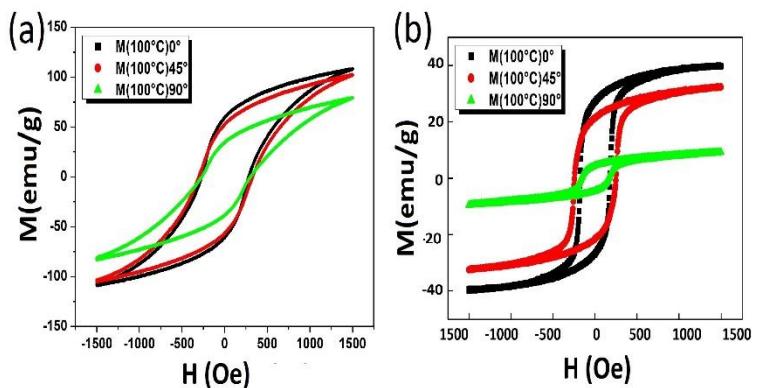


Fig. 2: (a) Magnetron dc sputtering system. (b) Inside processing chamber during deposition at high temperature.



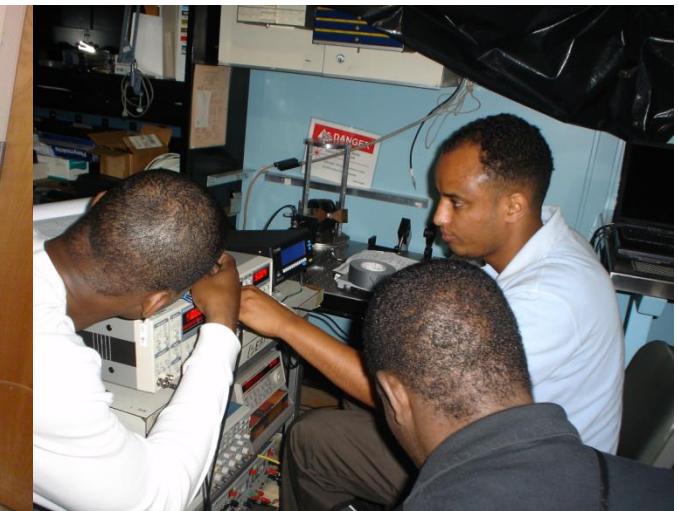
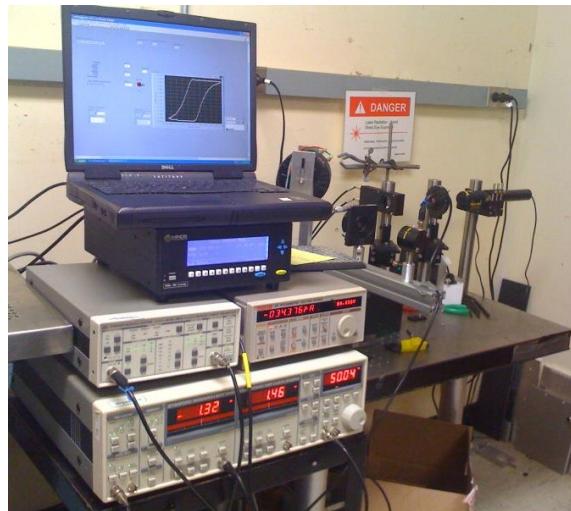
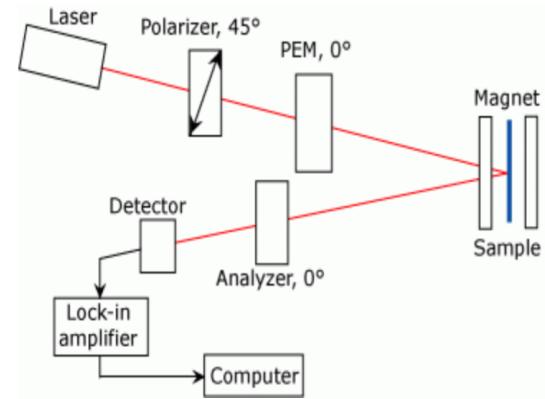
Magneto-Optics Kerr Effect Instrument

Morgan State University 2010

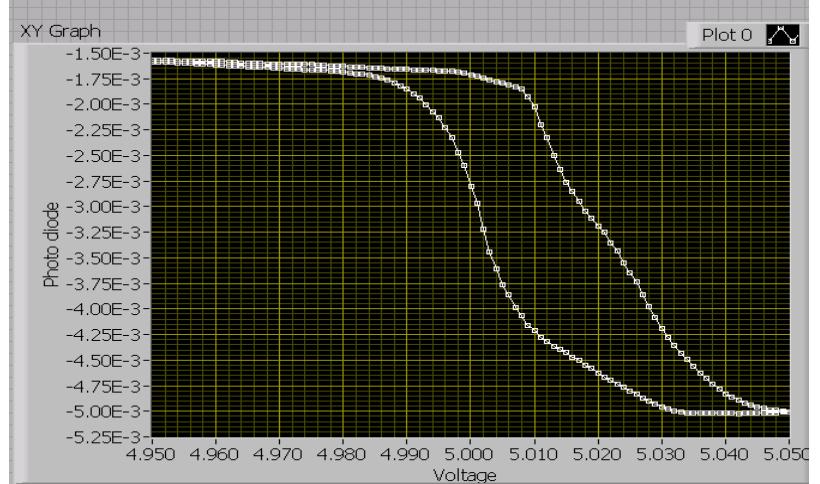
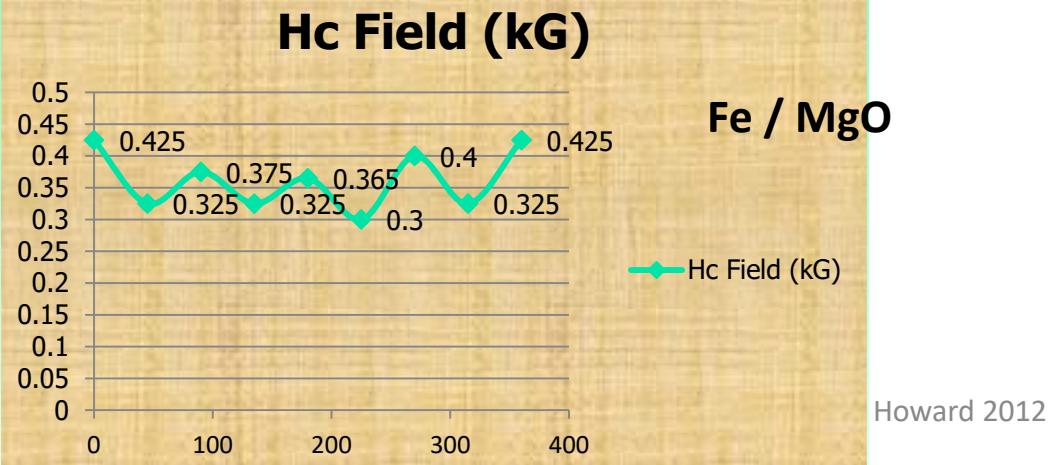
By Dereje Seifu

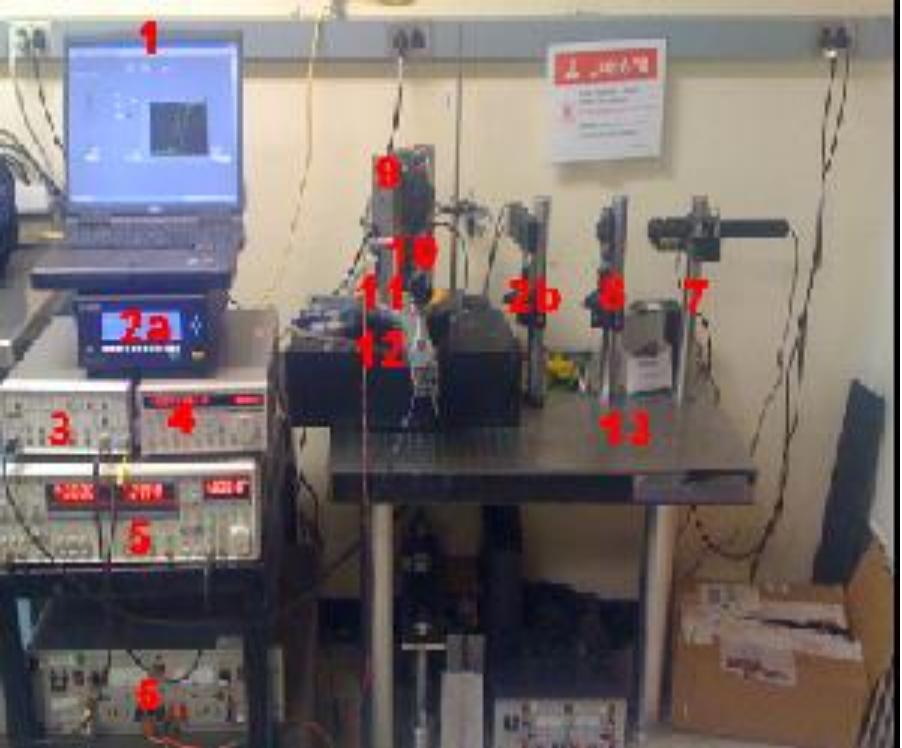


3- BNL-NSLS Summer 2009-2010 Magneto-Optic-Kerr-Effect (MOKE)



PEM Setting: quarter-wave retardation ($\lambda/4$)
Polarization Modulation: right and left circular polarized light
Lock-in reference: PEM's 1st Harmonic





1. Laptop with control software
- 2a. PEM-100 controller
- 2b. PEM optical head
- 3c. PEM electronic head
3. SRS Preamplifier
4. Keithley Picoammeter
5. SRS Lock-in Amplifier

6. BOP Power Supply
7. Laser
8. Polarizer
9. Electromagnet
10. Sample holder
11. Analyzer
12. Photo Diode

Magneto-Optic Kerr Effect (MOKE)

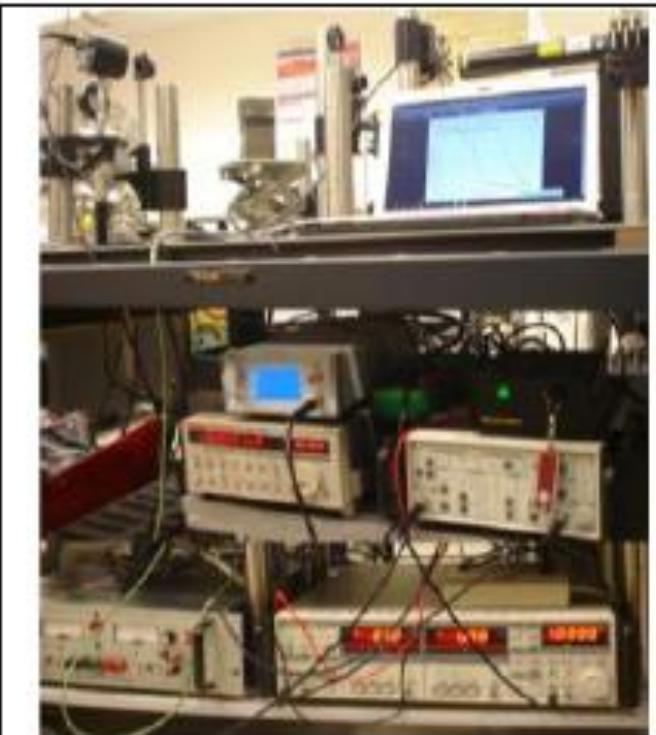
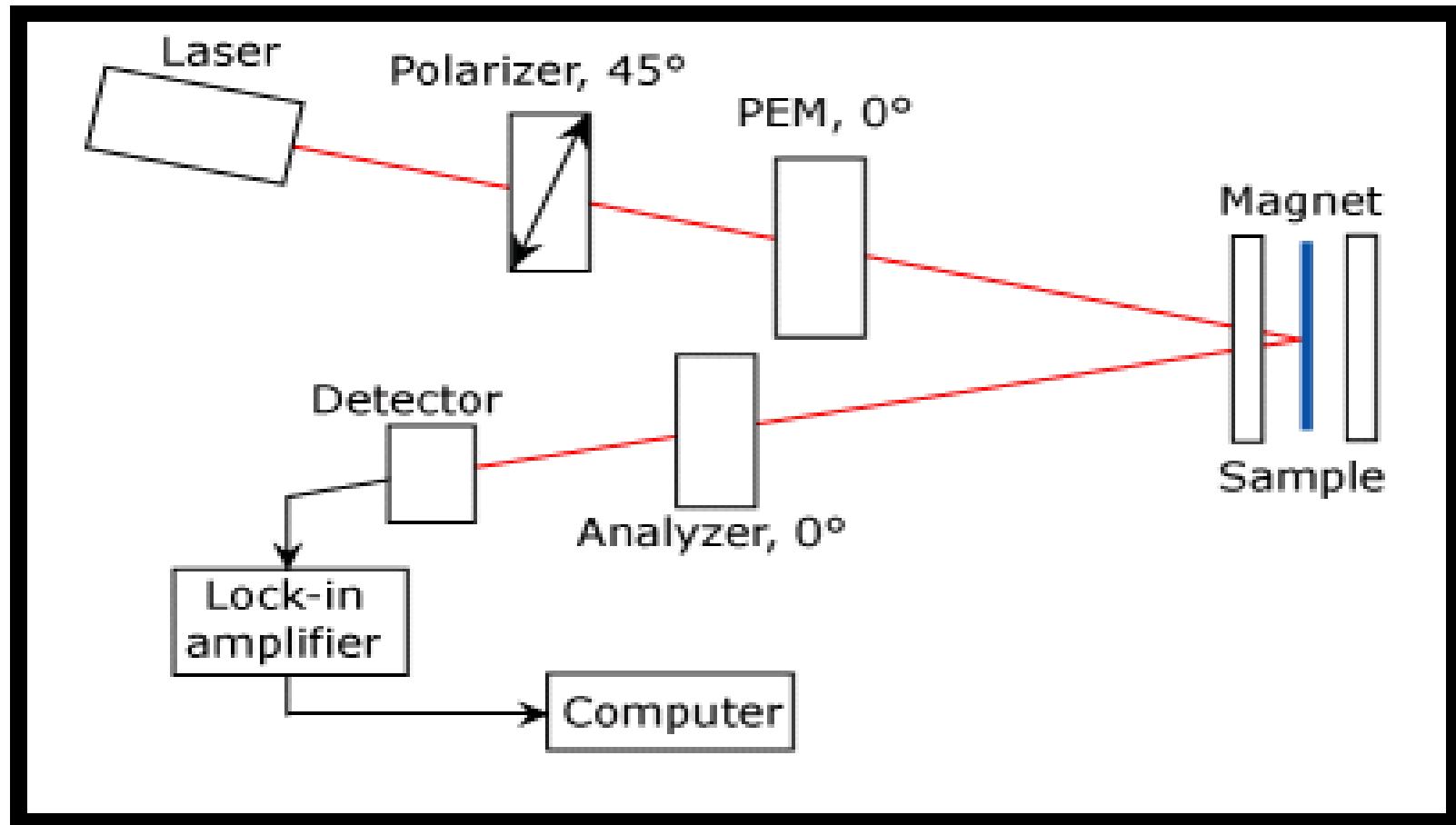


Fig. 1: MOKE setup at Morgan State University.

1. Laser
2. Optical Chopper
3. Electromagnet
4. Polarizer
5. Analyzer
6. BOP Power Supply
7. Photo Diode
8. SRS Preamplifier
9. Keithley Picoammeter
10. SRS Lock-in Amplifier
11. Laptop with control software



Magneto-Optical Kerr Effect (MOKE)

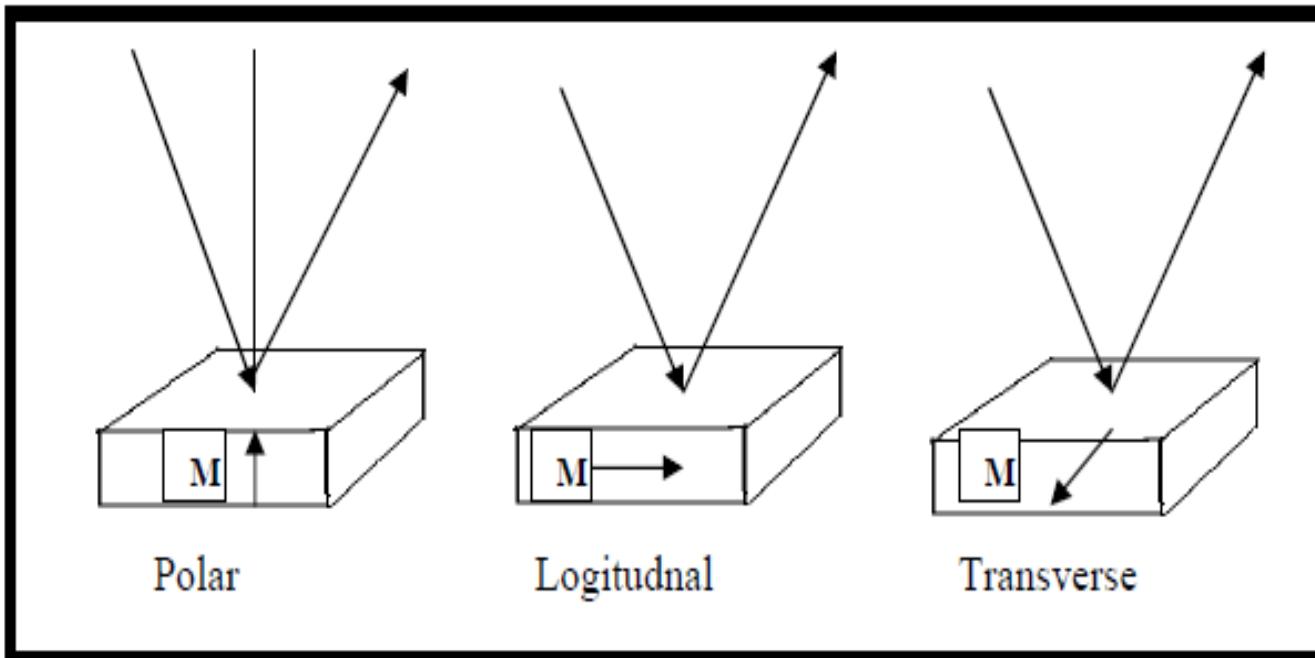
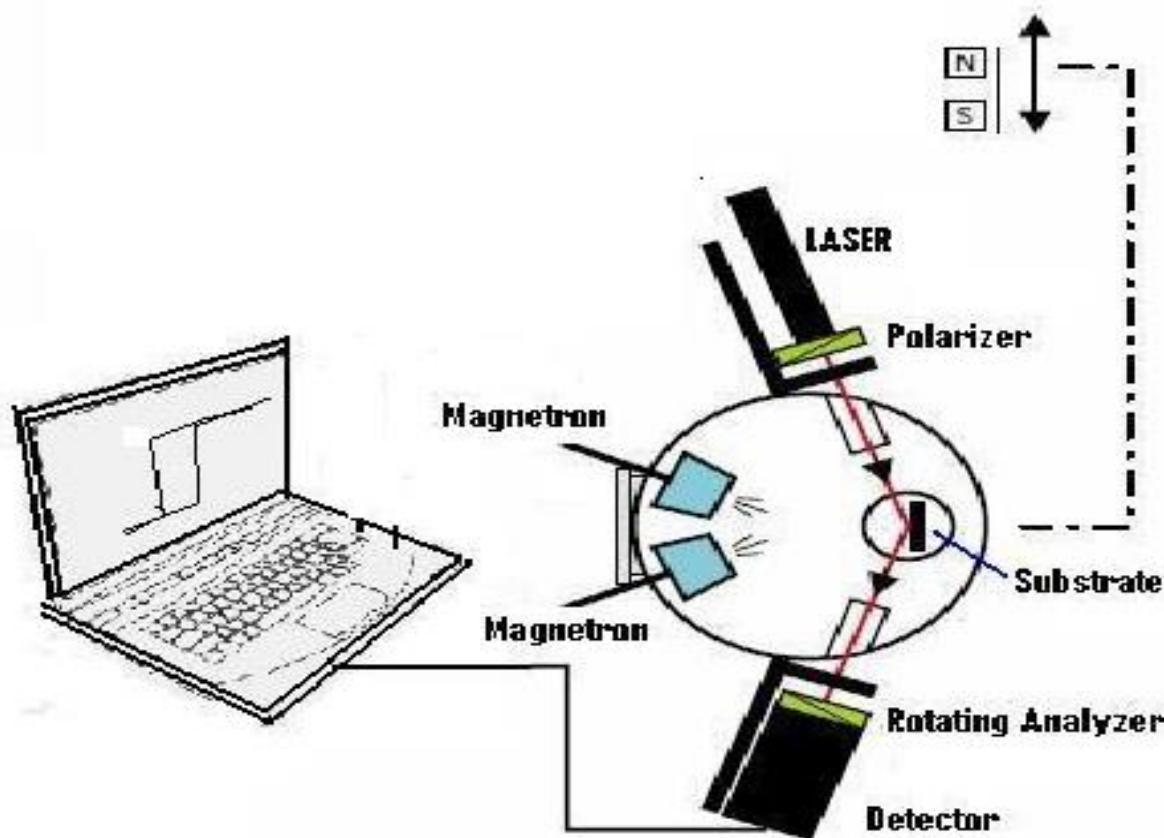


Figure 1 – The three types MOKE configurations.

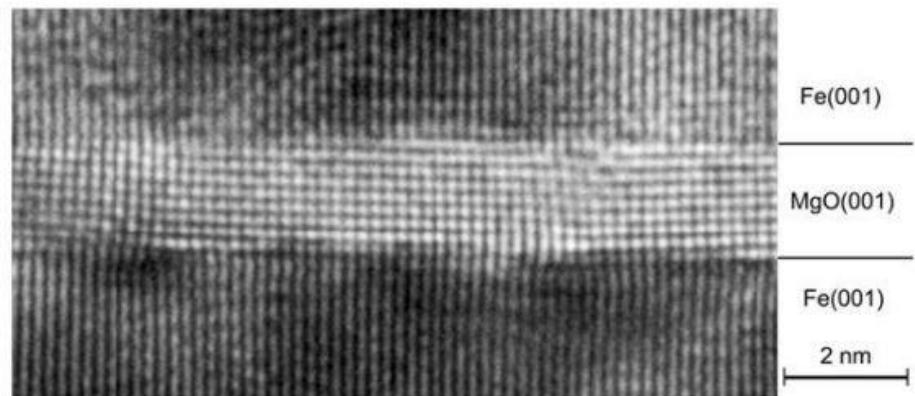
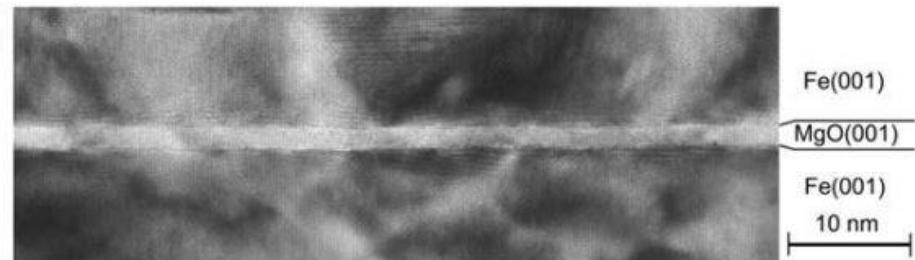
NSF-MRI-R²

Development of Magneto-Optics Kerr Effect
for in-situ dynamic
studies of film growth



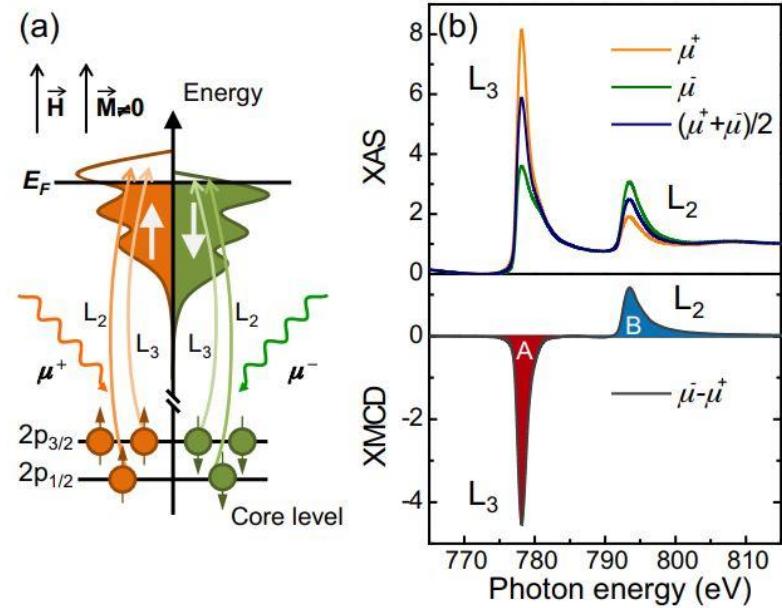
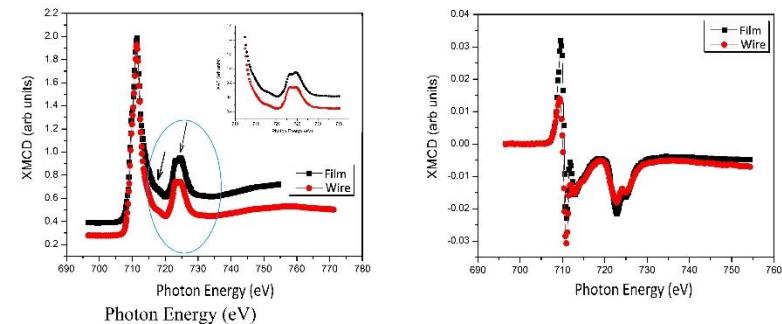


TEM / HRTEM



XMCD & XAS

The BNL National Synchrotron Light Sources



Simulation of Tunneling magneto-resistance in Fe/MgO/Fe

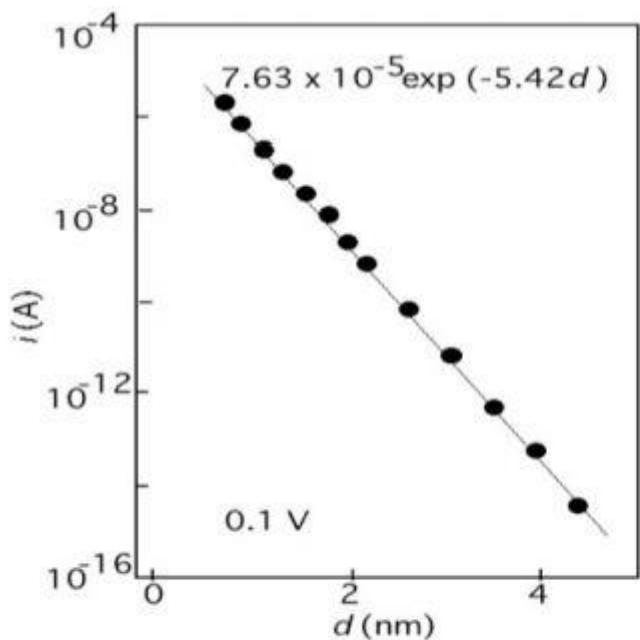


Figure 2. MgO thickness dependence of the tunneling current at 0.1 V.

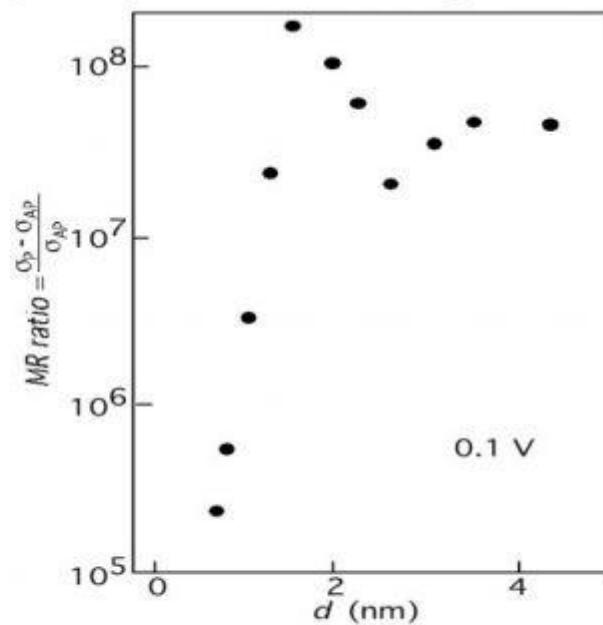
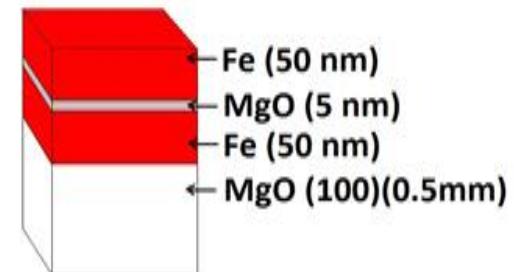
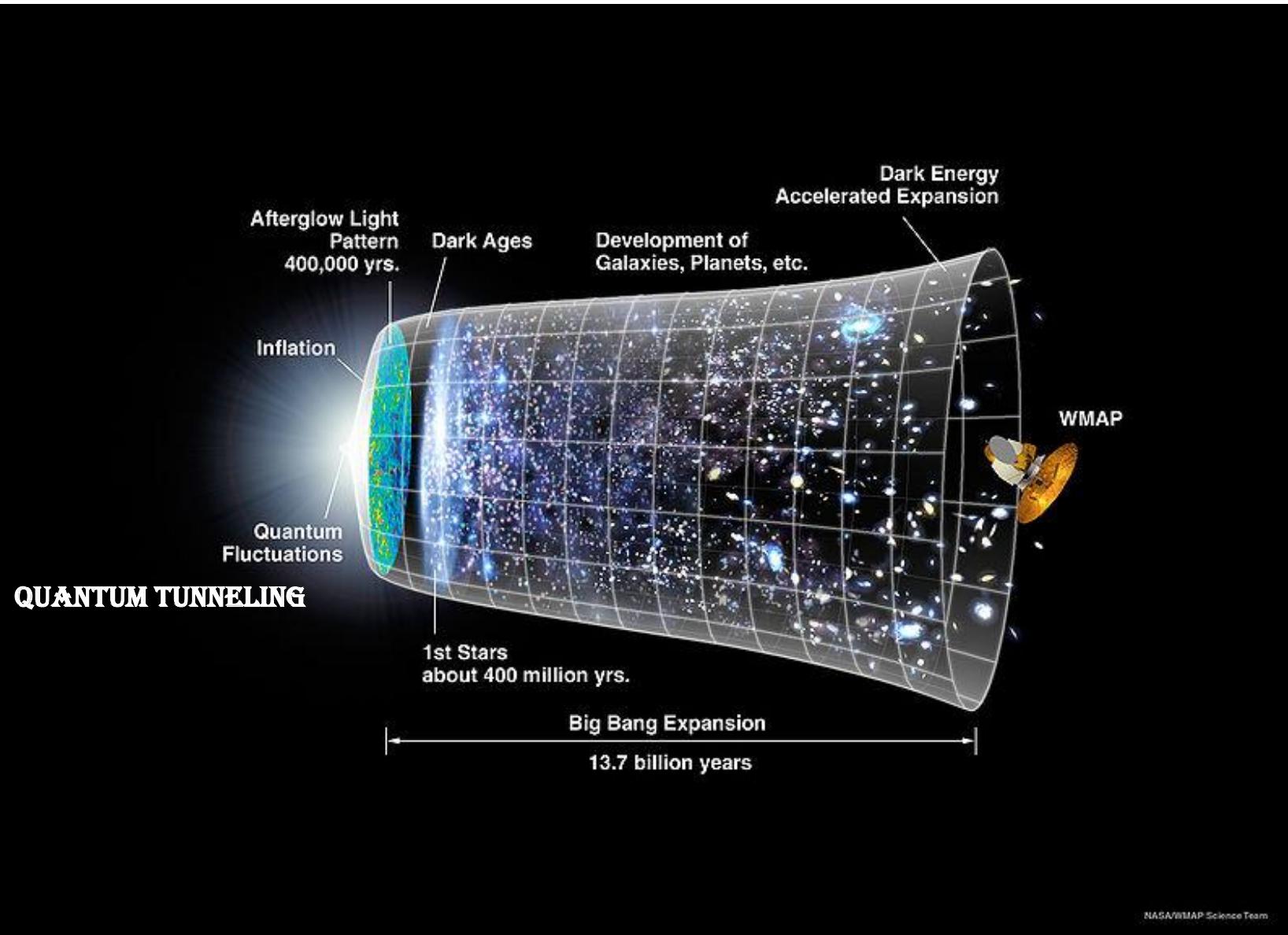


Figure 3. MgO thickness dependence of the TMR ratio in the Fe-MgO-Fe junction.

Journal of Physics: Conference Series 303 (2011)



Quantum Tunneling



Quantum Tunneling

Choose a quantum mechanism that is half way between 'mundane' and 'outlandish' – **quantum tunnelling**

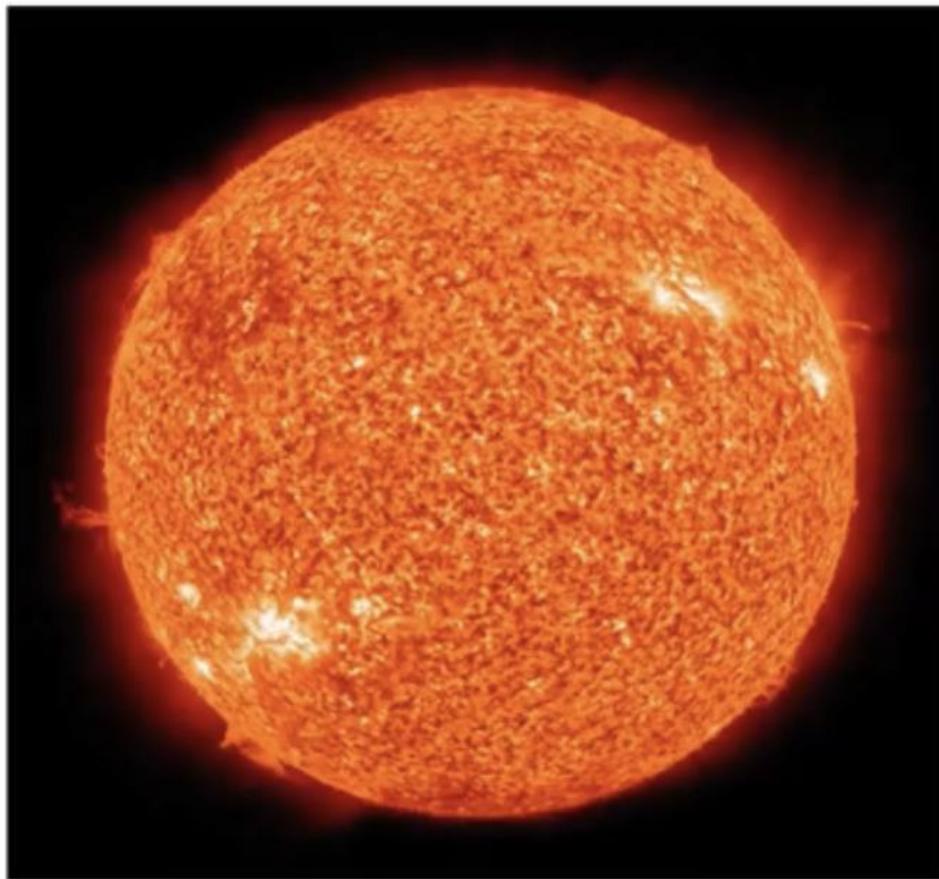


Image: NASA

References

BOOK CHAPTER

- Nanowires-Synthesis, Properties, and Applications (IntechOpen, 2019). Nanowires of Fe/MgO/Fe Encapsulated in Carbon Nanotubes (**D. Seifu***)

PUBLICATIONS (REFEREED)

- "Magnetic Properties of Fe/Topological Insulator/Fe Multilayer Films and Nano-columns," F. Alottebi, P. Seck, S.P. Karna, **D. Seifu***, IEEE, 2018.
- "Shape anisotropy and hybridization enhanced magnetization in nanowires of Fe/MgO/Fe encapsulated in carbon nanotubes," D. Aryee, **D. Seifu***, Journal of Magnetism and Magnetic Materials, 429, 2017. 14)
- "Nano Wires of Fe/MWCNTs and Nanometric Thin Films of Fe/MgO," A. Newman, S. Khatiwada, S. Neupane, **D. Seifu***, J. of Appl. Phys., 117, 144302, 2015.

Abstracts

- [**D. Seifu**, Tunneling Magneto Resistor Nano-columns, Bulletin of the American Physical Society, 65 \(2020\).](#)
- [**Seck, P., Seifu, D.**, "Shape anisotropy and hybridization enhanced magnetization in nanowires" ,NANOENERGY 2017 \(4th International Conference on Nanotechnology, Nanomaterials & Thin Films for Energy Applications\) , 2017, Finland](#)
- [**Aryee, D. and Seifu, D.**, Tunnel Magneto Resistance of Fe/Insulator/Fe, In *APS March Meeting Abstracts*, 2016.](#)
- [**Newman, A. and Seifu, D.**, March. Fe/MgO/Fe Tunnel Magneto Resistance Structure. In *APS March Meeting Abstracts* \(Vol. 1, p. 1241\), 2014.](#)
- [**Salomon, Vallery, and Seifu, Dereje** . "Fe/Bi₂Te₃/Fe Tunneling Magneto-Resistance with topological insulator barrier." In *APS March Meeting Abstracts*, vol. 1, p. 1242. 2014.](#)

M.Sc. MENTEES

- Masters of Science in Physics Thesis: Magneto-Optics Kerr Effect Instrumentation **Newman, Alexander**. Morgan State University, 2015. **Advisor: Dr. Dereje Seifu**
- Masters of Science in Physics Thesis: Tunneling Magnetoresistance In Iron (Fe) / Topological Insulator / Iron (Fe) **Aryee, Dennis**. Morgan State University, 2017. **Advisor: Dr. Dereje Seifu**
- Masters of Science in Physics Thesis: Magneto Optics Study of Fe/Topological- Insulator/Fe Tri-Layer System **Faisil Alottebi**, Morgan State University, 2018. **Advisor: Dr. Dereje Seifu**

PH.D. MENTEES

- Ph.D. in Industrial and Computational Mathematics: Applied Mathematics in Density Functional Theory Papa Seck, Morgan State University Advisor: Dr. Dereje Seifu

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<https://www.youtube.com/watch?v=ps2i55uun5o>

References

PATENT

- A. Hall, M. D. Coatney, O. J. Myers, B. Williams, and D. Seifu, "Smart Materials Integrated into a Carbon Fiber Polymer for Measuring Structural Damage", pending 2020.

PUBLICATIONS (REFEREED)

- "Magnetostrictive particulates of $Tb_{0.3}Dy_{0.7}Fe_2$ integrated into carbon fiber reinforced polymer for structural damage monitoring," **D. Seifu***, A.J. Hall, D. Elbert, P. McGuigan, O.J. Myers, R.C. Budhani, *AIP Advances*, 10, 075204, 2020.

Abstracts

- [D. Seifu, A. Hall, Magneto Restrictive Sensor, Bulletin of the American Physical Society, 65 \(2020\).](#)

M.Sc. MENTEES

- Masters of Science in Physics Thesis: Magneto-Optics Kerr Effect Instrumentation
Daba, Brook. Morgan State University, 2021. **Advisor: Dr. Dereje Seifu**

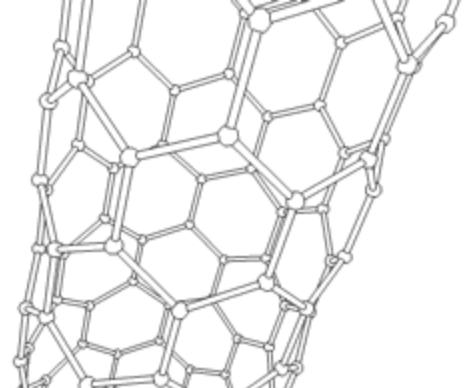
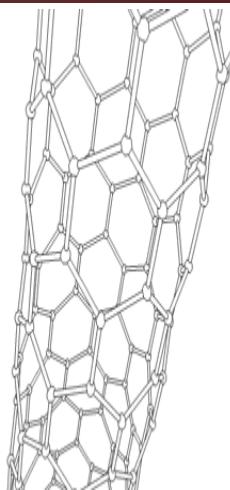
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Nanomagnetism

**Carbon Nanotubes,
Nano Wires, and Nano Magnets**

**Dr. Dereje Seifu
Professor
Department of Physics
Morgan State University
Baltimore, Maryland, USA**

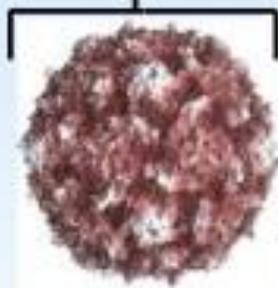
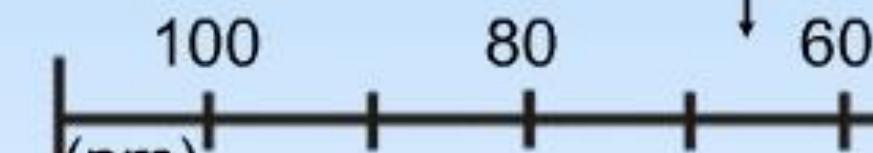
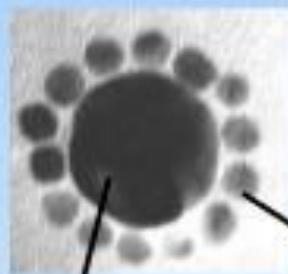


The Interesting Length Scale

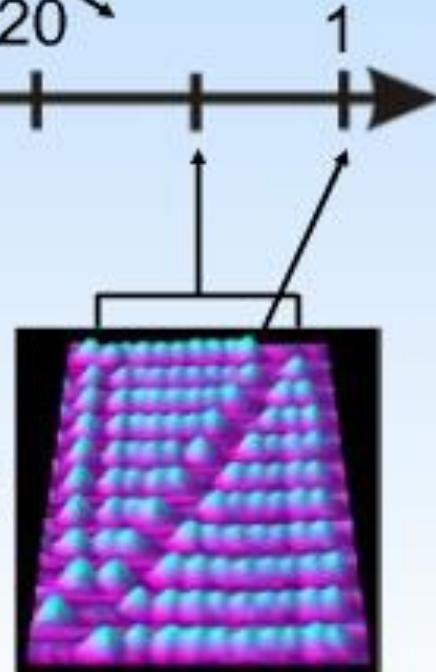
Bacteriophage
60-70 nm
Magnified 400,000X



Gold Particles
13 nm & 50 nm
Magnified 500,000X



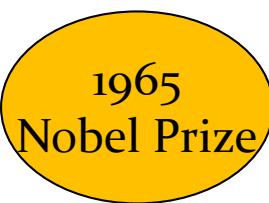
Flu Virus
100 nm
Magnified 320,000X



World's Smallest Abacus
 C_{60} Molecules on Cu(111)
1 nm C_{60} & 10nm lines
Magnified 15 millionX

"There's plenty of room at the bottom" (1959).

Feynman



As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing; that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

60 nm

400 nm

Richard P. Feynman, 1960

Space Shuttle Challenger disaster January 28, 1986

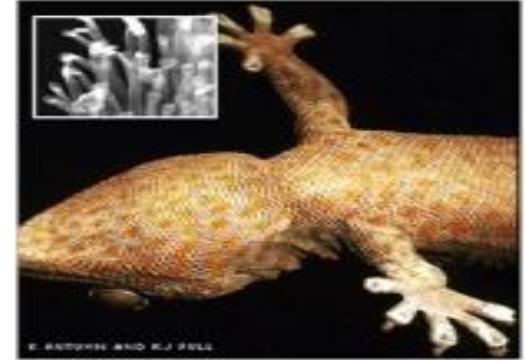
"For a successful technology, reality must take precedence over public relations, for nature cannot be fooled."



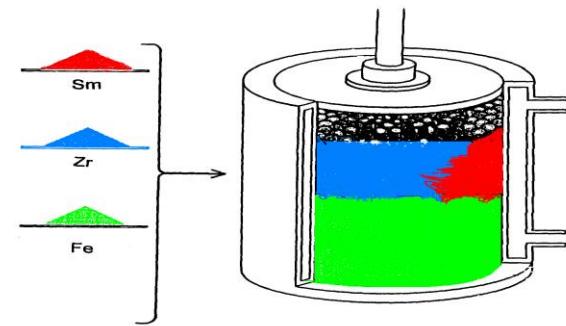
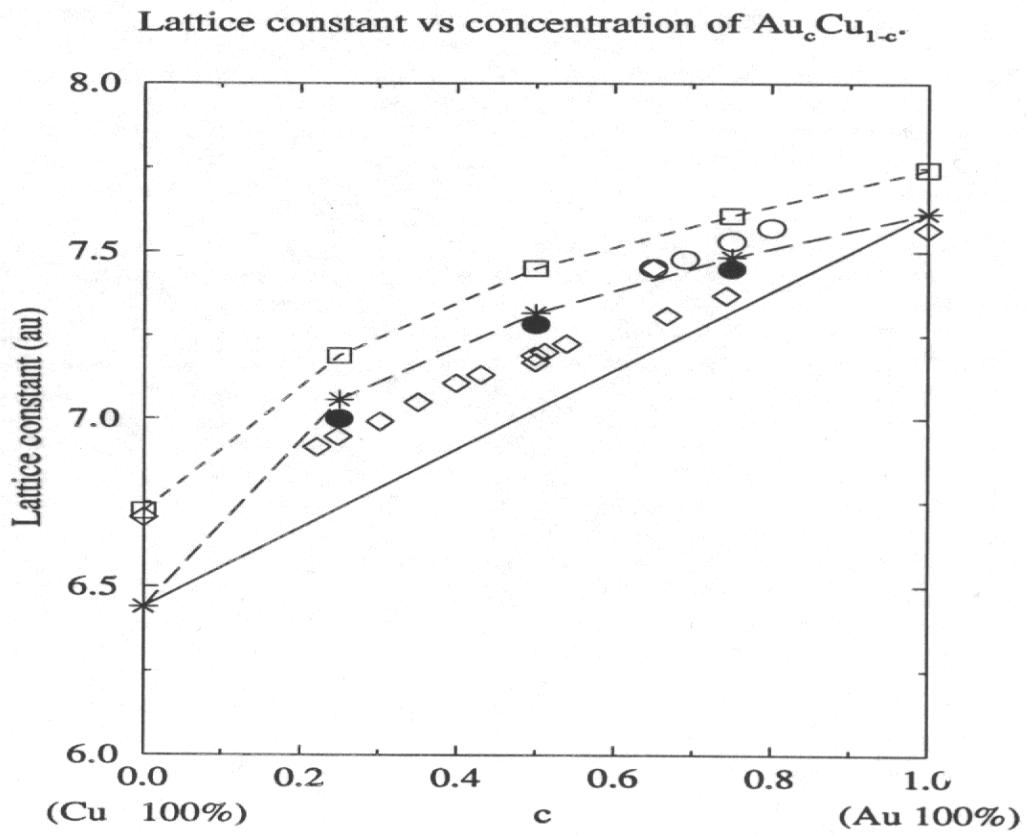
At the Nano-level

(where principles of quantum physics apply)

- Characteristic of materials change
 - C is 100 times stronger than steel
 - Al turns highly explosive
 - Au melts at RT
- In nature
 - Geckos hang upside down on the ceiling using nanotechnology (using its millions of tiny hairs on each toe creating van der Waals force it can actually support 200 times its own weight).

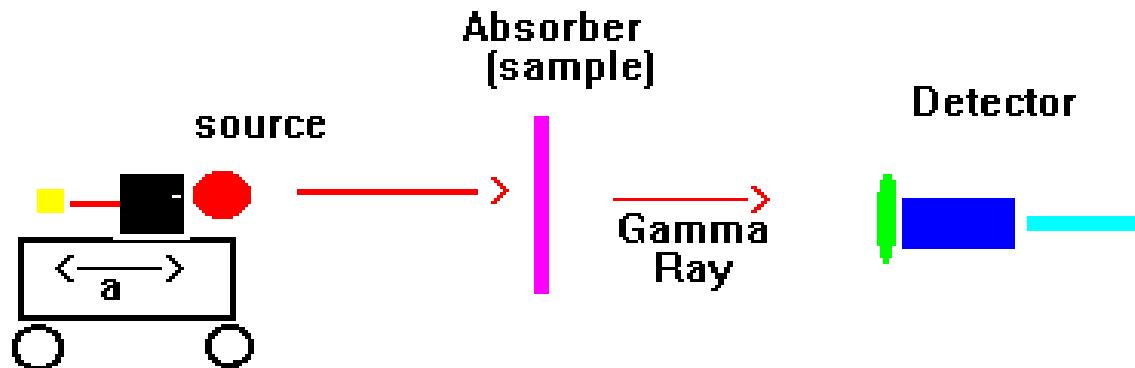


Mechanically Alloying



- * — * KKR-CPA-ASA
- Expt. R.G.Davies (1961)
- ◇ Expt. C.H.Johansson (1936)
- — □ KKR-CPA-MTA
- KKR-scr_CPA-ASA

Mössbauer Measurements



$a = \text{constant}$

v_{\max} (30 mm/s to 4 mm/s)

source [Fe⁵⁷
 Eu¹⁵¹
 Sn]

$$v = \pm c \left(\frac{\Delta E}{E_0} \right)$$

Doppler's Shift

$$f = f_0 \left(1 \pm \frac{v}{c} \right)$$

$$hf = hf_0 \left(1 \pm \frac{v}{c} \right)$$

$$E = E_0 \left(1 \pm \frac{v}{c} \right)$$

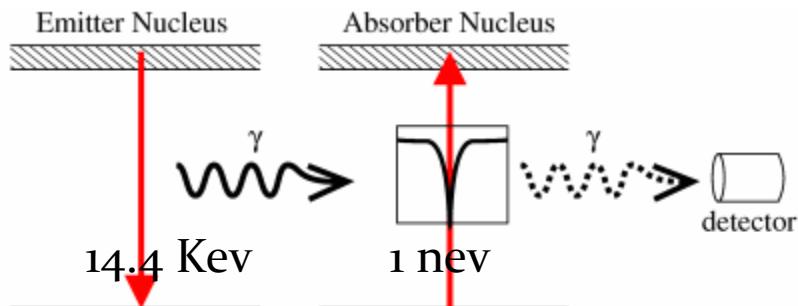
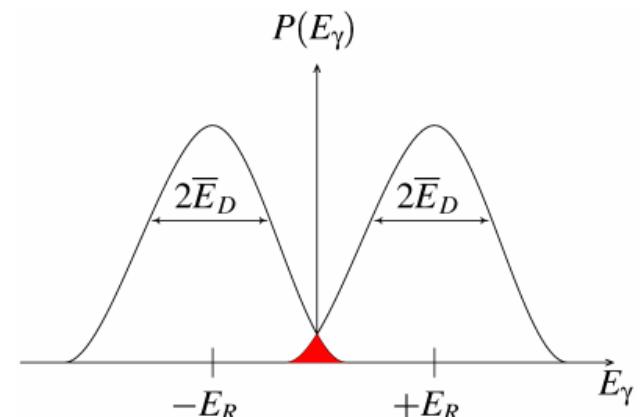
$$\Delta E = \pm \frac{E_0 v}{c}$$

Mössbauer Spectroscopy

(Nuclear Gamma Resonance Spectroscopy)

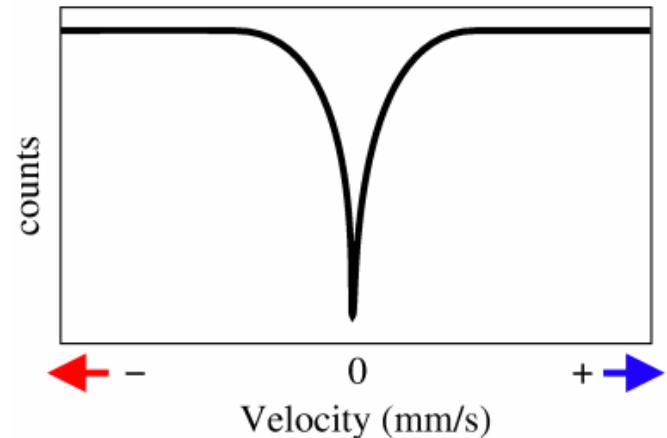


Rudolf Mössbauer The Nobel Prize in Physics 1961

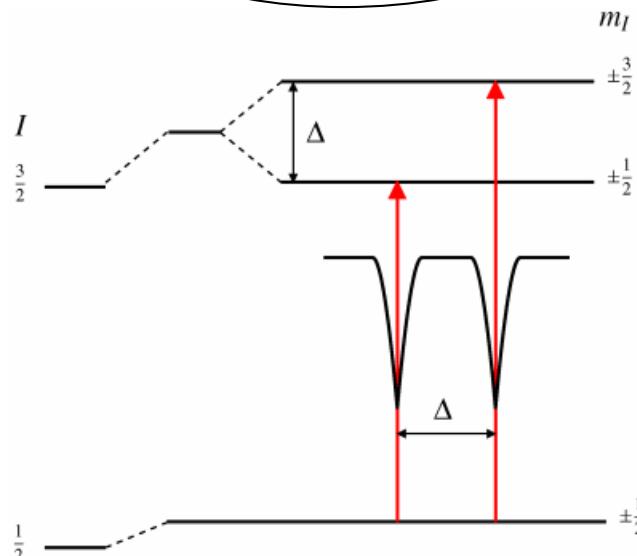


Hyperfine Parameters

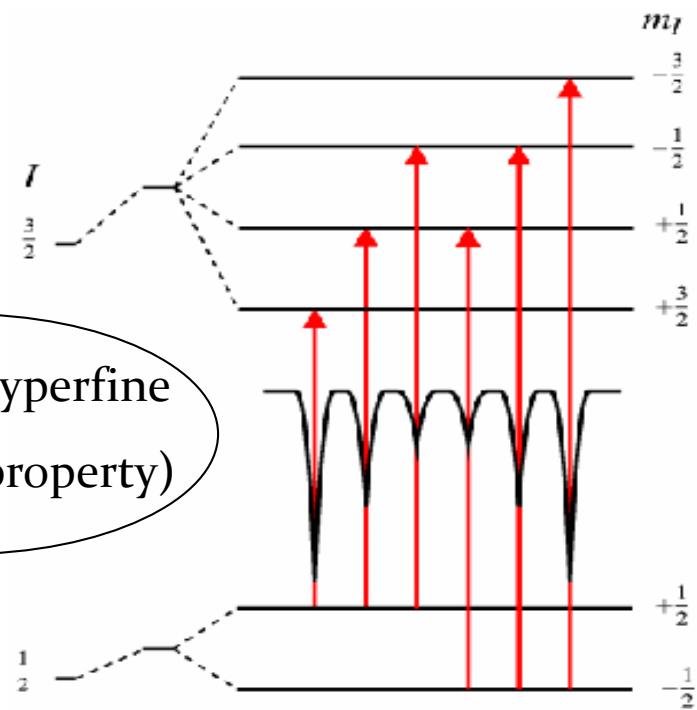
Isomer shift
(Chemical shift)



Quadrupole splitting
(structural property)

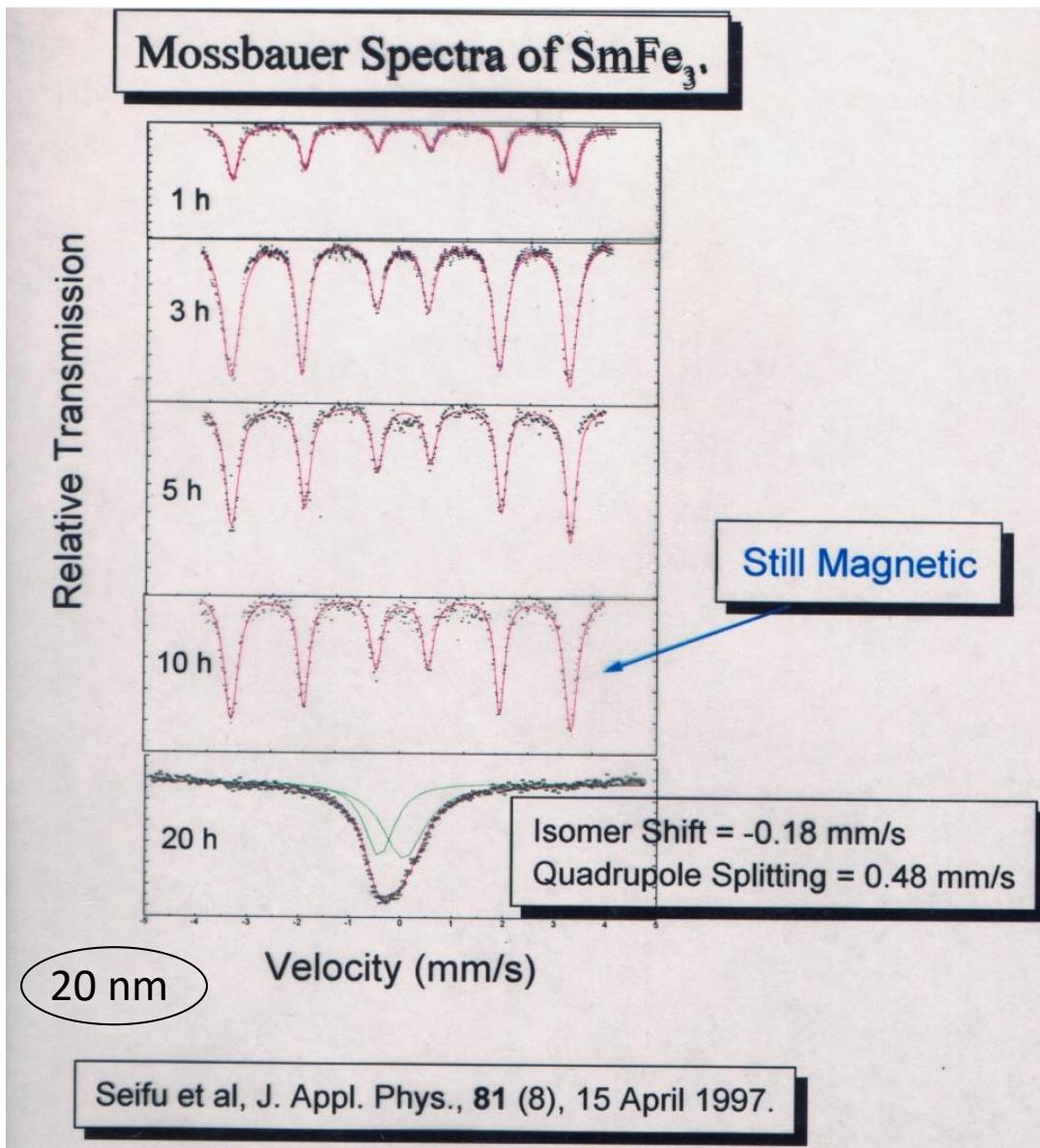


Magnetic Hyperfine
(Magnetic property)

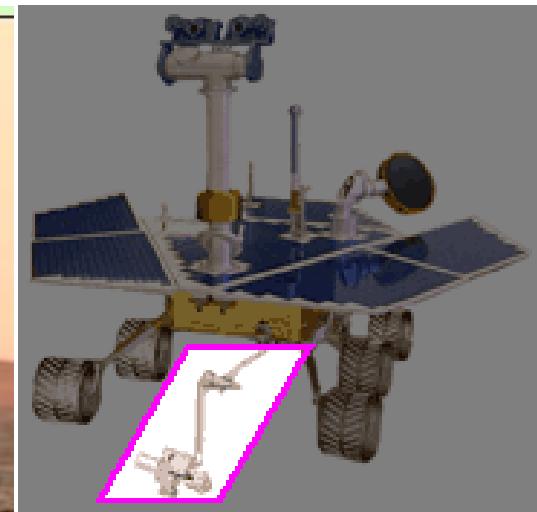
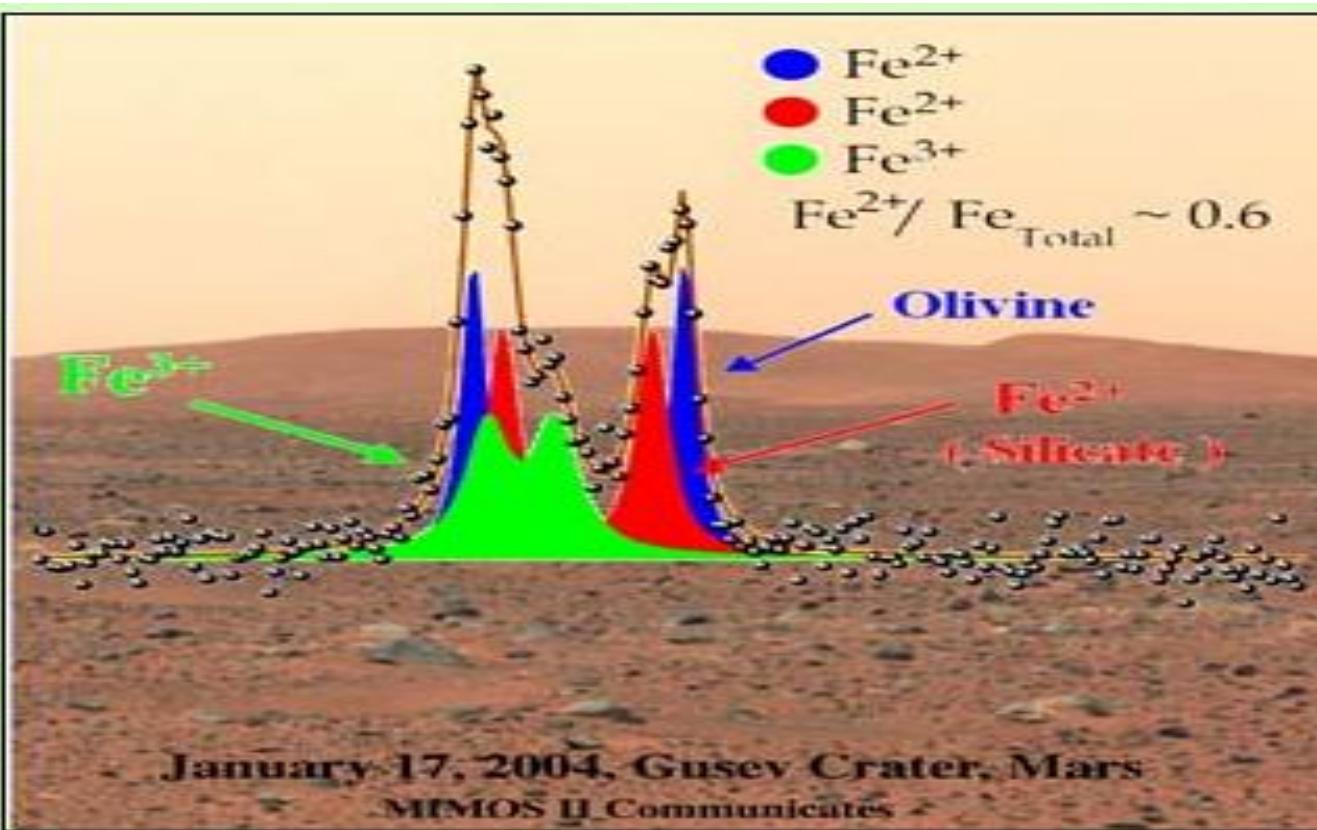


Superparamagnetism

Mössbauer spectra of Mechanically Alloyed SmFe₃

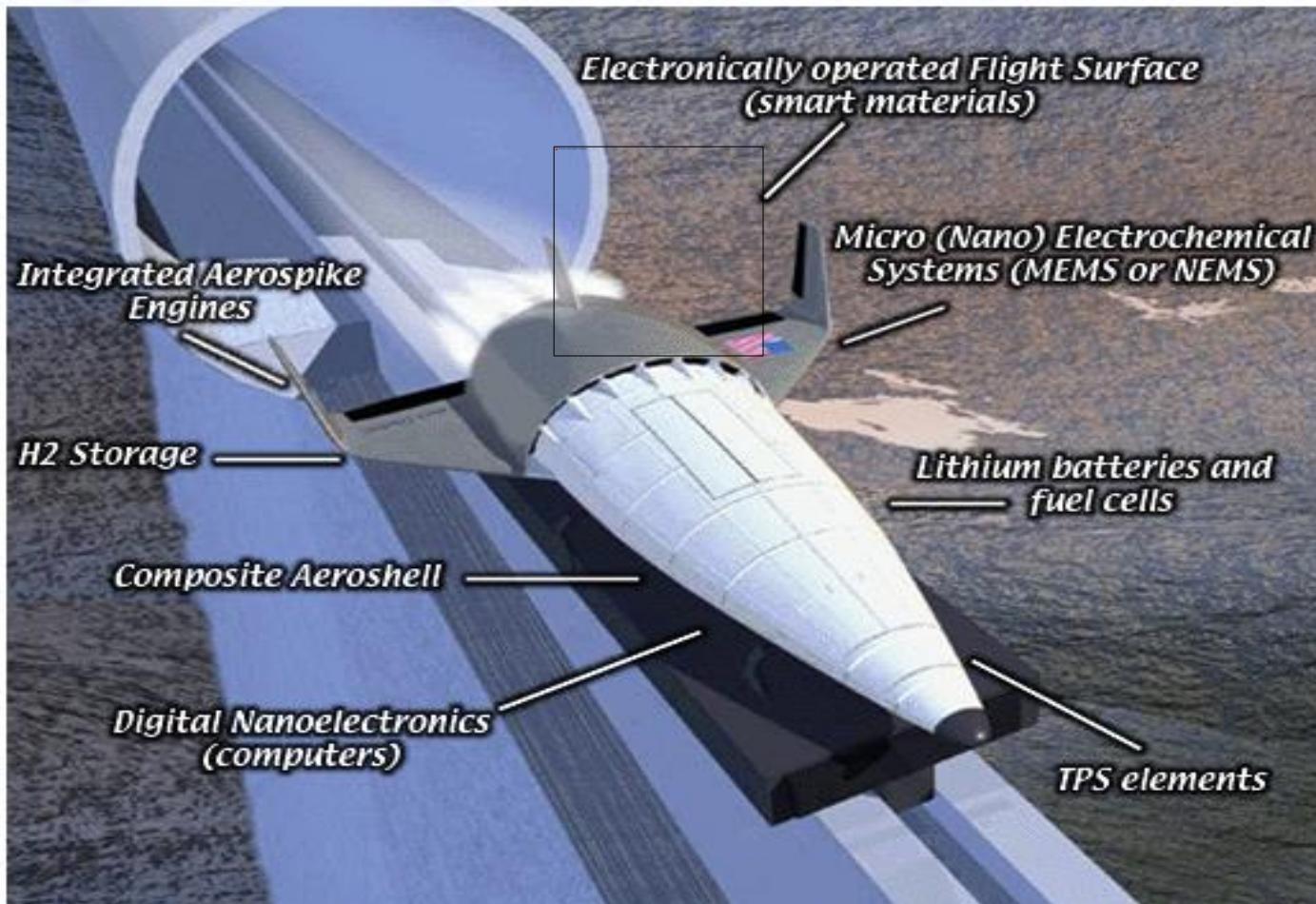


Mössbauer Measurements





Faster, Better, Cheaper *Space Transportation with Nanotubes*



Helical microtubules of graphitic carbon

Sumio Iijima

NED Corporation, Fundamental Research Laboratories,
34 Miyukigaoka, Tsukuba, Ibaraki 305, Japan

THE synthesis of molecular carbon structures in the form of C_{60} and other fullerenes¹ has stimulated intense interest in the structures accessible to graphitic carbon sheets. Here I report the preparation of a new type of finite carbon structure consisting of needle-like tubes. Produced using an arc-discharge evaporation method similar to that used for fullerene synthesis, the needles grow at the negative end of the electrode used for the arc discharge. Electron microscopy reveals that each needle comprises coaxial tubes of graphitic sheets, ranging in number from 2 up to about 50. On each tube the carbon-atom hexagons are arranged in a helical fashion about the needle axis. The helical pitch varies from needle to needle and from tube to tube within a single needle. It appears that this helical structure may aid the growth process. The formation of these needles, ranging from a few to a few tens of nanometres in diameter, suggests that engineering of carbon structures should be possible on scales considerably greater than those relevant to the fullerenes.

Solids of elemental carbon in the π^2 bonding state can form a variety of graphitic structures. Graphite filaments can be produced, for instance, when amorphous carbon filaments formed by thermal decomposition of hydrocarbon species are subsequently graphitized by heat treatment^{2,3}. Graphite filaments can also grow directly from the vapour-phase deposition of carbon^{4,5}, which also produces soot and other novel structures such as the C_{60} molecule⁶⁻⁸.

Graphitic carbon needles, ranging from 4 to 30 nm in diameter and up to 1 μm in length, were grown on the negative end of the carbon electrode used in the dc arc-discharge evaporation of carbon in an argon-filled vessel (100 torr). The gas pressure was much lower than that reported for the production of thicker

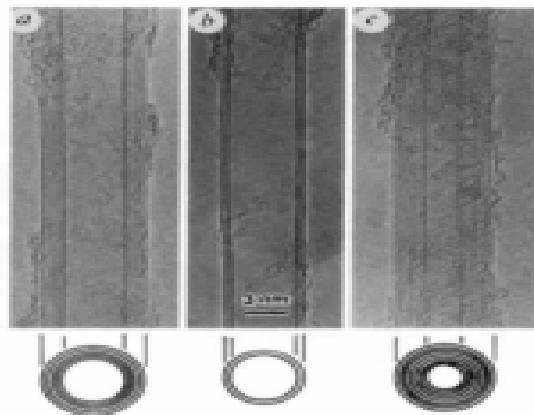


FIG. 3. Electron micrographs of microtubules of graphitic carbon. Parallel dark lines correspond to the (002) lattice images of graphite. A cross-section of each tube is illustrated. a, Tube consisting of three graphite sheets, diameter 6.7 nm. b, Two-sheet tube, diameter 5.5 nm. c, Seven-sheet tube, diameter 6.5 nm, which has the smallest hollow diameter (2.2 nm).

56

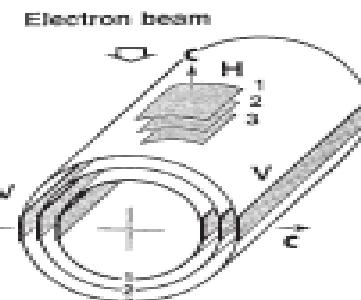


FIG. 2. Clinographic view of a possible structural model for a graphitic tubule. Each cylinder represents a coaxial closed layer of carbon hexagons. The meaning of the labels V and H is explained in the text.

graphite filaments⁹. The apparatus is very similar to that used for mass production of C_{60} (ref. 9). The needles seem to grow plentifully on only certain regions of the electrode. The electrode on which carbon was deposited also contained polyhedral particles with spherical shell structures, which were 5–20 nm in diameter. The needle structures were examined by transmission electron microscopy (electron energies of 200 keV).

High-resolution electron micrographs of typical needles show {002} lattice images of the graphite structure along the needle axes (Fig. 1). The appearance of the same number of lattice fringes from both sides of a needle suggests that it has a seamless and tubular structure. The thinnest needle, consisting of only two carbon-hexagon sheets (Fig. 1a), has an outer and inner tube, separated by a distance of 0.34 nm, which are 5.5 nm and 4.8 nm in diameter. The separation matches that in bulk graphite. Wall thicknesses of the tubes range from 2 to 50 sheets, but thicker tubes tend to be polygonized. This low dimensionality and cylindrical structure are extremely uncommon features in inorganic crystals, although cylindrical crystals such as serpentine¹⁰ do exist naturally.

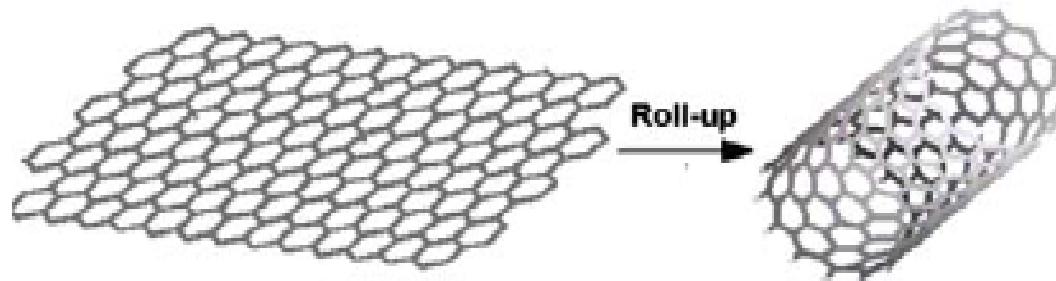
The smallest tube observed was 2.2 nm in diameter and was the innermost tube in one of the needles (Fig. 1c). The diameter corresponds roughly to a ring of 30 carbon hexagons; this small diameter imposes strain on the planar bonds of the hexagons and this causes two neighbouring hexagons on the ring to meet at an angle of $\sim 6^\circ$. For the C_{60} molecule, the bending angle is 42° , which is much larger than for these tubes. The C-C bond energy calculated for the C_{60} molecule is smaller than that of graphite¹¹, suggesting that bending the hexagons in C_{60} lowers the bond energy. A similar effect of the bending on bonding energies might apply here. One of the key questions about the tubular structure is how the ABAB hexagonal stacking sequence found in graphite is relaxed, as it is impossible to retain this ideal graphite structure for coaxial tubes. There should be a shortage of 8–9 hexagons in going from one circumference of a tube to that inside it. Disordered graphitic stacking is known as turbostratic stacking, but no detailed accounts of stacking patterns in such structures have been reported. The argument here is also applicable to the spherical graphitic particles mentioned earlier¹².

All the electron diffraction patterns (Fig. 2) taken from individual carbon needles are indexed by the (001) and (hk0) spots for hexagonal symmetry. The patterns always show strong (001) spots when the needle axes are perpendicular to the [001] axis, supporting the idea of a coaxial arrangement of graphitic tubes. As shown in Fig. 2, two side portions of each tube (indicated by shading and labelled 'V') will be oriented so that the

CNTs Mechanical / Electrical Properties

Material	Young's modulus (GPa)	Tensile Strength (GPa)	Resistivity (Ωcm)
SWCNTs	1054	150	Varies with chirality
MWCNTs	1200	150	$\sim 10^{-4}$
Steel	208	0.4	$\sim 10^{-5}$
Copper	130	0.2	$\sim 10^{-6}$
Al	70	0.017	$\sim 10^{-6}$

* Properties vary with structure



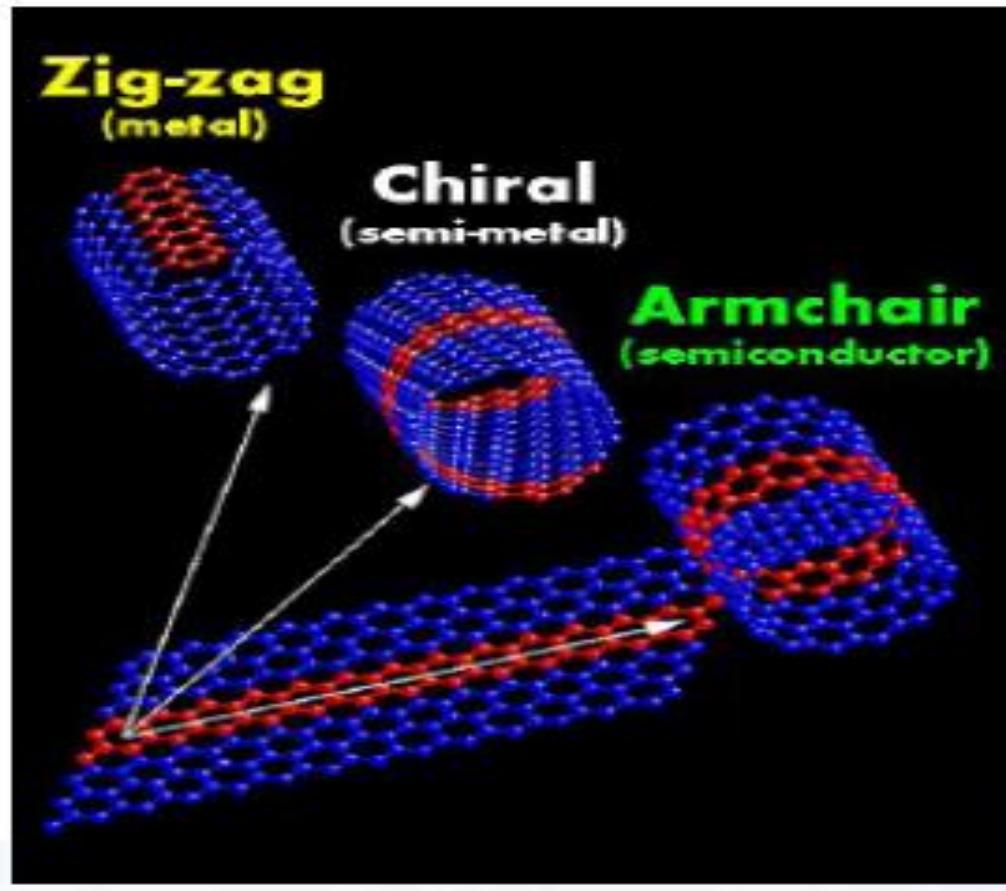
A sheet of Carbon

A Carbon Nanotube

Hollow interior => nanometer-sized

Howard 2012

Chirality of CNTs



Filled CNT applications

- Biosensors for harmful gases
- Electronic nano components
- material protection applications
- Field effect transistors (FET)
- Field emission displays
- Microscope probes
- Nanometric test tubes
- **Nano wires**
- **Nanomagnets**

Applications

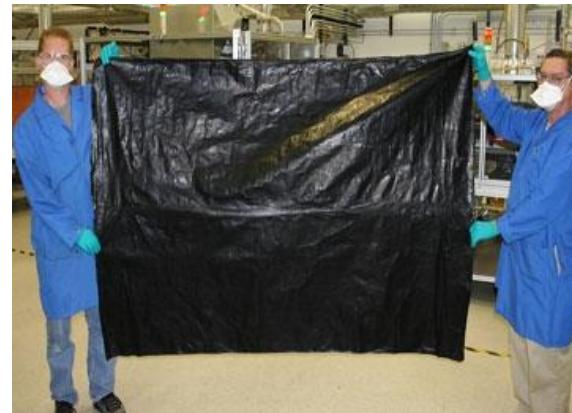
Nanowires could lead to improved solar cells



carbon nanotubes, researchers boost energy capacity of lithium batteries

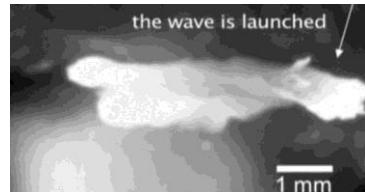


Can Carbon Nanotubes Cut Energy Consumption?



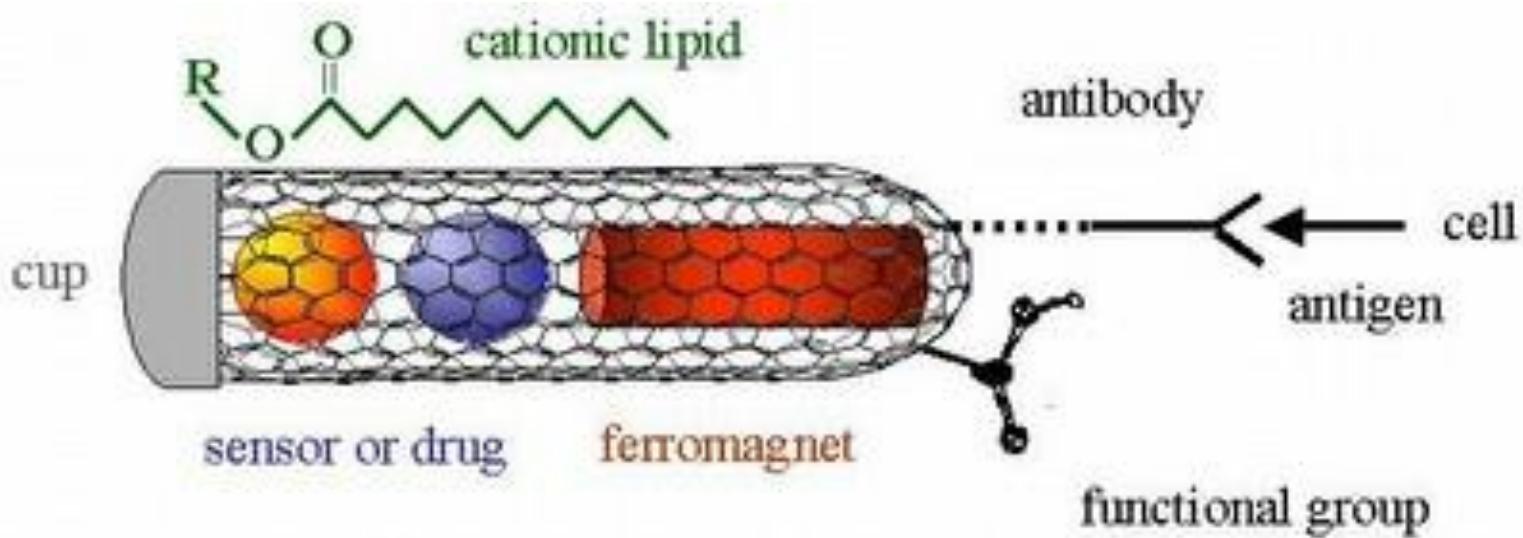
Heat channeling CNTs:

That set off a fast-moving heat wave that traveled through the nanotube's hollow cylinder 10,000 times faster than in the reactive fuel itself, and reached a temperature of 4,940 degrees F (3,000 Kelvin). The moving heat also pushed electrons along the nanotubes and created a noticeable electrical current.



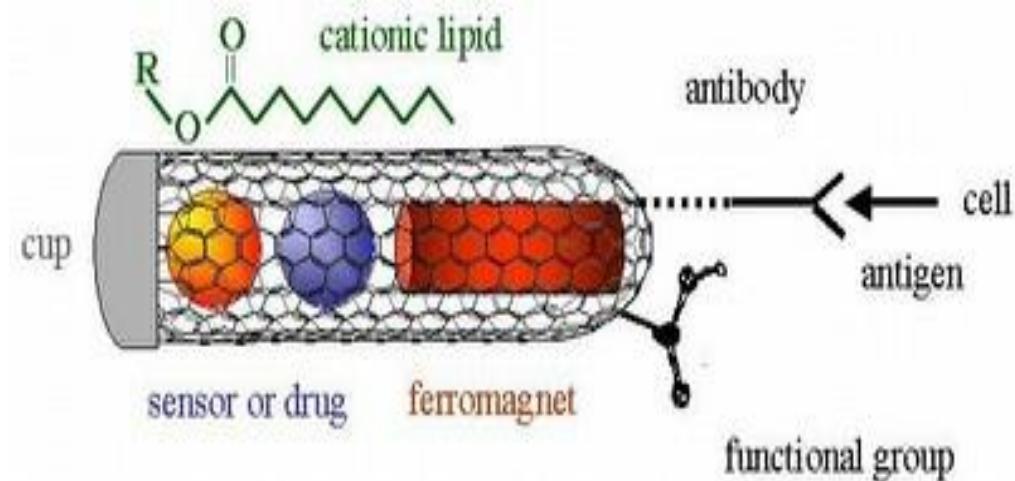
Howard 2012

Filling CNTs



- Unusual electrical & mechanical properties.
- Hollow interior => nanometer-sized capillary
- Investigate dimensionally confined phase transitions
- Template to create **nanowires** & **nanomagnets**
- Hybrid materials **ferroelectric + ferromagnet** for NEMS

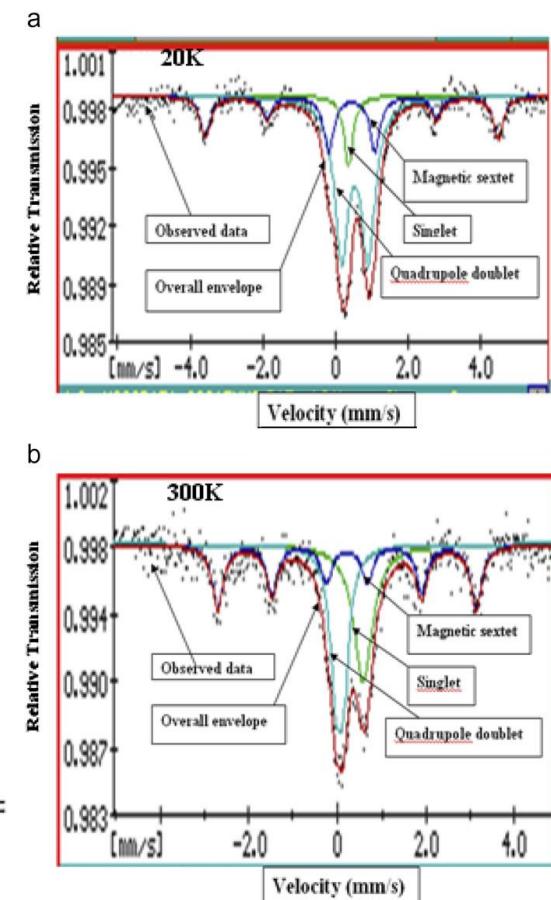
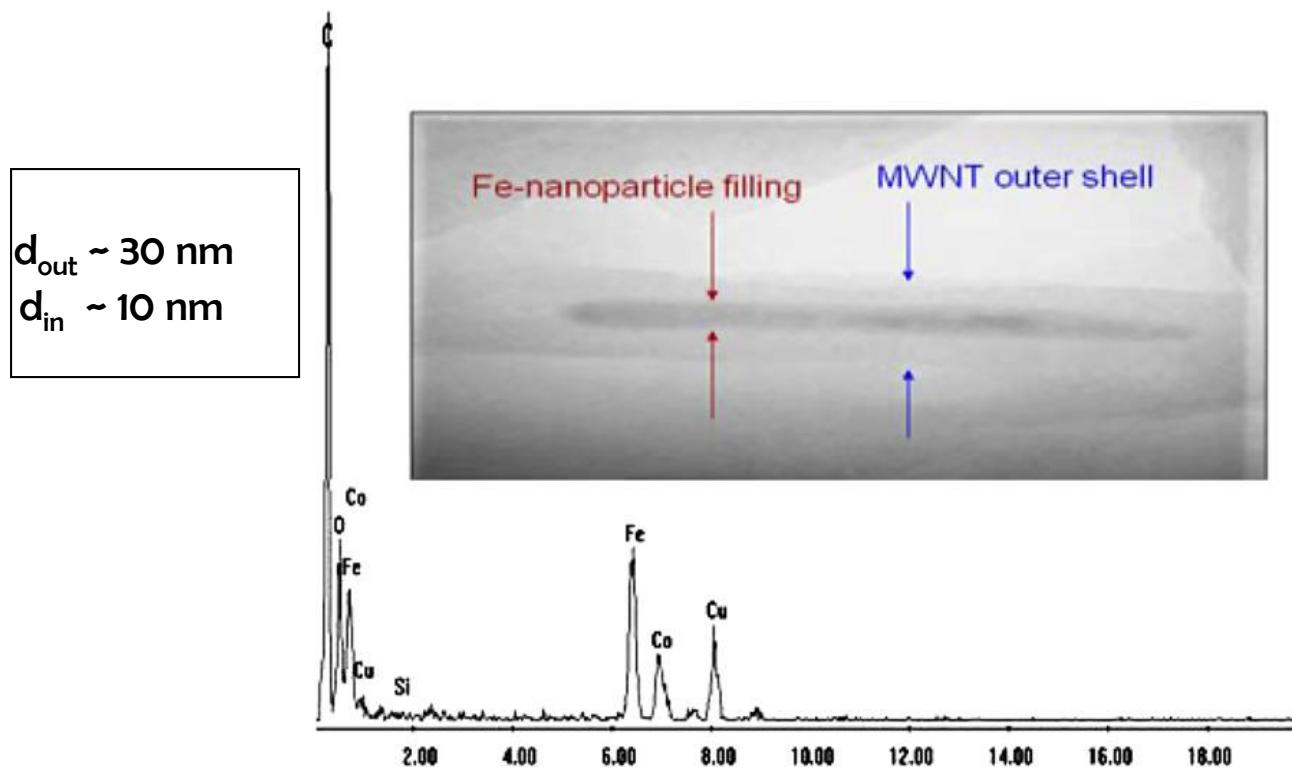
Filling CNTs



Approaches to Fill CNTs:

- Chemical method
- Physical method
 - Magnetron sputtering (DC and RF)
 - Pulsed Laser Deposition Filling
- Vapor-transport method

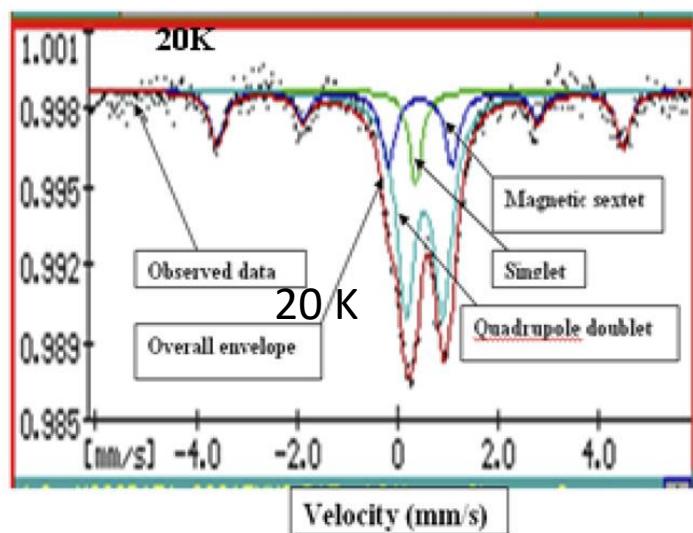
Chemical Method



Seifu, et al JMMM 320 (2008) 312–315

Mössbauer Measurements

a



b

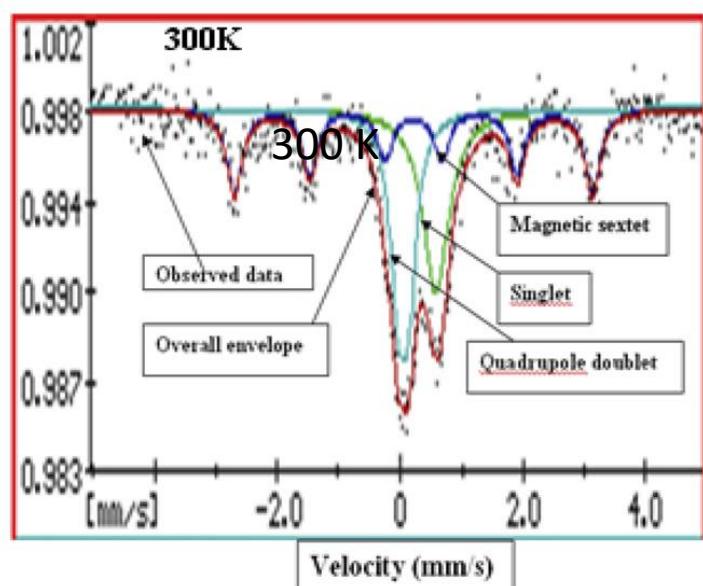
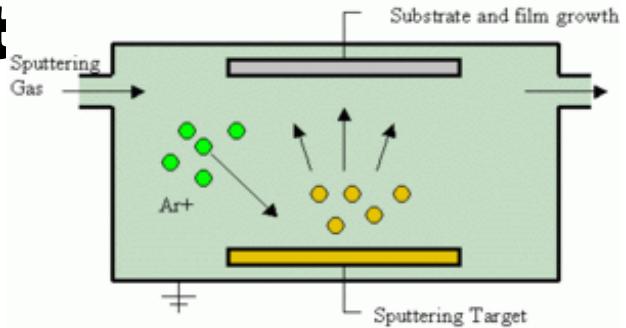


Table 1

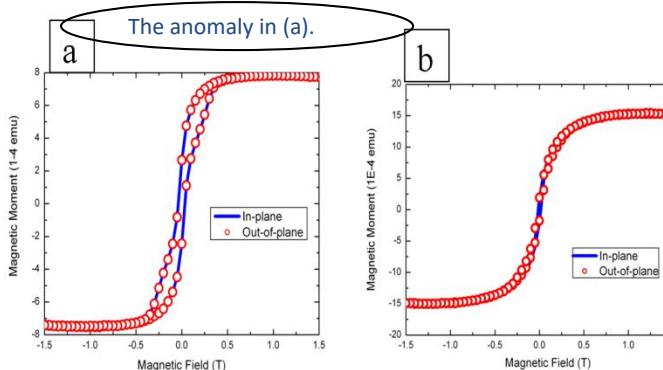
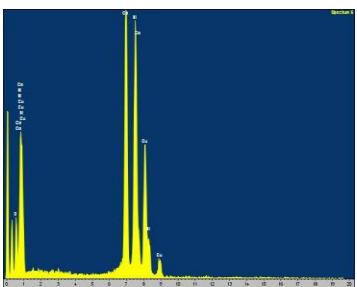
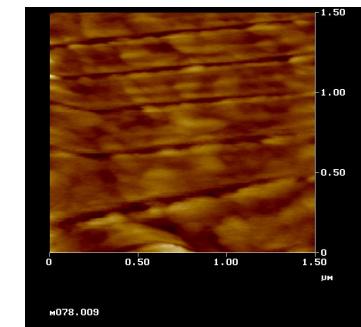
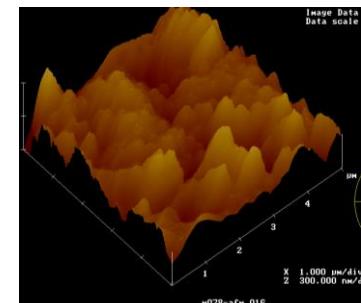
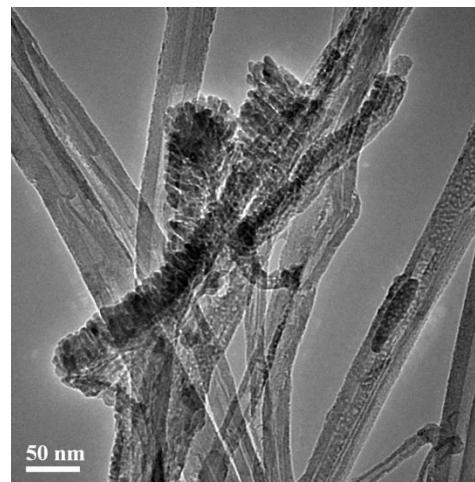
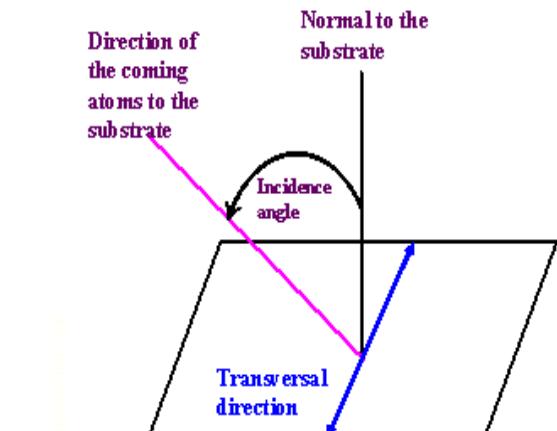
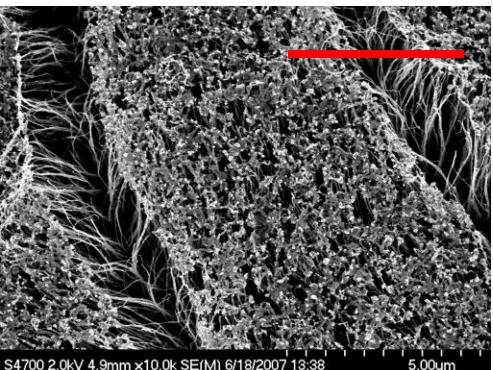
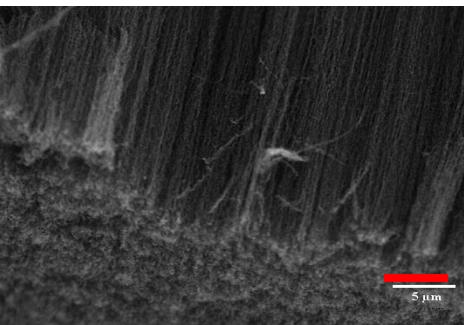
The ^{57}Fe Mössbauer hyperfine parameters for MWCNTs filled with $\text{Sm}_2\text{Fe}_{17}\text{N}_x$ at temperatures of 20 and 300 K

	20 K	300 K
Sextet		
A (%)	32	38
IS (mm/s)	0.43	0.21
H (kOe)	251	182
Quadrupole		
A (%)	59	32
IS (mm/s)	0.51	0.04
QS (mm/s)	0.73	0.18
Singlet		
A (%)	9	30
IS (mm/s)	0.34	0.58

DC Magnetron Sputt



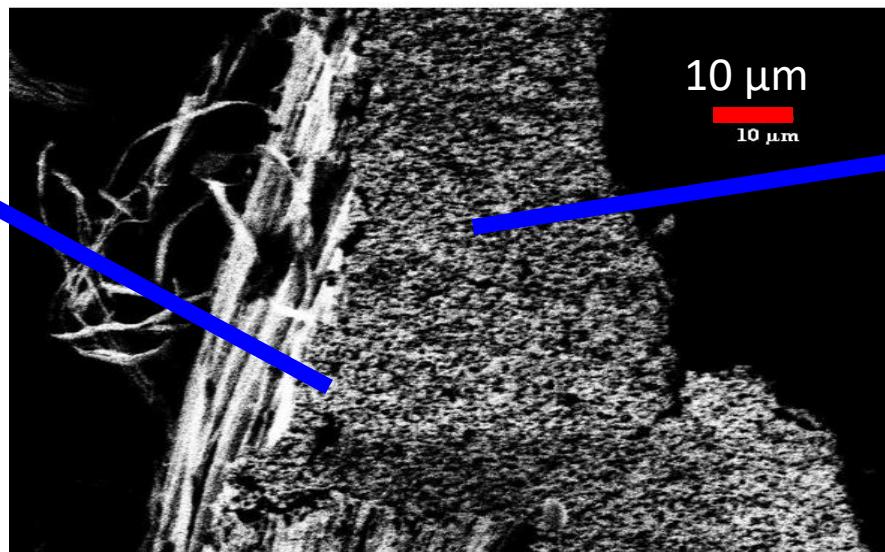
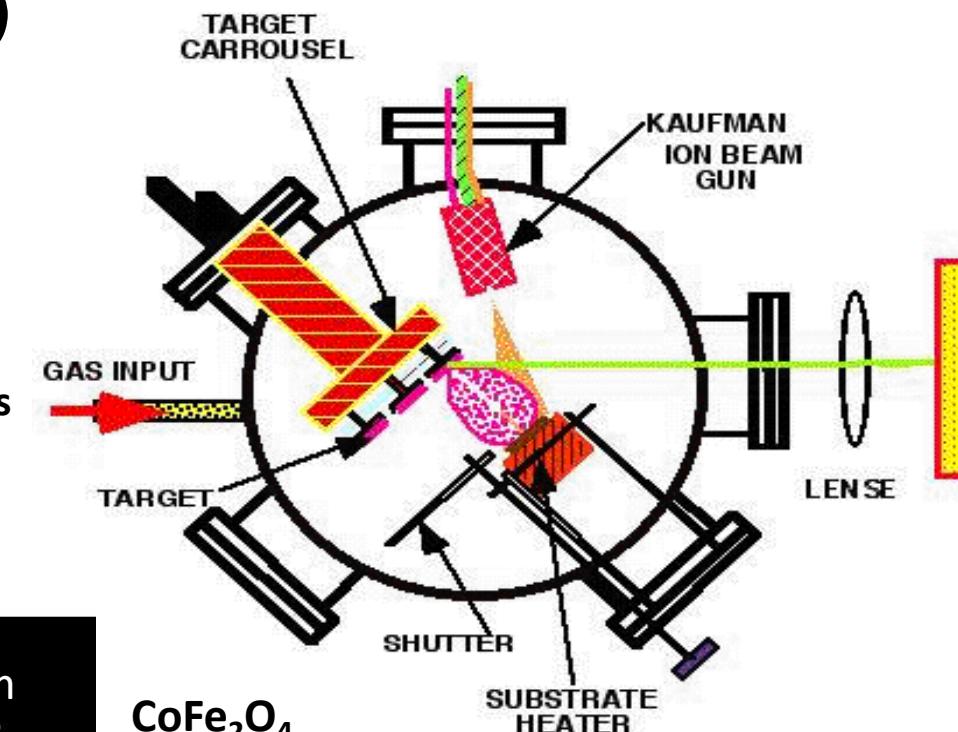
Vertically aligned MWCNTs grown by CVD on SiO_2 filled with Fe and CoNi



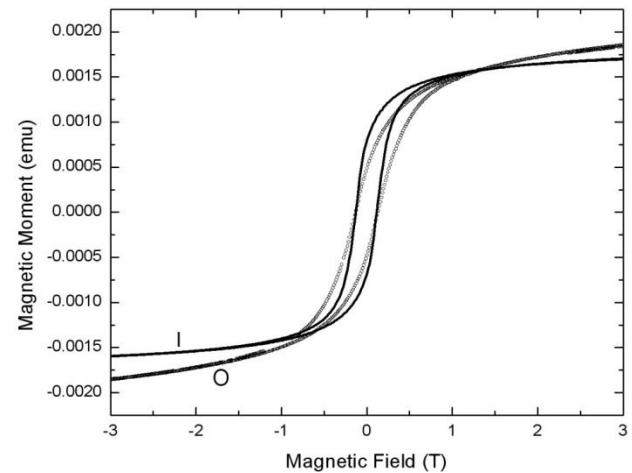
Pulse Laser Filling (PLD)

$P=2 \times 10^{-7}$ Torr, Excimer laser (KrF)

$E=1.5 \text{ J/cm}^2$, $F=3 \text{ Hz}$ $T=300 \text{ }^\circ\text{C}$, 12,000 shots fired to fill CNTs.



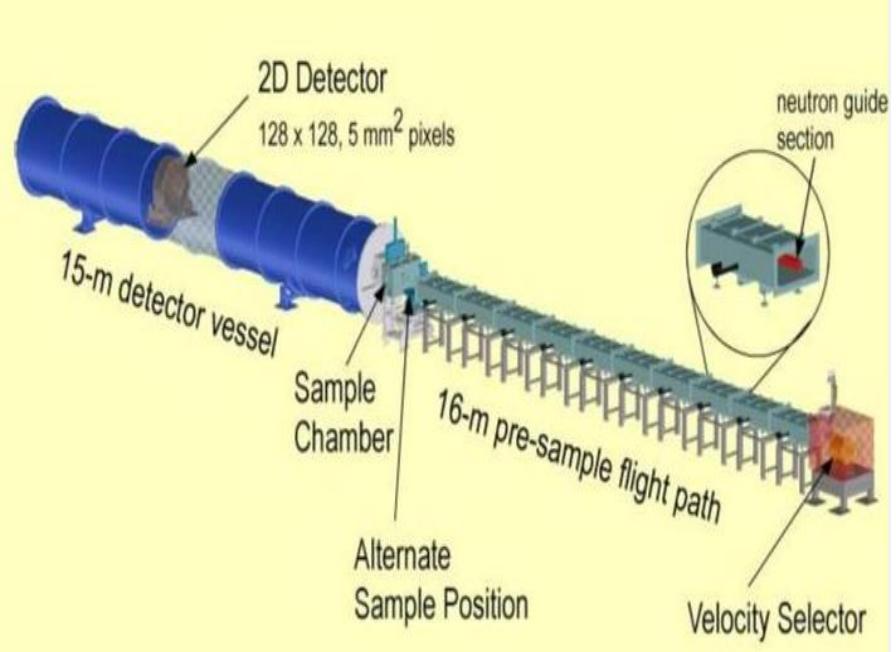
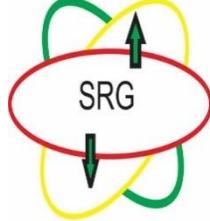
CoFe_2O_4



SEM of vertically grown MWCNTs on SiO_2 filled with CoFe_2O_4 by PLD.

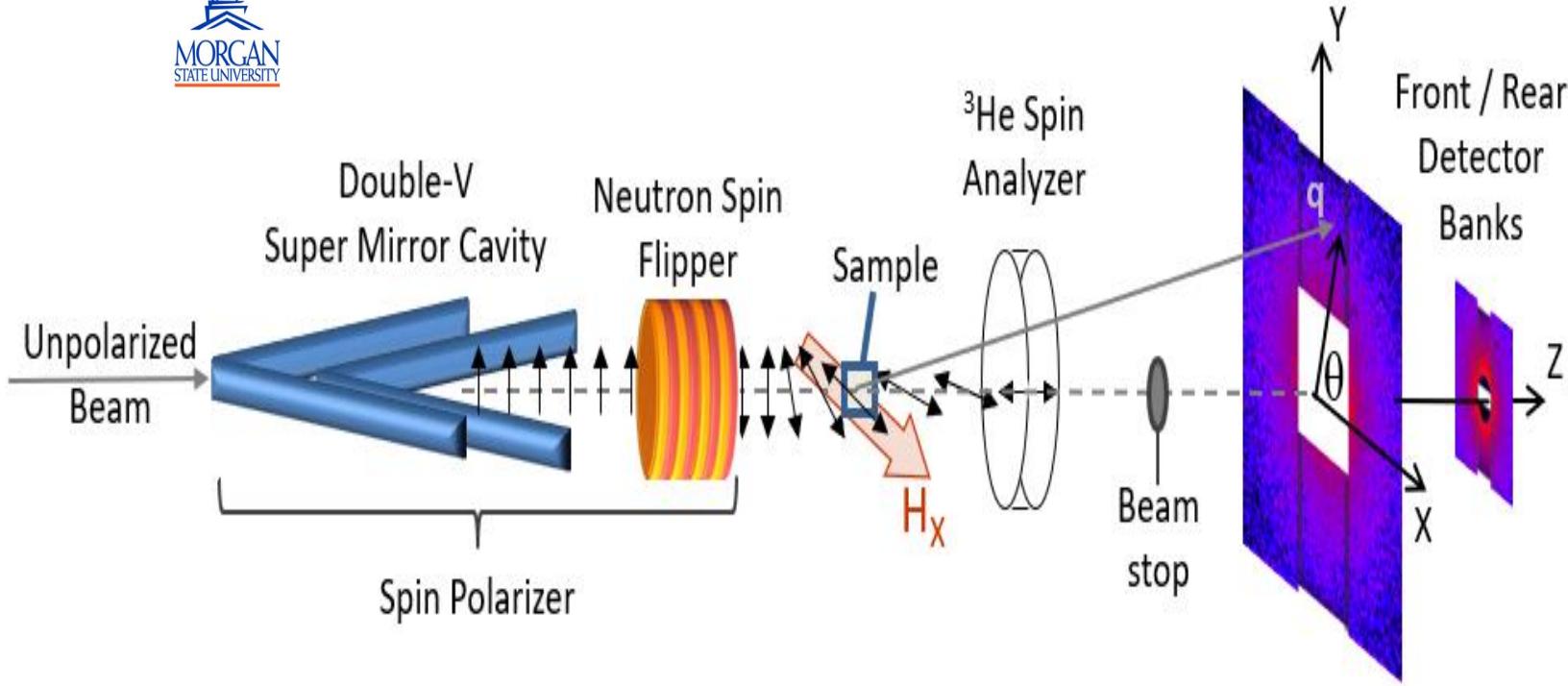
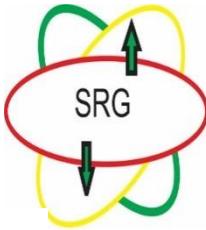
Howard 2012

THE SANS CHARACTERIZATION OF CNT-CFO AT NIST (SPECIFIC AIM 5)



- The 30m SANS instrument of NCNR at NIST

HOW SANS WORKS?



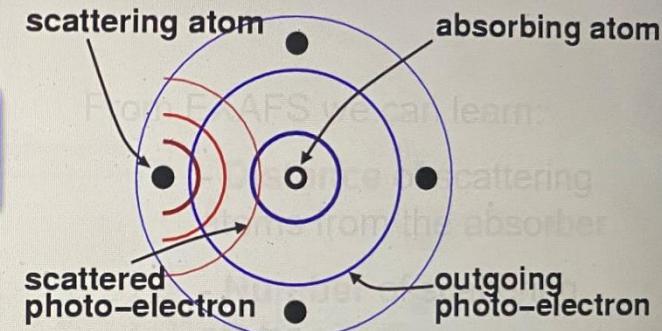
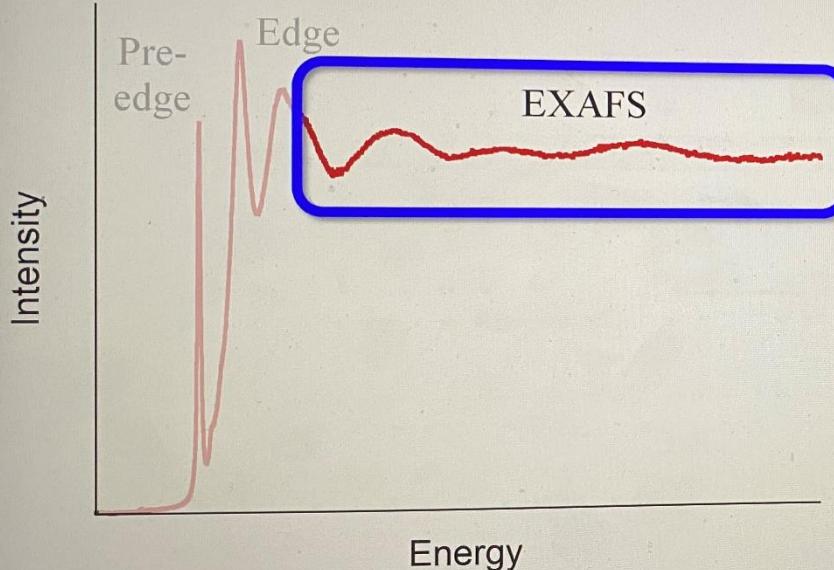
- A schematic of the VSANS instrument set-up

EXAFS



Extended X-ray Absorption Fine Structure (EXAFS)

Talking:



Once an electron is ionized from an atom, it can scatter off the electron clouds of adjacent atoms, giving rise to oscillations in the absorption signal (EXAFS)

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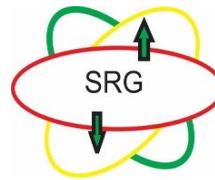
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- D. Seifu**, S. Karna, Carbonaceous magnetic nanocomposites, Bulletin of the American Physical Society, 65 (2020). T. Mekuria, H. Verma, **D. Seifu**, H. Hong, S.P. Karna, Carbon Nanotubes and CoFe_2O_4 Nanoparticles Composite for Nanomagnetic Sensors, 2018 IEEE 18th International Conference on Nanotechnology (IEEE-NANO), IEEE, 2018, pp. 1-2.
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Ph.D. MENTEES

- Ph.D. in BioEnvironmental Science Dissertation: Carbon Nanotube Magnetic Nanoparticle Composite as Nano Sensor for Monitoring Heavy Metals in Water **Tassachew Mekuria**, Morgan State University, ProQuest Dissertations Publishing, 2020. 27830194.
Advisor: Dr. Dereje Seifu

Acknowledgment



CURRENT MEMBERS OF RESEARCH GROUP

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- Mr. Shaan Sharma (Ph.D. Student 2021 - Present)
- Ms. Jyotsna Das (Ph.D. Student 2019 - Present)
- Mr. Brook Daba (M.Sc. Student 2019 - Present)

POSTDOCTORAL MENTEES

- [Dr. Himanshu Verma](#) Postdoctoral Research Associate from 2016 to 2017.
- [Dr. Suman Neupane](#) Postdoctoral Research Associate from 2014 to 2015.

Ph.D. MENTEES

- [Ph.D. in BioEnvironmental Science Dissertation: Carbon Nanotube Magnetic Nanoparticle Composite as Nano Sensor for Monitoring Heavy Metals in Water](#) Tassachew Mekuria, Morgan State University, ProQuest Dissertations Publishing, 2020. 27830194. Advisor: Dr. Dereje Seifu
- Ph.D. in Industrial and Computational Mathematics: Applied Mathematics in Density Functional Theory, Papa Seck, Morgan State University Advisor: Dr. Dereje Seifu

M.Sc. MENTEES

- Masters of Science in Physics Thesis: Magneto-Optics Kerr Effect Instrumentation **Newman, Alexander**. Morgan State University, 2015. **Advisors: Dr. Dereje Seifu**
- Masters of Science in Physics Thesis: Tunneling Magnetoresistance In Iron (Fe) / Topological Insulator / Iron (Fe) **Aryee, Dennis**. Morgan State University, 2017. **Advisors: Dr. Dereje Seifu**
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- Masters of Science in Science Thesis: Crystallization of Lysozyme on Metal Surfaces Using a Monomode Microwave System," **K. Mauge-Lewis**, Morgan State University, 2016. **Advisors: Dr. Kadir Aslan and Dr. Dereje Seifu**
- Masters of Science in Science Thesis: "Molecular Dynamics Investigation of Single-Walled Carbon Nanotube Interactions with Soluble Proteins," **Aryan Vahedi**, Morgan State University, 2015. **Advisors: Dr. James Wachira and Dr. Dereje Seifu**

REU STUDENTS

M. Stevens (1998), B. Holloway(2004), H. Wibeley (2004), Dr. N. Mosengue (2016), Dr. S. Khatiwada (2008), D. Kassaye (2008), D. Thompson (2010), A. Hadgu (2010), Dr. A. KC (2014), A. Newman (2014), D. Ayree (2014), K. Kamafrika (2015), T. Moody (2020)

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