Engineering Quantum Mechanics. Fall 2018.
TTh 9.00 a.m. – 10.50 a.m., ZHS 360.

Web site: http://www.afjlevi.org/
Web site: http://classes.usc.edu/term-20183/classes/ee

EE539: Abstract and Prerequisites

Instructor: **Tony Levi** ***Office:*** **KAP 132** ***Telephone:*** **(213) 740-7318** ***Email:*** **alevi@usc.edu**	***Office Hours:*** **TTh 8:00 a.m. - 8:45 a.m.** **or by appointment**
Grading: **Midterm 35%** **Homework 10%** **Final Exam 55%**	***Final Exam:*** **11:00 a.m. - 1:00 p.m.,** **Thursday, December 6, 2018, ZHS 360** First day of class – Tuesday, August 21, 2018 Last day of class – Thursday, November 29, 2018
Required Text: **Applied Quantum Mechanics, A.F.J. Levi, Cambridge University Press** **Paperback: ISBN: 978-0-521-18399-4** Free download for USC students: **Essential Classical Mechanics for Device Physics, IoP, ISBN: 9781681744124** ***Optional Text:*** **Optimal Device Design, Cambridge University Press, ISBN: 0521116600**	

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 commonplace. 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 MATLAB and display results in graphical form.
Physics background:
Basic understanding of Newtonian mechanics, waves, and Maxwell's equations.

Introduction: *Lectures 1 - 5*

Lecture 1-2

REVIEW OF CLASSICAL CONCEPTS

Extended discussion to include material from the book "Essential classical mechanics for device physics".
The linear and nonlinear oscillator
Electromagnetism
Mechanical model of light-matter interaction due to Lorentz.

Lecture 3

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
Secure quantum communication

Lecture 4-5

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?

THE SCHRÖDINGER WAVE EQUATION

The wave function description of an electron of mass m_0 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 6 - 7*

Lecture 6-7

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 descretized 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
Probability current density for scattering at a step
Impedance matching for unity transmission
PARTICLE TUNNELING
Electron tunneling limit to reduction in size of CMOS transistors
THE NONEQUILIBRIUM ELECTRON TRANSISTOR

Scattering in one-dimension: The propagation method: *Lectures 8 - 10*
Lecture 8
THE PROPAGATION MATRIX METHOD
Writing a computer program for the propagation method
TIME REVERSAL SYMMETRY
CURRENT CONSERVATION AND THE PROPAGATION MATRIX

Lecture 9
THE RECTANGULAR POTENTIAL BARRIER
Tunneling
RESONANT TUNNELING

Localization threshold
Multiple potential barriers
THE POTENIAL BARRIER IN THE δ-FUNCTION LIMIT
ENERGY BANDS IN PERIODIC POTENTIALS: THE KRONIG-PENNY POTENTIAL
Bloch's theorem
Propagation matrix in a periodic potential
Real and imaginary band structure

Lecture 10
THE TIGHT BINDING MODEL FOR ELECTRONIC BAND STRUCTURE
Nearest neighbor and long-range interactions
Crystal momentum and effective electron mass
USE OF THE PROPAGATION MATRIX TO SOLVE OTHER PROBLEMS IN ENGINEERING
THE WKB APPROXIMATION
Tunneling

RELATED MATHEMATICS: *LECTURE 11- 12*
Lecture 11-12
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 13 - 14*

Lecture 13

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 14

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 15*

Lecture 15

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

Lecture 16

Review

Midterm:

Class following Review

Fermions and Bosons continued: *Lecture 18 - 19*

Lecture 18 - 19

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 20 - 22*

Lecture 20

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

FERMI'S 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 21

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 22

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: *Lectures 24*

Lecture 23

NON-DEGENERATE CASE

Hamiltonian subject to perturbation W

First-order correction. Second order correction

Harmonic oscillator subject to perturbing potential in x, $x2$ and $x3$

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 25 - 26*

Lecture 24

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 25

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.