COURSE CONTENT FOR PAP777 for Undergraduates

Academic Year	2021/22	Semester	2
Course Coordinator	Assoc Prof	. Chong Yidong	
Course Code	PAP777		
Course Title	Graduate 0	Quantum Mecha	anics
Pre-requisites			nics II or equivalent and IY) programme and CGPA 4.0 or higher
No of AUs	4	X	
Contact Hours		39, Tutorial: 12 e each week; 1	hr tutorial each week)
Proposal Date	14 Feb 202		
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.

Intended Learning Outcomes (ILO)

Upon the successful completion of this course, you (as a student) will be able to do the following:

A. Scattering Theory:

- 1. formulate the quantum mechanical scattering problem in terms of scattering amplitudes and cross sections.
- 2. describe the scattering of non-relativistic quantum particles using quantum mechanical Green's functions.
- 3. use the first Born approximation to calculate scattering amplitudes for a given scattering potential.
- 4. discuss the physical origin of scattering resonances.
- 5. apply Fermi's Golden Rule to calculate resonance lifetimes.

B. Entanglement:

- 1. apply the postulates of quantum mechanics to systems of multiple particles.
- 2. discuss the Einstein-Podolsky-Rosen paradox and the implications of Bell's theorem.
- 3. calculate the entanglement entropy of a two-particle quantum state.
- 4. calculate the density matrix of a quantum subsystem, and use it to calculate measurement probabilities.
- 5. describe the many worlds interpretation of quantum mechanics, and how the measurement postulate emerges within this interpretation.

C. Many-body Quantum Mechanics:

- 1. express boson and fermion states using tensor product notation as well as secondquantized notation, and translate between the two representations.
- 2. formulate the second-quantized many-body Hamiltonian corresponding to a given first-quantized Hamiltonian with up to two-body interactions.
- 3. identify the ground state, and elementary excitations, of a given second quantized Hamiltonian describing non-interacting particles.

D. Quantum Electrodynamics:

1. derive the Hamiltonian of a non-relativistic charged particle in a classical

- electromagnetic field.
- 2. determine the Aharonov-Bohm phase shift induced by a magnetic vector potential.
- 3. apply quantization rules to Maxwell's equations for a free electromagnetic field, and identify the excitations corresponding to photons.
- 4. 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.

Component	Course LO Tested	Related Programme LO or Graduate Attributes	Weighting	Team / Individu al	Assessmen t Rubrics
1. Final Examinati on	All	Competence 1,2,3,4,5 Creativity 2 Communication 1	40%	Individual	Point-based marking. Open-ended marking scheme.
2. CA1: In-class quizzes	All	Competence 1,2,3,4,5 Creativity 2 Communication 1	20%	Individual	Point-based marking. Open-ended marking scheme.
3. CA2: Project Report	All	Competence 1,2,3,4,5 Creativity 1,2 Communication 1,2,3	20%	Team	Rubrics marking (see Appendix 1 for the rubric) Open-ended

Assessment (includes both continuous and summative assessment)

					marking scheme.
4. CA4: Mid-term Test	Topics A-C	Competence 1,2,3,4,5 Communication 1	20%	Individual	Point-based marking.
Total			100%		
		approach			
Approach	H	ow does this approa arning outcomes?	ch support st	udents in ach	nieving the
	H le Ti pr	ow does this approa	e central conce bles for calcula	epts of the cou tions of the typ	urse, and
Approach	Zes Th cc approximate zes	ow does this approa arning outcomes? ne lectures build up th ovide concrete examp	e central conce bles for calcula to be able to do ovide practice ures in the curr newly-acquire s of the previou	epts of the cou tions of the typ o. problems for t ent week, allo d knowledge.	urse, and be and difficulty he topics wing students to Feedback is

Reading and References

1. Online course notes.

Course	Policies and S	Student Responsibili	ties				
		al or Other Reasons					
If you are	e sick and una	ble to attend your clas	s / Mid	-terms, you hav	e to:		
cl 2. S	ass and make- ubmit the origir	nal Medical Certificate	* or offi	cial letter of exc	use to admir	nistrator.	
3. At	ttend the assig	ned replacement class	s (<i>subj</i> e	ect to availability	/) and make-	up mid-terms.	
		e mentioned above sh with the Singapore Me			apore by a m	nedical	
Academ	ic Integrity						
student r set of val	elies on adheri	epends on honesty an ing to the principles of the whole university c	acade	mic integrity and	to the NTU	Honour Code,	
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. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in th course.							
Course I	nstructors						
Instruc	tor	Office Location	Phor	one Email			
Assoc P Yidong	rof. Chong	SPMS-PAP-04-02	+65 6	5316 2967	Yidong@nt	tu.edu.sg	
Planned	Weekly Sche	dule					
Week	Торіс			Course LO		Readings/	
1	Coottoring Th			Activities			
1	Scattering Th	leory		attering ms of plitudes and (A1).	Lecture		
2	Scattering Th	neory	Ű		Lecture and in-class quiz		

1	Scattering Theory	Formulate the quantum mechanical scattering problem in terms of scattering amplitudes and cross sections (A1).	Lecture
2	Scattering Theory	Describe the scattering of non-relativistic quantum particles using quantum mechanical Green's functions. Use the first Born approximation to calculate the scattering amplitudes for a given scattering potential (A2, A3).	Lecture and in-class quiz

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3	Scattering Theory	Discuss the physical	Lecture and
	5 ,	origin of scattering	in-class quiz
		resonances (A4).	
4	Scattering Theory	Apply Fermi's Golden	Lecture and
		Rule to calculate resonance lifetimes (A5).	in-class quiz
5	Entanglement	Apply the postulates of	Lecture and
0	Lindigionion	quantum mechanics to	in-class quiz
		systems of multiple	
		particles. Discuss the	
		Einstein-Podolsky-Rosen	
		paradox and the	
		implications of Bell's theorem (B1, B2).	
6	Entanglement	Calculate the	Lecture and
U	Entangioment	entanglement entropy	Midterm Test
		and reduced density	
		matrix given a two-	
		particle quantum state.	
		Describe the many	
		worlds interpretation of	
		quantum mechanics, and how the measurement	
		postulate emerges within	
		this interpretation (B3,	
		B4).	
7	Many-body Quantum Mechanics	Express boson and	Lecture and
		fermion states using	in-class quiz
		tensor product notation	
		as well as second-	
		quantized notation, and translate between the two	
		representations (C1).	
8	Many-body Quantum Mechanics	Formulate the second-	Lecture and
		quantized many-body	in-class quiz
		Hamiltonian	
		corresponding to a given first-guantized	
		Hamiltonian with up to	
		two-body interactions	
		(C2).	
9	Many-body Quantum Mechanics	Identify the ground state,	Lecture, in-
		and elementary	class quiz,
		excitations, of a given	and final
		second quantized	project
		Hamiltonian describing non-interacting particles	
		(C3).	
10	Quantum Electrodynamics	Derive the Hamiltonian of	Lecture and
		a non-relativistic charged	final project
		particle in a classical	
		electromagnetic field	
		(D1).	
11	Quantum Electrodynamics	Determine the Aharonov-	Lecture, in-
		Bohm phase shift	class quiz,
		induced by a magnetic	and final
		vector potential (D2).	project
12	Quantum Electrodynamics	Apply quantization rules	Lecture and
		to Maxwell's equations	final project

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		for a free electromagnetic field, and identify the excitations corresponding to photons. Calculate the rate of spontaneous emission by an excited state of an atom (D3, D4).	
13	All	Revision of course topics, and discussion of further advanced topics.	Lecture and final project

Appendix 1: Assessment Rubrics

Assessment Component: CA 2: Project Report (20%)

Instructions: You are asked to do a short project to explore one of the course topics in greater detail. You may work either alone, or in pairs. If you want a partner, it is up to you to find one, and to figure out how to distribute the work. Both members of a team will get the same grade for the project. You must prepare a short project report (not more than 10 pages). The grade for the project will be entirely determined by the quality of the project report.

Grading Criteria	Exceptional	Effective	Acceptable	Developing
	(18-20%)	(15-17%)	(10-14%)	(<10%)
Learning outcomes A, B, C, or D (Depending on project topic.)	Clearly-written and extensive discussion of project topic, containing an original take on the topic that does not simply follow existing sources. Clear formulation of theoretical topics, including concrete calculations and not just theoretical derivations. Project report is well-formatted according to the standards of the scientific literature.	Clearly-written and extensive discussion of project topic, roughly following the presentation of the topic in other sources, but including some original element(s). For example, the report may include an in- depth explanation of the details of a numerical calculation not presented in textbooks, or the application of a theoretical method to a specific circumstance not treated elsewhere Project report largely follows the formatting quality standards of the scientific literature.	Clearly-written and extensive discussion of project topic, mostly following the presentation in other sources, The discussion includes an attempt to utilize the discussed theoretical technique(s) to perform a concrete numerical calculation of some sort, along similar lines to examples presented elsewhere. Project report largely follows the formatting quality standards of the scientific literature.	Discussion of the project topic that is conceptually incomplete or lacks clear presentation. Derivative of other sources, lacking an attempt to perform an original calculation, or to apply the theoretical technique(s) in any non-standard direction. Project report fails to follow the formatting quality standards of the scientific literature.

Graduate Attributes

What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY, PHME and PHMS programs, graduates should be able to:

	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics [PHMS only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis
	2	read and understand undergraduate level physics content independently;
Competency	3	make educated guesses / estimations of physical quantities in general;
Competency	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non- scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

1 Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;
Creativity	2	offer valid alternative perspectives/approaches to a given situation or problem.

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	1	describe physical phenomena with scientifically sound principles;
Communication	2	communicate (in writing and speaking) scientific and non- scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
Character	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

<i>Civic Mindedness</i> put together the skills and knowledge into their work i effective, responsible and ethical manner for the bene society.	∩ an ∌fits of
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