EE539 syllabus

Engineering Quantum Mechanics

EE 539, 4 Units
Fall 2024
10:00 am – 11:50 am, Mon/Wed, VPD110

Location of Verna and Peter Dauterive Hall (VPD)

Instructor: Tony Levi
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Discussion session: NA

Web sites:
http://www.afjlevi.org
http://classes.usc.edu/term-20243/classes/ee/
Final Examinations Schedule · USC Schedule of Classes

Grading
Midterm
35%
Homework
10%
Final Exam
55%

Required Text:

Problems and example exams
MATLAB and Python code

Office Hours:
Mon/Wed 8:45 a.m. – 9:45 a.m. or by appointment

Final Exam:
Time 8:00am – 10:00am
Date Monday, December 16, 2024
Location VPD110

First day of EE539 classes, Monday, August 26, 2024
Abstract
Quantum mechanics is the basis for understanding physical phenomena on the atomic and nano-meter scale. There are numerous applications of quantum mechanics in biology, chemistry and engineering. Those with significant economic impact include semiconductor transistors, lasers, quantum optics and photonics. As technology advances, an increasing number of new electronic and opto-electronic devices will operate in ways that can only be understood using quantum mechanics. Over the next twenty years fundamentally quantum devices such as single-electron memory cells and photonic signal processing systems will become common-place. The purpose of this course is to cover a few selected applications and to provide a solid foundation in the tools and methods of quantum mechanics. The intent is that this understanding will enable insight and contributions to future, as yet unknown, applications.

Prerequisites
Mathematics:
A basic working knowledge of differential calculus, linear algebra, statistics, and geometry.
Computer skills:
An ability to program numerical algorithms in C, MATLAB, Python, FORTRAN or similar language and display results in graphical form.
Physics background:
Should include a basic understanding of Newtonian mechanics, waves, and Maxwell’s equations.

Introduction: Lectures 1 – 3

Lecture 1
TOWARDS QUANTUM MECHANICS – PARTICLES AND WAVES
Diffraction, interference, and correlation functions for light
Black-body radiation and evidence for quantization of light
Photoelectric effect
THE PHOTON PARTICLE
The existence of the photon particle
The photon at a beam splitter
Random number generation and stochastic computing
Secure quantum communication

Lecture 2-3
WAVE-PARTICLE DUALITY
The link between quantization of photons and quantization of other particles
Diffraction and interference of electrons
When is a particle a wave?
Feynman paths
THE SCHRÖDINGER WAVE EQUATION
The wave function description of an electron in free-space
The electron wave packet and dispersion
The Bohr model of the hydrogen atom
Calculation of the average radius of an electron orbit in hydrogen
Calculation of energy difference between electron orbits in hydrogen
Periodic table of elements
Crystal structure
Three types of solid classified according to atomic arrangement
Two-dimensional square lattice, cubic lattices in three-dimensions
Electronic properties of semiconductor crystals
The semiconductor heterostructure

Using the Schrödinger wave equation: Lectures 4 – 5
Lecture 4-5
INTRODUCTION
The effect of discontinuities in the wave function and its derivative
WAVE FUNCTION NORMALIZATION AND COMPLETENESS
INVERSION SYMMETRY IN THE POTENTIAL
Particle in a one-dimensional square potential well with infinite barrier energy
NUMERICAL SOLUTION OF THE SCHRÖDINGER EQUATION
Matrix solution to the discretized Schrödinger equation
Nontransmitting boundary conditions. Periodic boundary conditions
CURRENT FLOW
Current flow in a one-dimensional infinite square potential well
Current flow due to a traveling wave
DEGENERACY IS A CONSEQUENCE OF SYMMETRY
Bound states in three-dimensions and degeneracy of eigenvalues
BOUND STATES OF A SYMMETRIC SQUARE POTENTIAL WELL
Symmetric square potential well with finite barrier energy
TRANSMISSION AND REFLECTION OF UNBOUND STATES
Scattering from a potential step when effective electron mass changes
Impedance matching unbound states across a potential step
The reflectionless sech² potential
IMPEDANCE MATCHING BOUND STATES ACROSS A POTENTIAL STEP
PARTICLE TUNNELING
Electron tunneling limit to reduction in size of CMOS transistors

Scattering in one-dimension: The propagation method: Lectures 6 – 8
Lecture 6
THE PROPAGATION MATRIX METHOD
Writing a computer program for the propagation method
TIME REVERSAL SYMMETRY
CURRENT CONSERVATION AND THE PROPAGATION MATRIX

Lecture 7
THE RECTANGULAR POTENTIAL BARRIER
Tunneling
RESONANT TUNNELING
Resonant tunneling between two quantum wells
Resonant tunneling between three potential barriers and unity transmission threshold
ENERGY BANDS IN PERIODIC POTENTIALS: THE KRONIG-PENNY POTENTIAL
Bloch’s theorem
Real, imaginary, and complex band structure

Lecture 8
THE TIGHT BINDING MODEL FOR ELECTRONIC BAND STRUCTURE
Nearest neighbor and long-range interactions
Crystal momentum and effective electron mass
The nonequilibrium electron transistor
USE OF THE PROPAGATION MATRIX TO SOLVE OTHER PROBLEMS IN ENGINEERING
THE WKB APPROXIMATION
Tunneling

Related mathematics: Lectures 9 – 10
Lecture 9-10
ONE PARTICLE WAVE FUNCTION SPACE
PROPERTIES OF LINEAR OPERATORS
Hermitian operators
Commutator algebra
DIRAC NOTATION
MEASUREMENT OF REAL NUMBERS
Time dependence of expectation values. Indeterminacy in expectation value
The generalized indeterminacy relation

**THE NO CLONING THEOREM**

**DENSITY OF STATES**
Density of states of particle mass $m$ in 3D, 2D, 1D and 0D
Quantum conductance
Numerically evaluating density of states from a dispersion relation
Density of photon states

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**The harmonic oscillator: Lectures 11 – 12**

**Lecture 11**

**THE HARMONIC OSCILLATOR POTENTIAL**
**CREATION AND ANNIHILATION OPERATORS**
The ground state. Excited states
**HARMONIC OSCILLATOR WAVE FUNCTIONS**
Classical turning point
**TIME DEPENDENCE**
The superposition operator. Measurement of a superposition state

**Lecture 12**
Time dependence in the Heisenberg representation
Charged particle in harmonic potential subject to constant electric field
**ELECTROMAGNETIC FIELDS**
Laser light
Quantization of an electrical resonator
Quantization of lattice vibrations
Quantization of mechanical vibrations

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**Fermions and Bosons: Lecture 13**

**Lecture 13**

**INTRODUCTION**
The symmetry of indistinguishable particles. Slater determinant
Pauli exclusion principle. Fermion creation and annihilation operators – application to tight-binding
Hamiltonian
**FERMI-DIRAC DISTRIBUTION FUNCTION**
Equilibrium statistics
Writing a computer program to calculate the chemical potential and Fermi-Dirac distribution at finite temperature
**BOSE-EINSTEN DISTRIBUTION FUNCTION**
**CURRENT AS FUNCTION OF VOLTAGE BIAS**
Semiconductor heterostructure diode structures in the depletion approximation.
Metal-insulator-metal.
Reduced dimensions
Review: Lecture 14

Midterm:

Fermions and Bosons continued: Lectures 16 – 17
Lecture 16 – 17
PHOTON FOCK STATES
The Mandel effect
n-photons at a beam splitter
n-photons at a FP resonator
THE MANDEL EFFECT
Dual photon source
Fiber-optic beam splitter and delay line
Photon counting and correlation

Time dependent perturbation theory and the laser diode: Lectures 18 – 20
Lecture 18
FIRST-ORDER TIME-DEPENDENT PERTURBATION THEORY
Abrupt change in potential
Time dependent change in potential
CHARGED PARTICLE IN A HARMONIC POTENTIAL
FIRST-ORDER TIME-DEPENDENT PERTURBATION
THE GOLDEN RULE
IONIZED IMPURITY ELASTIC SCATTERING RATE IN GaAs
The coulomb potential. Linear screening of the coulomb potential
Correlation effects in position of dopant atoms
Calculating the electron mean free path

Lecture 19
EMISSION OF PHOTONS DUE TO TRANSITIONS BETWEEN ELECTRONIC STATES
Density of optical modes in three dimensions
Light intensity
Background photon energy density at thermal equilibrium
Fermi’s golden rule for stimulated optical transitions
The Einstein A and B coefficients
Occupation factor for photons in thermal equilibrium in a two-level system
Derivation of the relationship between spontaneous emission rate and gain
THE SEMICONDUCTOR LASER DIODE
Spontaneous and stimulated emission. Optical gain in a semiconductor. Optical gain in the presence of electron scattering

DESIGNING A LASER CAVITY
Resonant optical cavity. Mirror loss and photon lifetime
The Fabry-Perot laser diode. Rate equation models

Lecture 20
NUMERICAL METHOD OF SOLVING RATE EQUATIONS
The Runge-Kutta method. Large-signal transient response. Cavity formation

NOISE IN LASER DIODE LIGHT EMISSION
Effect of photon and electron number quantization
Langevin and semiclassical master equations

QUANTUM THEORY OF LASER OPERATION
Density matrix
Single and multiple quantum dot, saturable absorber

Time independent perturbation theory: Lecture 21
Lecture 21
NON-DEGENERATE CASE
Hamiltonian subject to perturbation W
First-order correction. Second order correction
Harmonic oscillator subject to perturbing potential in $x$, $x^2$ and $x^3$

DEGENERATE CASE
Secular equation
Two states
Perturbation of two-dimensional harmonic oscillator
Perturbation of two-dimensional potential with infinite barrier

Angular momentum, the hydrogenic atom, and bonds: Lectures 22 – 23
Lecture 22
ANGULAR MOMENTUM
Classical angular momentum
The angular momentum operator
Eigenvalues of the angular momentum operators $L_z$ and $L^2$
Geometric representation

SPHERICAL HARMONICS AND THE HYDROGEN ATOM
Spherical coordinates and spherical harmonics
The rigid rotator
Quantization of the hydrogenic atom
Radial and angular probability density
Lecture 23

ELECTROMAGNETIC RADIATION
- No eigenstate radiation
- Superposition of eigenstates
- Hydrogenic selection rules for dipole radiation
- Fine structure

BONDS.
- The hydrogen molecule ion.
- The hydrogen molecule covalent bond
- Valence bond description.
- Molecular orbital description
- The ionic bond

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Toward quantum engineering: Lecture 24

Lecture 24

OPTIMAL DEVICE DESIGN
- Optimal design of a heterojunction tunnel diode
- Optimal design of density of states
- Coherent quantum control

QUANTUM INFORMATION PROCESSING
- Representations of a single qubit on the Bloch sphere and unitary operations
- Two-qubit entangled Bell states
- Two-qubit controlled gates
- Bell’s inequality
- Teleportation