This document describes details of the Advanced Quantum Mechanics module and should be read in conjunction with the Senior Physics Handbook.

Lecturer: Joe Khachan  
Room: 363 (Physics building)  
Tel: (02) 9351 2713  
Email: j.khachan@physics.usyd.edu.au

GENERAL GOALS OF THIS MODULE ARE THAT YOU:

- See that quantum mechanics is much wider than the application of Schrödinger’s equation.
- Become familiar and are able to use operator methods.
- Be able to relate operator methods to matrix methods.
- Use both of these methods in a number of applications that involve angular momentum such as spectroscopy and quantum computing.
- Become familiar with some approximation methods in applications where solutions in closed form are not tractable.
- Relate this theory to its applications in atomic physics.

REFERENCE BOOK

The textbook for the Advanced stream is Introductory Quantum Mechanics (Fourth Edition) by Richard L. Liboff, and all students will be expected to have access to a copy. Other useful books are: David J. Griffiths Introduction to Quantum Mechanics second edition Pearson/Prentice Hall 2005, R.W. Robinett Quantum Mechanics, Oxford University Press, 1997, which has a call number of 530.12/510, a more mathematical book is Bransden and Joachain Introduction to Quantum Mechanics, Longman Publishers, 1989.

WEB RESOURCES

The lecturer’s notes will be available under the University’s WebCT environment, which can be accessed from the USYDnet site intranet.usyd.edu.au. Access requires a Unikey (Extro account) Username and Password that is issued with your confirmation of enrolment. The University provides computer facilities in the Access Centres www.usyd.edu.au/su/is/labs/.

ASSIGNMENTS and ASSESSMENT

There will be two assignments for the Quantum Mechanics module, counting a total of 25% towards your total assessment for the module. The other 75% comes from the examination at the end of the semester.

ASSUMED KNOWLEDGE

For this module (Advanced Senior Quantum Mechanics) it is assumed that you have passed, at the intermediate level, courses that include: Quantum Mechanics, Differential and Integral Calculus, and Linear Algebra.
LEARNING OUTCOMES AND REQUIRED READING

THE STATISTICAL INTERPRETATION
(Read notes 1.1 - 1.2, and Liboff 2.7 – 2.9)
• Explain our interpretation of quantum mechanics and how it differs from other possible interpretations.

PROBABILITY, EXPECTATION VALUES, AND OPERATORS
(Read notes 2.1 – 2.2, and Liboff 3.3)
• Explain the meaning of expectation value and use it to derive basic operators such as those for momentum and kinetic energy.
(Read notes 2.3, and Liboff 4.5 & 4.6)
• Explain the physical significance of a Hermitian operator and be able to mathematically show whether an operator is Hermitian.
(Read notes 2.4, and Liboff 2.7)
• Mathematically obtain the uncertainty associated with an operator.

EIGENFUNCTIONS, EIGENVALUES, AND COMMUTATORS
(Read Chapter 3, and Liboff 5.2 & 5.3)
• Explain the physical significance of an eigenvalues in quantum mechanics.
• Explain the physical significance when two operators commute.
• Be able to calculate the value of a commutation relation.

THE SCHRÖDINGER EQUATION IN THREE DIMENSIONS
(Read notes 4.1 & 4.2, and Liboff 10.6)
• Understand the solution of the Schrödinger equation for the hydrogen atom.
• Understand the origins of the \( n, l \) and \( m_l \) quantum numbers and the relationship between them.
(Read notes 4.3, and Liboff 9.1)
• Be able to write the definition of angular momentum into an operator.
• Show that the operator \( L^2 \) has the same form as the differential equation that contains the spherical harmonics of the hydrogen atom.
• Use the properties of the above mentioned differential equation to obtain the mathematical properties of the \( L^2 \) and \( L_Z \) operations on spherical harmonics.

MATRIX FORMULATION OF QUANTUM MECHANICS
(Read notes 5.1 – 5.2, and Liboff 4.3 – 4.6)
• Be able to apply the orthonormality condition to wave functions.
• Relate Dirac’s BraKet notation to their counterparts in integral format.
• Be able to rewrite the orthonormality condition and expectation value in BraKet notation.
(Read notes 5.3 – 5.5, and Liboff 11.1 – 11.3, 11.5)
• Be able to rewrite an operator equation in terms of a matrix equation.
• Be able to solve a matrix equation for its eigenvalues and eigenvectors.
• Know the relationship between an eigenvector and an eigenfunctions.
• Be able to use raising and lowering operators.
(Read notes 6.1 – 6.2, and Liboff 11.6)
• Extend all the mathematical properties of the angular momentum operator to the spin operator.
• Know how the Pauli spin matrices are related to the matrix representation of the spin operator.
(Read notes 6.3, and Liboff 11.8 and eigenenergies section of 11.9)
• Relate the magnetic dipole moment of an electron to its orbital and spin angular momentum.
• Obtain the energy levels of an electron in a magnetic field.
ADDITION OF ANGULAR MOMENTUM
(Read notes Chapter 7 before 7.1, and Liboff 9.4)
- Add angular momentum operators of coupled spins and obtain the result of the operation of the total angular momentum operator on an appropriate Ket.
- Explain the physical significance of Clebsch-Gordon coefficients and be able to derive them.

(Read notes 7.1 – 7.4, and Liboff 9.5, 12.1 and fine structure section of 12.2, 12.4)
- Apply the coupling of angular momentum to the vector model of an atom.
- Show that the fine structure of an atom can arise from the vector model of the atom.
- Apply the selection rules to the electron transitions between the fine structure energy levels.
- Relate the hyperfine structure to the vector addition of the electron and nuclear angular momenta.

PRELUDE TO QUANTUM COMPUTING - BELL’S THEOREM
(Read notes Chapter 8, and Liboff 11.13)
- Explain the EPR experiment.
- Explain how spin can be measured by a Stern-Gerlach apparatus.
- Be able to write these spin measurements in matrix notation.
- Be able to obtain the correlation coefficient that is used to test the existence of hidden variables.
- Explain the significance of Bell’s inequality to hidden variables.
- Explain the significance of the Aspect experiment to hidden variable theories.
- Explain entanglement and its physical significance.

QUANTUM COMPUTING
(Read notes 9.1 – 9.4, and Liboff 16.1 – 16.4)
- Explain the similarities and differences between classical bits and quantum bits (qubits).
- Be able to write quantum gates in both matrix and Dirac notation.
- Be able to use quantum gates to carry out basic quantum computing operations.
- Understand the circuit diagram notation of quantum computation.

(Optional reading of the notes 9.5)
- (As an option) Understand the Deutsch algorithm.

PERTURBATION THEORY
(Read notes Chapter 10 up to and including 10.2, and Liboff 13.1)
- Be able to derive and use first and second order perturbation theory.
(Read notes 10.3 – 10.5, and Liboff 13.2 & 13.3)
- Apply perturbation theory to degenerate energy levels.
- Apply degenerate perturbation theory to the Stark effect.
(Read notes 10.6)
- Apply the variational method to the helium atom.

INDISTINGUISHABLE PARTICLES
(Read notes Chapter 11, Liboff 12.3, 12.5 and Bose-Einstein condensation section of 12.8)
- Be able to test for the indistinguishability of boson and fermion wave functions.
- Explain how the indistinguishability of fermions leads to the Pauli Exclusion Principle.
- Use the Slater determinant to write down the wave function of a collection of indistinguishable fermions.
- Explain how Bose-Einstein condensation can arise and its physical significance.