Integrating Condensed Matter Physics into a Liberal Arts Physics Curriculum

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Condensed matter physics had an image problem, until...

Zeppenfeld & Eigler (1991)

Crommie, Lutz & Eigler (1995)
Challenges for Educators

- Attract more students to STEM disciplines
- Communicate the increasingly interdisciplinary nature of scientific research

Nanoscience and nanotechnology have opened a new window into public consciousness.
Special Challenges in Liberal Arts Colleges

• BA physics majors typically take no more than 10-14 physics courses.
• Specialization into subfields is not built into the curriculum, but instead comes with collaborative work with a faculty member.
• Limited potential to introduce new, specialized courses.
• New approaches need to be integrated into existing curricular structure.
Nanoscience in the Physics Curriculum

- Provides a means to reach out to prospective science students.
- Provides examples of contemporary research problems that can be integrated into standard courses.
- Provides an interdisciplinary flavor.
Signature Programs at Lawrence

• Educational programs that grow from a faculty member’s research expertise
• Use special facilities to connect a broad spectrum of students to an important area of physics.
  – Recruit prospective students by exposing them to a contemporary field
  – Provide experience to all physics majors, not just those involved in collaborative research.
  – Provide a distinctive teaching perspective.
Present Programs

• Laser Spectroscopy (John Brandenberger)
• Computational Physics (David Cook)
  – Began with chaos simulations but is moving to astrophysical modeling.
• Nanoscale Imaging and Structure (Jeff Collett)
  – Structural measurements with scanning probe microscopy & X-ray scattering are used to understand condensed matter.
Structural Measurement Capability

• Scanning Probe Microscopes
  – Six Nanosurf Easyscan STM’s
  – Two Nanosurf Easyscan AFM’s (contact mode only)
  – Park Instruments XE-100 multimode scanning probe microscope
    • Contact and Non-Contact Modes
X-ray Diffraction Facility

- Bruker AXS GADDS system with HiStar multiwire proportional counter.
- Locally developed software to combine multiple exposures into a three dimensional reciprocal space map.
Integrating Fundamental Condensed Matter Science into the Curriculum Using Structural Experiments

- Quantum Tunneling in Introductory Modern Physics
- Imaging unit in Introduction to Nanoscience and Nanotechnology Course (Chemistry Dept.)
- STM and AFM use in Advanced Physics Lab experiments
- Breaking the reciprocal space barrier in solid state physics with diffraction and AFM.
- Nanoscience special topics in other courses
- AFM imaging of liquid crystal surfaces (student independent research)
Outreach

• Outreach activities
  – STM unit in outreach program for high school and community college chemistry teachers supported by NSF-NUE grant.
  – Lawrence Physics Workshop units in STM and AFM imaging for high school students.
    • Students make images of the surface of graphite and of arrays of nanospheres as part of day of a lab-intensive experiences.
STM Imaging in Introductory Modern Physics (Freshman Physics)

- Imaging Graphite—reliable 3-hour experiment
- Objectives:
  - Create an image at atomic scale and compare with graphite model.
  - Explore simple barrier model of quantum tunneling
    - Measure $I_{\text{tunnel}}$ vs height
    - Measure $I_{\text{tunnel}}$ vs bias voltage
  - Expose limitations in simplest model to show that surfaces need to be considered more carefully.
What’s In an Image?

• Peak to Peak Spacing = 0.24 nm
Where are the atoms?

• Bright spots correspond to points where the tip was moved toward the sample surface.

Atoms are actually located in the dark regions!
Basic Quantum Tunneling Model

\[ I_t(d, V_t) = A(V_t) eV_t e^{-2\kappa d} \]

\[ \kappa = \sqrt{\frac{2m}{\hbar^2}} \Phi \]

Assumptions:
- Large gap
- Square Barrier
- Electron tunnels from Fermi Level
Current starts to grow but the curve bends over; it’s not exponential over the whole range.

The simple model only applies for wide gaps.
Wide Gap Fits

- Plot semilog graph of $I_t$ vs $z$ for the smallest currents.
- Linear fit gives $2\kappa = \sqrt{\frac{2m\Phi}{\hbar^2}}$
- A fit of the work function gives a value of about 0.7 eV compared with photoelectric effect measurements of about 4.5 eV. The potential for electrons never reaches the vacuum level. The surface model needs a closer look.
Introduction to Nanoscience and Nanotechnology (Chemistry 225)

• Open to students with introductory physics, chemistry, or biology.

• Course breakdown:
  – Size Matters
  – Synthesis of Nanoparticles
  – Imaging at the Nanoscale: STM & AFM
  – Biological Applications
  – Nanoscience in the Scientific Literature
N&N Imaging Unit-STM

- Quantum Tunneling
- Graphite Lab (Imaging)
- Image Gold Nanoparticles
N&N AFM Introduction

- AFM uses deflection of laser to detect cantilever bending

Diagram:
- Laser
- Cantilever
- Four-quadrant Detector
- Sample

Four-quadrant Detector senses bending and twisting of the cantilever.
Modes of Interaction

http://www.mechmat.caltech.edu/~kaushik/park/1-2-2.htm
Non-contact Mode

• Tip driven at resonant frequency
• In non-contact region the sample tip interaction varies approximately linearly with separation
• In this region if the tip is oscillating the effective spring constant becomes
• The resonant frequency drops along with the response of the tip to the driving force
• Phase also shifts dramatically at resonance

\[ \omega_0 = \sqrt{\frac{k}{m}} \]

\[ F_s = -F_0 + k_1 z \]

\[ k_{\text{eff}} = k - k_1 \]

\[ \omega_1 = \sqrt{\frac{k_{\text{eff}}}{m}} \]

\[ \delta(\omega) = \tan^{-1} \frac{\gamma \omega}{\omega_0^2 - \omega^2} \]
Response of Noncontact Cantilever

\[ f_0 = 281.75\text{kHz} \]
NCM : Polystyrene Spheres
NCM: Line Profile
Breaking the Reciprocal Space Barrier

- Bragg Picture:

\[ n\lambda = 2d \sin \theta \]

- Bragg Picture:

  - \( d \): spacing between planes of atoms
  - \( \theta \): angle of incidence
  - \( \lambda \): wavelength of the incoming beam
  - \( n \): order of reflection

Incoming beam

Scattered beam

\( 2\theta \)

d = spacing between planes of atoms
Fourier Picture

\[ S(\vec{k}_{out} - \vec{k}_{in}) = \int \langle \rho(\vec{r}) \rho(0) \rangle e^{-i(\vec{k}_{out} - \vec{k}_{in}) \cdot \vec{r}} d^3 \vec{r} \]

Constructive Interference: \( \vec{G} \) is perpendicular to Bragg planes

\[ |\vec{G}| = \frac{2\pi}{d} \]
Developing Intuition for the Fourier Picture

- Perform set of experiments to reinforce connections.
- Look at extensions to Fourier picture to include inelastic scattering of x-rays.
- Connect to use of Fourier picture in processes involving electrical and thermal conduction.
Experiment 1: Powder Diffraction (Almost)

• Pre-lab: Use reciprocal lattice to calculate plane spacings in aluminum

• Data shows peaks from individual crystals
Curve Fits

<table>
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<tr>
<th>Peak#</th>
<th>D-Spacing</th>
<th>2-Theta</th>
<th>Intensity</th>
<th>FWHM</th>
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Relation of G to Crystal Planes

- Sample: Planes parallel to surface
  - HOPG monochromator
  - Cleaved MgO Crystal

- Find 1\textsuperscript{st} and 2\textsuperscript{nd} order peaks and show that constructive interference occurs only when the sample has the correct orientation. \( \vec{G} \) is always perpendicular to the surface of the crystal
3D Crystal: heptyloxybenzilidinedihexyloxybenzilidine-heptylaniline (Modified HCP)

- Lattice + Basis

\[
\vec{a}_1 = a(1,0,0) \\
\vec{a}_2 = a\left(\frac{1}{2}, \frac{\sqrt{3}}{2}, 0\right) \\
\vec{a}_3 = c(0,0,1) \\
\vec{r}_1 = (0,0,0) \\
\vec{r}_2 = \frac{1}{3}(\vec{a}_1 + \vec{a}_2) + \frac{1}{2}\vec{a}_3
\]

- Reciprocal Lattice

\[
\vec{b}_1 = \frac{4\pi}{a\sqrt{3}} \left(\frac{\sqrt{3}}{2}, -\frac{1}{2}, 0\right) \\
\vec{b}_2 = \frac{4\pi}{a\sqrt{3}} (0,1,0) \\
\vec{b}_3 = \frac{2\pi}{c} (0,0,1)
\]
Slice Through X-Y Plane
The Fourier Picture in Scanning Probe Microscopy

Real Space Image

Fourier Image
Inelastic Scattering

• Lattice vibrations (phonons) cause atoms to oscillate about their equilibrium positions.

• Scattering process produces scattering away from reciprocal lattice points.

\[ \vec{r}_{\text{atom}} = \vec{R} + \vec{u}(\vec{q}) \cos(\vec{q} \cdot \vec{R} - \omega_q t) \]

\[ \vec{k}_{\text{out}} - \vec{k}_{\text{in}} = \vec{G} + \vec{q} \]

\[ \omega_{\text{out}} = \omega \pm \omega_q \]

\[ \text{Intensity} \propto \alpha (\vec{G} \cdot \vec{q})^2 \]
Layer Sliding Modes in Heptyloxybenzilidene-heptylaniline

• Molecular layers slide easily over one another leading to modes with polarization in the xy plane and a wave vector in the z direction.

\[ \vec{u} = u_0 \hat{x} \cos(qz - \omega_q t) \]
Ridges of scattering from phonons
Connection to Other Processes

- Elastic scattering of electron waves through reciprocal lattice vectors opens band gaps
- Inelastic scattering by phonons or defects produces electrical resistance and limits thermal conductivity.
Other Nanoscience Examples

• Quantum Dots
  – Spherical Quantum Well in Quantum Mechanics
  – Bandgap of CdSe Quantum Dots grows by nearly 1eV as radius shrinks
  – Energy levels stay discrete.
    • Charge States Cause Coulomb Blockade
    • Single electron transistor
One Dimensional Systems

• Carbon Nanotubes
  – 1D subbands from discrete quantization around the circumference of the tube.
  – Properties of graphene can vary from metallic to semiconducting depending on the circumference of the tube.

• 1D Metals show conductance quantization in multiples of $2e^2/h$ as more subbands become occupied.
Undergraduate Research Example: Surface Structure of a Molecular Crystal

• Experimental Challenge: Map the surface of a soft molecular crystal with modulated layers to see if modulation extends to the surface.

• Because of temperature sensitivity of sample, both sample and tip must be heated to 60°C
Liquid Crystal Film Device

Wiper

Film

Calibration Sample
AFM Heated Tip Modification

Thermoelectric Device

To Temperature Controller

RTD

Wafer

Cantilever
Results: Maps of Layer Steps
Profiles of Layer Steps
Conclusions

- Nanoscale imaging is a powerful tool for recruiting, teaching, and engaging prospective scientists.
- Condensed Matter Physics can be integrated into the undergraduate curriculum in a liberal arts setting by incorporating key exercises and ideas into existing courses.
Support

• Grant from W. M. Keck Foundation to establish signature program in surface physics with scanning probe microscopy.
• NSF-NUE grants to develop the nanoscience and nanotechnology program.