PHYS 666: Solid State Physics I

INSTRUCTOR
Michel van Veenendaal
Office: FW223, Phone: 815-753-0667 or 630-252-4533
E-mail: veenendaal@niu.edu
Office Hours: I am around Tuesdays and Thursdays
Web page with lecture notes: www.niu.edu/~veenendaal/666.htm

PREREQUISITES:
This course will be tough without having done quantum mechanics (560/1 or something equivalent)

Mathematical concepts:
Fourier transforms
differential equations (Schrödinger equations)
linear algebra (matrices, eigenvalue problems)

• Homework: several homework sets will be given. They will be posted on the web site.
• Midterm: one midterm will be given.
• 1986-90: undergraduate Delft University of Technology (Ir.), the Netherlands
• 1990-94: Ph.D. University of Groningen (Dr.), the Netherlands
• 1994-97: European Synchrotron Radiation Facility, Grenoble, France
• 1997-98: NIU
• 1998-2002: Philips Electronics
• 2002-present: NIU
  o 2002-2008 Associate Professor
  o 2008- Professor
  o 2009-2013 Presidential Research Professor

• 2005-present: joint with Argonne National Laboratory (Physicist)

Theoretical physicist
specialty: condensed matter physics
REQUIRED TEXTBOOK:
Solid State Physics
by N. W. Ashcroft and N. D. Mermin
(Harcourt, 1976).

REFERENCED TEXTBOOK
Introduction to Solid State Physics
7th Edition by C. Kittel
(John Wiley & Sons, 1996).
Solid State Physics vs. Condensed-Matter Physics

- Condensed-matter physics is the more modern term
- Condensed-matter physics is broader and applies to concepts that work in solids, but could equally applied to liquid (for example, superconductivity vs. superfluidity, soft-condensed matter)
- 1978 Division of Solid-State Physics of the American Physical Society went to the Division of Condensed-Matter Physics
- 1/3 of U.S. physicists classify themselves as Condensed-Matter Physicists
- Condensed-matter physics is closely related and overlaps with inorganic chemistry, physical chemistry, quantum chemistry, electrical and mechanical.
WHY DO WE WANT TO DO SOLID STATE PHYSICS?
A significant increase in the rate of discovery, innovation and technological change is needed. BES must lead a bold new initiative focused on solving the critical scientific roadblocks in next-generation, carbon-free energy technologies.

Significant discoveries will come at the intersection of control science with advanced materials and chemical phenomena, and there is a clear first-mover advantage to those who focus their research efforts here. BES must lead U.S. energy research efforts in this direction lest the U.S. fall behind in global competition for discoveries of future energy sources and systems.

It will take “dream teams” of highly educated talent, equipped with forefront tools, and focused on the most pressing challenges to increase the rate of discovery. BES must lead the development of these dream teams to close gaps between needs and capabilities in synthesis, characterization, theory, and computation of advanced materials.

U.S. leadership requires BES to lead a national effort to aggressively recruit the best talent through a series of workforce development and early career programs aimed at inspiring today’s students and young researchers to be the discoverers, inventors, and innovators of tomorrow’s energy solutions.
Nanoscience
Catalysis, photosynthesis

Batteries

Superconductivity

Solid-state lighting

Solar cells
New electrode materials
WHAT IS A SOLID?
A solid is generally seen as a nice crystal made up of atoms.

And we will generally be dealing with those.
BUT ALSO

heterostuctures

Amorphous materials

Soft condensed matter

Conducting polymers

Before you are able to deal with this, we have to get through the basics
Structure (nuclei)

- Superconductivity
- X-rays: Bragg-reflection
- Neutron scattering

Electronic structure (electrons)

- Conduction of light, sound
- Thermal properties
- magnetism
- Optical properties
- Electrical properties

Interaction with external fields

- Reactivity catalysis

Mechanical properties

- Surface
- Impurities

E-M radiation: spectroscopy

Light: optics

Neutron scattering: magnetic
HISTORY OF SOLIDS....
Whole ages are classified by our ability to control solids

Stone age

bronze age
(3300–1200 BC)

17th century BC.

China (1600–1046 BC).

iron age
(1200 BC till present?)
Even our information age relies on our ability to manipulate materials (Si)
Ancient cultures:

Aristotle (384 BC – 322 BC)

Modern: solid, liquid, gas, combustion/chemical reactions
People recognized early on the difference in properties between metals

Philosopher’s stone turning common metals into gold
EARLIER THEORIES TO DESCRIBE SOLIDS
Obviously, scientists tried to deal with solids before atoms and electron

- Mechanics
- Optical properties
- Thermal conductivity
- Conductive properties

Many of these questions can be addressed without understanding the underlying nature of a material

Of great importance is the strong development of calculus and differential equations starting from Newton and Leibniz, through Euler (1707–1783), Gauss (1777–1855) through the French schools (Ecole polytechnique/normale/militaire): Lagrange (1736–1813), Laplace (1749–1827), Fourier (1768–1830), Navier (1785–1836), Cauchy (1789–1857), Poisson (1781–1840), etc.

Condensed-matter physics tries to connect the properties of the nuclei and electrons to the macroscopically observed quantities
Continuum mechanics

Hooke’s law

\[ F = -kx \]  \hspace{1cm} (1676)

*Ut tensio, sic vis*

As the extension, so the force.

Euler-Bernoulli equation:

\[ \frac{\partial^2}{\partial x^2} \left( EI \frac{\partial^2 u}{\partial x^2} \right) = w. \]  \hspace{1cm} (1750)

- \( u \) deflection of the beam at some position \( x \)
- \( w \) is a distributed load or a force per unit length
- \( E \) is the elastic modulus
- \( I \) is the second moment of area
Augustin Louis Cauchy (1789 –1857)

Cauchy stress tensor

\[
\sigma_{ij} = \begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{bmatrix} \equiv \begin{bmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{bmatrix} \equiv \begin{bmatrix}
\sigma_{x} & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \sigma_{y} & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \sigma_{z}
\end{bmatrix}
\]

How are the underlying atomic properties related to the elasticity?

(1822)
Interactions of radiation and matter

Reflections, color, refraction, absorption are all manifestations of interactions of radiation and matter.

Euclid (~300 BC) already wrote a book on Optics.

Lenses: Lippershey, Janssen, Galileo

\[ \frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \]

Snell’s law is a direct consequence of the electronic properties of the material.

What determines the optical properties of a material: opaque, reflecting, transparent?
Late 18th and 19th century: mechanical approach to condensed matter physics

- optical theories by Thomas Young and Jean Fresnel
- A wide variety of theories on elasticity (Navier, Cauchy)
- Theories for heat conductivity by Joseph Fourier
Thermal conductivity

Newton's law of cooling

\[ \frac{dQ}{dt} = h \cdot A(T_{\text{env}} - T_0) \]  

(1643-1727)

Fourier’s law

\[ q_x = -k \frac{dT}{dx} \]  

(1822)

- \( q \) is the local heat flux,
- \( k \) is the material's thermal conductivity
- \( dT/dx \) is the temperature gradient

Why do materials have different thermal properties?

Joseph Fourier  
(1768–1830)
• Interaction between light and matter, theory of birefringence by Franz Neumann

• Early theories of electrical conductivity by, among others, George Ohm and Gustav Kirchhoff
Crystal structures

• First scientific approach René-Just Haüy (1743-1822) using an atomistic picture

  • Extended by Christian Samuel Weiss, introduced crystallographic axis

  • Auguste Bravais: discovered the 14 space lattice types
  • Woldemar Voigt classified the 230 different space groups
THE RISE (and fall) OF THE ATOMICISTIC PICTURE
Leucippus (first half of 5th century BC)
Democritus (c. 460 BC – c. 370 BC)

The *Atomos* Concept

Smallest atom cannot be divided any further

Greeks: atoms determine properties

water → iron

Dalton: atoms determine composition

Aristotle: Horror vacui
Johannes Kepler (1571 –1630)

*Strena Seu de Nive Sexangula*
*A New Year's Gift of Hexagonal Snow*

The Kepler conjecture
Corpuscular theory

Let the cavity contain very minute corpuscles, which are driven hither and thither with a very rapid motion; so that these corpuscles, when they strike against the piston and sustain it by their repeated impacts, form an elastic uid which will expand of itself if the weight is removed or diminished..."
In physics atomistic ideas were pushed to the background in the late 18th and most of the 19th century

Unreasonable:
Not if one considers the enormous successes of continuum theories in
• Mechanics
• Thermodynamics (i.e. not statistical)
• Electricity and magnetism
• Optics

“Who needs atoms?” reigned during this period.
Not so in chemistry:

I. Law of Conservation of Mass

II. Law of Definite Proportions
Mass relationships during chemical reactions:
copper carbonate (CuCO₃) always gives 51.5% copper, 38.8% oxygen, and 9.7% carbon

III. Law of Multiple Proportions

1 g Carbon + 1.33 g O $\rightarrow$ CO
1 g Carbon + 2.66 g O $\rightarrow$ CO₂
Ratio first and second oxide 1:2
Dalton’s law of partial pressures

\[ P_{\text{total}} = p_1 + p_2 + \cdots + p_n \]

John Dalton (1766 –1844)
Culmination in Mendeleyev’s Periodic table

Dmitri Mendeleyev (1834 –1907),
REVOLUTION IN PHYSICS
$E = h\nu$

Quantum energy of a photon.

$h = \text{Planck's constant} = 6.626 \times 10^{-34} \text{ Joule}\cdot\text{sec} = 4.136 \times 10^{-15} \text{ eV}\cdot\text{s}$

The wavelength of the peak of the blackbody radiation curve gives a measure of temperature.

$\lambda_{\text{peak}} = 2.898 \times 10^{-3} \text{ m}\cdot\text{K}$

Energy per unit volume per unit frequency

$S_\nu = \frac{8\pihc}{c^3} \frac{\nu^3}{e^{\hbar\nu/kT} - 1}$

Energy per unit volume per unit wavelength

$S_\lambda = \frac{8\pihc}{\lambda^5} \frac{1}{e^{h\nu/\lambda kT} - 1}$
Classical electron theory

- discovery of electron J. J. Thompson, Lorentz

Drude model

Treats electrons as a gas following Boltzmann statistics as opposed to Fermi-Dirac statistics. Quantities of by several orders of magnitude (gets a lucky break with Wiedemann-Franz law)
$E = h\nu$  

Quantum energy of a photon.

$h = \text{Planck's constant} = 6.626 \times 10^{-34}$ Joule·sec $= 4.136 \times 10^{-15}$ eV·s

![Graph showing kinetic energy vs. frequency for different materials](image)

![Diagram of a photovoltaic cell](image)
MODERN SOLID STATE PHYSICS

Solid state physics based on atoms generally based on quantum-mechanics (although sometimes classical mechanics)
Classical electron theory

• Drude model (1900)

Treats electrons as a gas following Boltzmann statistics as opposed to Fermi-Dirac statistics. Quantities of by several orders of magnitude (gets a lucky break with Wiedemann-Franz law)

Paul Drude (1863 –1906)
X-ray diffraction

1895: discovery of X-rays by Wilhelm Röntgen (Nobel 1901)

1912: discovery of X-ray diffraction by Max von Laue, Nobel 1914
(other contributors Ewald, Sommerfeld)

1913: interpretation by William and Lawrence Bragg, Nobel 1915
First applications of quantum mechanics

Specific heat of solids: The change in internal energy with respect to temperature experiments by Nernst

Calculations by Einstein and Deye

\[ E(k) = \omega_0 \]

Walther Nernst (1864 –1941)

Einstein

Peter Debye (1884 –1966)

Nobel Chem 1936

\[ E(k) \sim k \]
Fermi-Dirac statistics
Sommerfeld theory including Fermi-Dirac statistics

Specific heat much smaller since very few electrons participate in the conduction

Solves dilemma of Drude-Lorentz theory

Completely ignores the presence of ions!

Still fails to describe many properties...
In addition, Sommerfeld was a star in producing world-class scientists (a selection)

Albert Einstein told Sommerfeld: “What I especially admire about you is that you have, as it were, pounded out of the soil such a large number of young talents.”
**Bloch’s theorem**

Inclusion of the ions in the theory of metals

Inclusion of translational symmetry is essential

\[ \psi_k(r) = \frac{1}{\sqrt{V}} e^{ik \cdot r}, \]

Free electrons

\[ \psi_{nk}(r) = e^{ik \cdot r} u_{nk}(r), \]

Bloch electrons (Bloch’s theorem)

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Bloch and Heisenberg
Band gaps and Brillouin zones

Sir Rudolf Peierls, (1907–1995),

Léon Brillouin (1889 –1969)
Independent-particle vs. many-body physics

This is a fundamental problem in physics that is not well understood!
There are very extensive codes based on the independent-particle approximation

- Density functional theory
- Local Density Approximation
- Molecular orbital theory
- Quantum chemistry

Linus Pauling (1901-1994)  
Nobel chem 1954

Walter Kohn (1923)  
Nobel chem 1998

John Pople (1925-2004)
However, often we have to deal with many-body effects

- Effects where electron-electron interactions are important

**Mott-insulator state**

Why is NiO an insulator and not a metal?

Philip W. Anderson (1923)  
John van Vleck (1899-1980)  
Sir Nevill Mott (1905-1996)  
Nobel 1977
WHAT IS THIS?
The first transistor!
Bell-Labs (1947)

John Bardeen, Walter Brattain, and William Shockley working on the first transistor

Nobelprize 1956
Moore’s Law
Optical lithography

\[ \text{RES} = k_1 \frac{\lambda}{\text{NA}} \]
Other device technology: giant magnetoresistance

Albert Fert (1938)     Peter Grünberg (1939)
Nobel 2007

Read heads of hard drives
More exotic phenomena (only at low temperatures)
Quantized resistance, quantum Hall effect, fractional quantum Hall effect

Robert B. Laughlin (1950)
Daniel C. Tsui (1939)
Horst L. Störmer (1949)
Nobel 1998
Klaus von Klitzing (1943)
Nobel 1985
Daniel C. Tsui (1939)
Nobel 1998
EMERGENT PHENOMENA

The whole is greater than the sum of its parts.

Sometimes when you put things together new order appears

- Magnetism
- Superconductivity
- Superfluidity
An example: Antiferromagnetism

( as opposed to ferromagnetism

Louis Néel (1904 –2000)

Nobel 1970
Experimental developments:

Low-temperature physics:

**Kamerlingh-Onnes**

1908: Liquefaction of Helium

1911: Discovery of superconductivity

Heike Kamerlingh Onnes (1853 –1926)

Nobel 1913
Only explained in 1957:

Cooper pairs

John Bardeen (1908 –1991)
Leon Cooper (1930)
John Robert Schrieffer (1931)

Nobel 1972
High temperature superconductivity

Phase diagram

T

NON-FERMI-LIQUID

PSEUDO-GAP

FERMI-LIQUID

AF

SG

SC

x

Still under debate....

Johannes Georg Bednorz (1950)

Karl Alexander Müller (1927)

Nobel 1987
Infinitely fascinating, apparently, superconductors

Plus all kinds of interesting junction effects

Nobel 1973

Brian Josephson (1940)
Leona Esaki (1925)
Ivar Giaever (1929)

Alexei Abrikosov (1928-)
Nobel prize 2004
A strongly related phenomena (especially theoretically) is superfluidity.

Helium II

Lev Landau (1908 – 1968) Nobel 1962

Sir Anthony Leggett, KBE, FRS (1938-)
Nobel 2004