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
Office: KAP 132
Phone: (213) 740-7318
E-mail: alevi@usc.edu
Teaching Assistant: Fugu Tian
Email: fugutian@usc.edu
Discussion session: Fridays at 9.00 am in RTH B105

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:
Applied Quantum Mechanics (third edition), Cambridge University Press, ISBN: 1009308076

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

Last day of EE539 classes, Wednesday, December 4, 2024

Papers:
Wave packet tunneling and imaginary wave vector dispersion, 2023.
Supersymmetry with scattering states, 2021.
Behavioral regimes and long-lived emitter states in mesolasers, 2019.
Coherent control of photon resonator dynamics, 2014.
Single electron memory
Huang 2004
Yano Review 1999
Single electron transistor
Uchida 2003
Tunnel FET
Saraswat 2008
Quantum communication
Bennett 1992
Bienfang 2004
Gisin Review 2002

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 $sech^2$ 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

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

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-EINSTIEN 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

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