Course Requisites (if applicable)

Pre-requisites	For graduate students: No pre-requisites For undergraduates: PH3101 Quantum Mechanics II or equivalent
Co-requisites	
Pre-requisite to	
Mutually exclusive to	
Replacement course to	
Remarks (if any)	

Course Aims

The course covers advanced concepts in quantum mechanics, with a focus on multi-particle systems. You will learn how to quantitatively describe the scattering of quantum mechanical particles, the effects of scattering resonances, entanglement between quantum subsystems, and the quantization of fields such as the electromagnetic field. Key analytical and numerical methods taught in this course include quantum Green's functions, Fermi's golden rule, density matrices, and second quantization. This course provides the theoretical background for advanced courses in quantum field theory, high energy physics, and condensed matter physics.

Course's Intended Learning Outcomes (ILOs)

Upon the successful completion of this course, you (student) would be able to:

ILO 1	Formulate the quantum mechanical scattering problem in terms of scattering amplitudes and cross sections.
ILO 2	Describe the scattering of non-relativistic quantum particles using quantum mechanical Green's functions.
ILO 3	Use the first Born approximation to calculate scattering amplitudes for a given scattering potential.
ILO 4	Discuss the physical origin of scattering resonances.
ILO 5	Apply Fermi's Golden Rule to calculate resonance lifetimes.
ILO 6	Apply the postulates of quantum mechanics to systems of multiple particles.
ILO 7	Discuss the Einstein-Podolsky-Rosen paradox and the implications of Bell's theorem.
ILO 8	Calculate the entanglement entropy of a two-particle quantum state.
ILO 9	Calculate the density matrix of a quantum subsystem and use it to calculate measurement probabilities.
ILO 10	Describe the many worlds interpretation of quantum mechanics, and how the measurement postulate emerges within this interpretation.
ILO 11	Express boson and fermion states using tensor product notation as well as second-quantized notation and translate between the two representations.
ILO 12	Formulate the second-quantized many-body Hamiltonian corresponding to a given first-quantized Hamiltonian with up to two-body interactions.
ILO 13	Identify the ground state, and elementary excitations, of a given second quantized Hamiltonian describing non-interacting particles.
ILO 14	Derive the Hamiltonian of a non-relativistic charged particle in a classical electromagnetic field.
ILO 15	Determine the Aharonov-Bohm phase shift induced by a magnetic vector potential.
ILO 16	Apply quantization rules to Maxwell's equations for a free electromagnetic field and identify the excitations corresponding to photons.

ILO 17	Calculate the rate of spontaneous emission by an excited state of an atom.

Course Content

A. Scattering Theory
Definition of scattering amplitudes, the differential scattering cross section, and the total scattering cross section. Special forms for incoming and outgoing waves in one, two, and three dimensions (e.g. Hankel functions). Definition and applications of the quantum mechanical Green's function. The Born series method for approximating scattering amplitudes. Definition of bound states, free states, and quasi-bound states (resonances). Derivation and applications of Fermi's Golden Rule.

B. Entanglement

How the postulates of quantum mechanics apply to multi-particle systems. Linear algebraic rules for tensor products. Calculations of partial measurement probabilities. The concept of quantum entanglement. Formulation of the Einstein-Podolsky-Rosen thought experiment, and Bell's Theorem. Definition of quantum mechanical entropy, and how to calculate it. Density matrices. The many worlds interpretation and its philosophical implications.

C. Many-body Quantum Mechanics

Definition of particle-exchange symmetry. Boson states and fermion states, expressed via tensor product notation as well as creation/annihilation operator notation. Use of creation/annihilation operators for expressing many-body Hamiltonians, and their eigenstates. Second quantization of single-particle quantum theories. Quantization of classical field theories.

D. Quantum Electrodynamics

Quantization of the non-relativistic Lorentz force law. The Aharonov-Bohm effect. The Dirac equation and its solutions in the presence of an electromagnetic field. Quantization of the source-free Maxwell equations, and the concept of the photon. Formulation of the electron-photon interaction. Calculation of the rate of spontaneous emission.

Reading and References (if applicable)

1. Online course notes

Planned Schedule

Week or Session	Topics or Themes	ILO	Readings	Delivery Mode	Activities
1	Scattering Theory	1			Lecture
2	Scattering Theory	2, 3			Lecture and in-class quiz
3	Scattering Theory	4			Lecture and in-class quiz
4	Scattering Theory	5			Lecture and in-class quiz
5	Entanglement	6, 7			Lecture and in-class quiz
6	Entanglement	8, 9, 10			Lecture and Midterm Test
7	Many-body Quantum Mechanics	11			Lecture and in-class quiz
8	Many-body Quantum Mechanics	12			Lecture and in-class quiz
9	Many-body Quantum Mechanics	13			Lecture and in-class quiz
10	Quantum Electrodynamics	14			Lecture and final project
11	Quantum Electrodynamics	15			Lecture, in-class quiz, and final project
12	Quantum Electrodynamics	16, 17			Lecture and final project

Week or Session	Topics or Themes	ILO	Readings	Delivery Mode	Activities
13	All	All			Lecture, final project, revision of course topics, and discussion of further advanced topics.

Learning and Teaching Approach

Approach	How does this approach support you in achieving the learning outcomes?
Lectures	The lectures build up the central concepts of the course and provide concrete examples for calculations of the type and difficulty that you are expected to be able to do.
In-class quizzes	The in-class quizzes provide practice problems for the topics covered during the lectures in the current week, allowing you to apply and practice your newly acquired knowledge. Feedback is provided for the quizzes of the previous week, to correct mistakes and misunderstandings.
Project	You will select a research topic of interest, and perform an in-depth study of the topic, culminating in a project report. This develops the ability to apply the principles developed in the lectures to new topics and scenarios outside the scope of the lectures.
Technology-Enhanced Learning (TEL)	The in-person lectures will be recorded and some of the assignments will involve programming.

Assessment Structure

Assessment Components (includes both continuous and summative assessment)

No.	Component	ILO	Related PLO or Accreditation	Weightage	Team/Individual	Rubrics	Level of Understanding
1	Continuous Assessment (CA): Test/Quiz(CA1: In-class quizzes)	All		20	Individual	Analytic	Multistructural
2	Continuous Assessment (CA): Others(CA2: Project Report)	All		20	Team	Holistic	Extended Abstract
3	Continuous Assessment (CA): Others(CA4: Midterm Test)	1-13		20	Individual	Analytic	Multistructural
4	Summative Assessment (EXAM): Others([final examination])	All		40	Individual	Analytic	Multistructural

Description of Assessment Components (if applicable)

Formative Feedback

Formative feedback is given through discussion within tutorial lessons, a discussion after the midterm, a written response to each project report, and an examiner's report for the final exam.

NTU Graduate Attributes/Competency Mapping

This course intends to develop the following graduate attributes and competencies (maximum 5 most relevant)

Attributes/Competency	Level
Collaboration	Intermediate
Creative Thinking	Advanced
Curiosity	Advanced
Learning Agility	Intermediate
Problem Solving	Advanced

Course Policy

Policy (Academic Integrity)

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values. As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. On the use of technological tools (such as Generative AI tools), different courses / assignments have different intended learning outcomes. Students should refer to the specific assignment instructions on their use and requirements and/or consult your instructors on how you can use these tools to help your learning. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Policy (General)

You are expected to complete all assigned pre-class readings and activities, attend all seminar classes punctually and take all scheduled assignments and tests by due dates. You are expected to take responsibility to follow up with course notes, assignments and course related announcements for seminar sessions they have missed. You are expected to participate in all seminar discussions and activities.

Policy (Absenteeism)

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / midterms, you must:

Send an email to the instructor regarding the absence and request for a replacement class and make-up midterms.

Submit the original Medical Certificate* or official letter of excuse to administrator.

Attend the assigned replacement class (subject to availability) and make-up midterms.

*The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Policy (Others, if applicable)

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