Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	AY23/24	**Semester**	2
Course Coordinator	KOH Teck Seng		
Course Code	PH3406		
Course Title	Open Quantum Systems		
Pre-requisites	PH3101 Quantum Mechanics II		
Mutually Exclusive	-		
No of AUs	4		
Contact Hours	Lectures: 26; Tutorials: 26 (2 hr – lecture each week, 2 hr – tutorial each week)		
Proposal Date	10 November 2023		

Course Aims

This course aims to introduce basic formalism and interpretation of decoherence of open quantum systems, so that you have a more complete understanding of the philosophical, mathematical and experimental foundations of quantum mechanical phenomena. It applies the mathematical formalisms to describe contemporary experiments in quantum computing, and explores the role decoherence plays in interpretations of quantum mechanics.

Intended Learning Outcomes (ILO)

By the end of this course, you (as a student) would be able to:

1. Explain the concepts of entanglement, composite systems, and density matrices, and make use of their mathematical definitions.
2. Derive and apply the interaction picture formalism to time-dependent quantum systems.
3. Derive and apply the Born-Markov master equation to simple Markovian open systems.
4. Derive and apply the Lindblad master equation to simple Markovian open systems.
5. Apply the concepts of decoherence, relaxation and dephasing to simple quantum systems, and calculate their Markovian dynamics.
6. Apply the formalism of open systems to canonical models of open systems, such as the collisional model, the spin-boson model and the spin-spin model.
7. Apply the formalism of linear dynamical maps to describe the evolution of open quantum systems, with a focus on quantum computation and quantum error correction.
8. Explain and reconcile the approaches from physical arguments and linear maps with the Kraus representation theorem.
9. Describe standard interpretations of quantum mechanics, implications and paradoxes.
10. Explain and justify how concepts and implications of decoherence may resolve some paradoxes, and identify their limitations.

Course Content

<u>(I) Standard Quantum Mechanics (closed systems)</u>
I.1 Recap of standard quantum mechanics (PH3101)
I.2 Interaction picture formalism
I.3 Density matrix formalism
I.4 Von-Neumann equation

<u>(II) Formalisms of Open Quantum Systems</u>
II.1 Composite and reduced systems

II.2 System-environment interaction
II.3 Born-Markov master equation
II.4 Lindblad master equation
II.5 Linear maps and Kraus representation theorem

(III) Models of decoherence and applications
III.1 Collisional model
III.2 Spin-boson model
III.3 Spin-spin model
III.4 Decoherence in contemporary experiments
III.5 Quantum error correction

(IV) Philosophy and quantum foundations
IV.1 Decoherence and quantum-to-classical transition

Assessment (includes both continuous and summative assessment)

Component	Course LO Tested	Weight	Team / Individual	Assessment Rubrics
1. Homework sets	1--8	20%	Individual	Point-based
2. Midterm Tests	1--8	20%	Individual	Point-based
3. Project	All	20%	Individual (Written Report) 10% / Individual (Oral presentation) 10%	See Appendix
4. Final Examination	All	40%	Individual	Point-based
Total		100%		

Formative feedback

You will be given feedback in four ways:

1. By working through examples provided during lectures
2. By response to postings on the course discussion board
3. By attending consultation hours
4. By studying the comments provided by the instructors after the grading of homework, midterm, and project

Learning and Teaching approach

Lectures	Pre-lecture readings will be assigned, in partial flip-classroom approach. Face-to-face lectures in small class sizes for direct interaction and feedback.
Tutorials	Pre-tutorial problems will be assigned, for student preparation before class. Tutorials will have a focus on student-centred learning.
Project	Inquiry approach to project work.

Reading and References

There is no compulsory reference text. Apart from lecture notes provided, good reference materials are available through NTU Library or as open-source material on the internet. They are:

Open quantum systems

1. Maximilian Schlosshauer, Decoherence and the quantum-to-classical transition, Springer (2007). Available from NTU Library (ebook). Permalink: https://ntu-sp.primo.exlibrisgroup.com/permalink/65NTU_INST/3es15n/alma991016542604305146

2. Maximilian Schlosshauer, *Decoherence, the measurement problem, and interpretations of quantum mechanics*, Rev. Mod. Phys. 76, 1267 (2005). doi:10.1103/RevModPhys.76.1267 https://link.aps.org/doi/10.1103/RevModPhys.76.1267

3. Daniel Lidar, *Lecture notes on the theory of open quantum systems*, arXiv:1902.00967 https://arxiv.org/abs/1902.00967v2

4. H-P Breuer and F Petruccionne, The theory of open quantum systems, Oxford University Press (2002). Available from NTU Library (hardcopy). Permalink: https://ntu-sp.primo.exlibrisgroup.com/permalink/65NTU_INST/12u36pr/alma991012784779705146

Quantum computation and quantum error correction

4. Michael A. Nielsen and Isaac Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press (2010). Available from NTU Library (ebook). Permalink: https://ntu-sp.primo.exlibrisgroup.com/permalink/65NTU_INST/3es15n/alma991016374261205146

Course Policies and Student Responsibilities

(1) General

You are expected to complete all assigned pre-class readings and activities, attend all tutorial classes punctually and take all scheduled assignments and tests by due dates. You are expected to participate in all tutorial discussions and activities.

(2) Absenteeism

Absence from the midterm test without a valid reason will affect your overall course grade. Valid reasons include falling sick supported by a medical certificate and participation in NTU’s approved activities supported by an excuse letter from the relevant bodies. There will be no make-up opportunities for CA components.

All project assignments must be submitted on time. Failure to do so will affect your score.

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.

Use of Generative Artificial Intelligence (GAI) such as ChatGPT is allowed in the course but students need to adhere to NTU's prevailing guideline. i.e. **Give proper citations if you use any AI tool**. Extending the practice of correctly citing references in your work under NTU's policies on citation and plagiarism, the University requires students to **(i) identify any generative AI tools used** and **(ii) declare how the tools are used in submitted work**. Please note that even with acknowledgement, copying of output generated by AI tools (in part or whole) may still be regarded as plagiarism.

Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
KOH Teck Seng (Dr)	SPMS-PAP-03-08	(65) 6514 1066	kohteckseng@ ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course ILO	Activities
1	Standard quantum mechanics, interaction picture	1—2	
2	Von-Neumann equation	1—2	
3	Composite systems	1—2	Homework due
4	Composite systems	1—2	
5	Decoherence and quantum foundations	9—10	
6	Master equation approaches	3—4	Midterm test 1
7	Master equation approaches	3—4	
	Recess week		
8	Models of decoherence	5—6	Homework due
9	Models of decoherence	5—6	
10	Dynamical maps and Kraus representation theorem	7—8	
11	Quantum error correction	7—8	Midterm test 2
12	Quantum error correction	7—8	
13	Project Presentations	All	Individual presentations

Appendix: Rubrics for Project (20%)

Oral Presentation (Assessed Individually) – 10%

Criteria	Unsatisfactory (1)	Satisfactory (2)	Good (3)	Exemplary (4)
Presentation Skills: (a) Organization (25%)	Inadequate content, with some links across slides. Takeaways are either unclear or contain some ambiguity.	Adequate content with across slides. Key takeaways for some slides clear. Citations are given, but with missing references.	Relevant content, mostly linked coherently across slides. Key takeaways for most slides are clear. Citations are appropriate and in consistent format.	Relevant content are linked coherently across slides. Key takeaways for each slide are clear. Citations are appropriate and in consistent format.
Presentation Skills: (b) Delivery & Timing (25%)	Unclear and unengaging. Grossly under or over-estimate presentation time.	Mostly clear and understandable. Kept to allocated presentation time.	Clear and well prepared. Kept to allocated presentation time. Reasonable emphasis on own contribution	Engaging, clear and well prepared. Kept to allocated presentation time with emphasis on own contribution.
Q&A: (a) Subject Knowledge (25%)	Does not display adequate knowledge of the subject matter.	Displays some knowledge of the subject matter.	Displays good knowledge of the subject matter.	Displays comprehensive and deep knowledge of the subject matter.
Q&A: (b) Ability to Explain Answers (25%)	Unable to understand and answer questions.	Able to understand and answer some questions.	Able to understand and answer most questions.	Able to understand and answer all questions and also provide relevant information.

Written Report (Assessed Individually) – 10%

Criteria	Unsatisfactory (1)	Satisfactory (2)	Good (3)	Exemplary (4)
Organization and Clarity (25%)	Organization has inadequate connection between ideas. Writing is mostly unclear or inaccurate. Word limit not kept.	Organization displays some logical and coherent connection of ideas. Writing is mostly clear and accurate, with many errors. Word limit kept.	Organization displays mostly logical and coherent connection of ideas. Writing is mostly clear and accurate, with some errors. Word limit kept.	Organization displays logical and coherent connection of ideas. Writing is clear and accurate, with no errors. Word limit kept.
Literature Review (25%)	Unclear state of the sub-field. Reviews contain some inappropriate sources. Inadequate background or motivation.	Communicates state of sub-field. Reviews some appropriate sources. Gives some background and/or motivation.	Clearly communicates state of sub-field. Reviews appropriate sources. Gives some background and/or motivation.	Clearly and accurately communicates state of sub-field. Reviews appropriate and up-to-date sources. Gives comprehensive background and motivation.
Application of Physics (50%)	Incorrect or inappropriate use of physical theories in the modeling of problem. Inadequate explanation of methodology, assumptions, approximations or computational techniques.	Correct and appropriate use of physical theories in the modeling of problem. Some aspects of methodology, assumptions, approximations and computational techniques missing or lacking in detail.	Correct and appropriate use of physical theories in the modeling of problem. Methodology, assumptions, approximations and computational techniques mostly clearly explained.	Correct and appropriate use of physical theories in the modeling of problem. Methodology, assumptions, approximations and computational techniques clearly and comprehensively explained.