Course Syllabus
PY511, Fall 2024
Quantum Mechanics I

Instructor: Professor Shyamsunder Erramilli
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Office hours: Tu : 3:20 PM – 4:20 PM, PHO 824 (TBC)
Thu: 3:30 PM – 5:30 PM PHO 824

Grader: TBN
Lecture: TuTh 2:00 PM – 3:15 PM, **SCI B58 (To be confirmed)**
Discussion: Fri 10:10 AM – 11:00 PM, **SCI B58 (TBC)**
Course Website: On *Blackboard* at learn.bu.edu with assignments submitted on *Gradescope*
Lecture Material: Class notes will be available on blackboard.

Goals for the course listed on the Physics department website: Axioms of Quantum Mechanics. General theory of quantum mechanics, including the Schrödinger, Heisenberg, and interaction pictures. The path integral formulation. Angular momentum: orbital and spin angular momentum, addition of angular momenta, Wigner-Eckart theorem. Scattering theory: time-independent, partial waves and phase shift, identical particles, time dependent, and propagators.

Textbook:

- J. Sakurai and Jim Napolitano, *Modern Quantum Mechanics*, Cambridge University Press Third Edition (2021). An excellent book, check out our Prof El-Batanouny's comments on the backcover! (*Nearly Fatal flaw* – Sakurai uses cgs units which we seek to banish, exorcize, vanquish and otherwise obliterate from Planet Earth. *Natural Units* & SI are the best).
- Interferometry and the debt to Classical Mechanics will be drawn heavily from our own Professor Polkovnikov's book in preparation - currently available in draft form.
- Additional notes on new Experiments will be supplied as Lecture Notes.

Some Awesome Graduate level texts:

• Landau and Lifschitz, *Quantum Mechanics: Nonrelativistic Theory,* 3rd ed Butterworth-Heinemann. *Evolutionists think that Physics has evolved over thousands of years of experiment and theory. We Creationists know that Physics was created in Nine Volumes in 1939 by Landau and Lifschitz. All known evidence is completely consistent with the Creationist Theory of Physics.*

• R. Shankar, *Principles of Quantum Mechanics*, Springer (1994). A very clear, if wordy, exposition from a brilliant teacher.

• Cohen-Tannoudji, Diu and Laloe, *Quantum Mechanics Vol I-II*, Wiley (1978). Comprehensive, with lots and lots of examples.

• S. Weinberg, *Lectures on Quantum Mechanics, Cambridge*. Masterful text from a Great One, who (i) refused to use the Dirac bra-ket notation and (ii) explained why not.

• K. Gottfried, *Quantum Mechanics Volume I*. The promised Volume II has never appeared. A generation of us older Physicists have been waiting for Godot.

Numerical methods:

• For numerical methods in Physics with MATLAB, Alejandro Garcia, *Numerical Methods for Physics,* 2nd edition Prentice Hall (2000). A revised Python version was released in 2017.

Homework: Homework problems will be assigned weekly. The list of problems in the homeworks serve as a 'Question Bank'. At least 50% of Examination questions will be based closely on the homework problems. During weekly discussion sections, student "volunteers" will lead the presentation of selected homework problems. Late homework will not be accepted.

Exams: There will be two mid-term exams and a final exam. *Exams may be a Take-home exams that requires you to submit your solutions online, using Python Jupyter notebooks.*

Grading: The course grade will be based on the following weights:
Class and Discussion section participation - 5%
Homework and Quizzes - 20%
Computational Assignments and Labs (Python*) – 15%
Midterm Exams - 30% (October and November)
Final Exam - 30%

Integrity and Honesty
All students are required to adhere to the Boston University rules on academic conduct and regulations regarding cheating. Violations of the academic conduct code will be brought before the appropriate University Committees. In particular, all exams are to be the sole work of individual students. Students may discuss with other students the various homework assignments, but each student must write up submitted solutions in their own words and equations.

Course Content
PY511 is an advanced course dealing with graduate level quantum theory, the first course in a two-course sequence PY511-PY512. The topics to be covered are listed below. ***It is expected that students will have had a one-year undergraduate course sequence on quantum mechanics, equivalent to PY451-PY452 here at Boston University.*** Much of the course will rely on mathematical techniques and tools learned in undergraduate math courses involving linear algebra, vector calculus, partial differential equations and the Green function. Most students will be enrolled in or have taken the equivalent of the PY501 course on Mathematical Methods in Physics.

Computational exercises
You are required to learn to perform computational exercises and simulations on elementary Quantum systems and learn to report your results with clearly labeled plots and figure captions. Almost every homework has a computational component. The Physics department has transitioned to a Python-based approach in undergraduate courses. You are encouraged to submit computational assignments in the form of Python based Jupyter notebooks. However, submissions using MATLAB or Mathematica may also be accepted.

To keep things manageable for the course grader: For those wishing to use Mathematica or other platforms please note that although your solutions may be accepted and graded, the grader and instructors cannot provide any help and assistance. Please note that you are still required to learn some Jupyter/Python by the time of the midterm examinations.

Commitment to Diversity https://www.bu.edu/physics/community/
The Quantum Physics of a hydrogen atom in the galaxy MRG-M0138, gravitationally lensed from ~10 billion light years away and observed by Hubble in 2021, is precisely the same Quantum Physics of a hydrogen atom in my skin. Physics is truly *Universal* in the grandest sense of the term. We Physicists on the other hand harbor the same prejudices held by our fellow humans. The Physics department at Boston University pledges "...to be proactive and work together to dismantle the many structural barriers that continue to limit access, representation, and diversity in science, and more broadly in academia". Please visit the link if you would like to learn more about inclusion events and get involved.

Topics. Chapter Numbers refer to Sakurai and Napolitano supplemented by Course notes

I. Foundations of Quantum Mechanics (6 lectures)

1. *Quantum Physics: Amazing, not Spooky*. Chapter 1.1 (2 lectures)
    - a) Sequential Stern-Gerlach filters
    - ***b) Einstein's second (first?) greatest discovery: non-locality***
    - c) Single particle Interference: Photons, Electrons and Atoms
    - d) Experimental arguments for a probabilistic world
    - e) The Debt to Classical Mechanics (Prof Polkovnikov's notes)

2. Axioms, Chapter 1.2 -1.3 (2 lectures)
    - a) The *Five** Axioms of Quantum Mechanics
    - b) *Axiom 5 – "Collapse of the Wavefunction", Copenhagen vs Many Worlds
    - c) Entanglement and the Arrow of Time
    - d) The Blessing and Curse of Dirac notation
    - e) Impact of Quantum Computers on notation and what "Measurement" means

3. Unitarity, Representation and Basis states Chapter 1.4-1.5 (2 lectures)
    - a) Unitarity, Symmetry and the Uncertainty Principle
    - b) Schrödinger, Heisenberg, and the Dirac Interaction Pictures
    - c) Time dependence: Dyson Series and the Magnus Expansion
    - d) Position and Momentum Representation: Oscillators
    - e) Changing Basis states: Neutrino oscillations, Flavor and Mass eigenstates

II. Single Particle Interferometers and The Two-Level System (6 lectures)

1. Single Particle Interferometers: (3 lectures) Course notes
    - a) Mach-Zehnder Interferometer for Photons and Atoms
    - b) Hilbert space representation of Beam Splitters, Mirrors, Phase Plates
    - c) Quantum Non-Demolition: Can we *safely* detect a Photon-activated Bomb?
    - d) ***Can you detect a Photon without destroying it***? Physics Nobel 2012.
    - e) Entangled Particles, Exercise in Quantum Teleportation

2. Two Level System: Spin-1/2 Systems (3 lectures) Course notes Chapter 3
    - a) ***Dirac's Happy Blunder***: The Story of Spin
    - b) Neutrino oscillations, ***BU g-2 experiment*** Course notesChapter 2
    - c) Spin resonance: Rabi's Exact soln Chapter 5.5.3/Problem 5.35
    - d) The Bloch Sphere: Coherence, Population, T_1 and T_2 Course notes
    - e) Qubit Lab: Simulating the Ramsey Interferometer on a computer

III. The Anharmonic Oscillator and the Birth of Matrix Mechanics (5 lectures)

1. How to Quantize a Classical Model Chapter 1.6, 2.6, Chapter 4 (3 lectures)
    - a) More Debt to Classical Mechanics: Poisson Brackets Anatoli's notes
    - b) From the Lagrangian to the Action to the Hamiltonian Chapter 2.6.4
    - c) *Seven things you know* about the Oscillator Course notes
    - d) *And Six things you did not know*: Birth of Matrix Mechanics Course notes
    - e) Coherent States, Squeezed States Course notes Ex 2.21 and Chapter 7.8.2

2. Continuous Symmetries, Gauge Invariance and Discrete Symmetries (2 lectures)
    - a) Translation, Continuous symmetries (Chapter 1)
    - b) Gaussian Wavepackets, Group velocity, dispersion Chapter 1
    - ~~c)~~ Rotations~~, SO(3)~~, SU(2) and U(1) (Chapter 3.3)
    - d) The Wigner-Eckart Theorem, Python exercise (Chapter 3)
    - e) Gauge Invariance and Conservation Laws Chapter 2

IV. Quantum Experiments: 21st Century Inventions (7 lectures)

1. Gauge Transformations: Chapter 2.7 and Classical and Quantum Hall effect (3 lectures)
    a) Flux Quantization (*never use cgs units. Ever!)* Chapter 2 Course notes
    b) Landau Levels Course notes
    c) ***The Integer Quantum Hall Effect*** Chamon and El-Batanouny course notes
    d) Quantum Metrology and the Redefinition of SI units Homework problem
    e) Gauge Symmetry and the Integer Quantum Hall Effect (Chamon notes)

2. Qubits from Superconductors (2 lectures) Course notes
    a) The DC and AC Josephson effect, Giaever's Tunnel Junctions (Nobel 1974)
    b) The Classical Lagrangian and Hamiltonian for an LC circuit Course notes
    c) The SQUID and the Flux Quantum, and Circuit QED Course notes
    d) The need for anharmonicity to make an Oscillator into a Qubit Course notes
    e) The Transmon: Anharmonic oscillator and spins and Artificial AtomsCourse notes

V. **Computational Exercises (labs + parts of assignments)** [subject to time constraints]
    a) Stern-Gerlach Experiment
    b) Elitzur-Vaidman Bomb Detector
    c) Bloch Sphere representation and Rabi Flopping
    d) Gaussian Wavepackets in 1+1 D Python Lab/Anatoli
    e) 1D Schrödinger equation by Crank-Nicholson method, Select problems
        i. Eigenstates of anharmonic oscillators Python Lab/Anatoli
        ii. Central Potentials, Hydrogen Atom
        iii. Quantum Wells, Semiconductor Heterostructures in a 128 Gb USB stick
    f) The Hartman Effect , and is Tunneling Infinitely fast? *Theory vs Experiment*