Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	AY 20/21	**Semester**	1
Course Coordinator	Prof Sum Tze Chien		
Course Code	PH4408		
Course Title	Nuclear Physics		
Pre-requisites	PH3101		
No of AUs	3 AU		
Contact Hours	Face to Face: 39 hours 3 hours a week (3 hours of lecture or 2 hours of lectures and 1 hour of tutorial (on alternate week)		
Proposal Date	11 September 2020		

Course Aims

This course aims to provide a basic understanding of the structure of nuclei and their properties, with a strong focus on linking theory with experimental observations of nuclear behaviour. The course will provide an overview of the basic properties of the nucleus and its structure; introduce the nuclear models developed to explain the properties of the nucleus; aims to quantitatively describe the energy balances and spin/parity selection rules of alpha, beta and gamma decay processes in radioactivity; as well as to familiarize one with the applications of nuclear physics including fusion and fission. This course will thus equip you with the fundamental concepts that will provide you the foundation for advanced studies in nuclear physics and particle physics or prepare you to follow or initiate research in field or to work in industry jobs related to nuclear science and technology.

Intended Learning Outcomes (ILO)

By the end of the course, you should be able to:

1. Describe and discuss the fundamental nature of nuclei and nuclear phenomena.
2. Determine how models are constructed to explain phenomena and their limitations.
3. Employ quantitative analysis and reasoning skills to interpret nuclear phenomena.
4. Describe and discuss the physics of nuclear power generation – nuclear fission & nuclear fusion; radiation safety and shielding and environmental issues.

<u>Nuclear Properties (NP)</u>

1. Explain the difference between the nuclear charge and nuclear matter distributions and establish the empirical relationship between nuclear radius and mass number.

2. Use basic classical mechanics concepts to derive the Rutherford Scattering formula and calculate the cross-sections.

3. Explain the difference the between atomic mass and nuclear mass. Calculate the binding energy of nuclei. Describe the experiments to measure nuclear mass.

4. Describe the properties of the nuclei (i.e., radius, binding energy, angular momentum, magnetic dipole moment, electric quadrupole moment, parity, etc.).

5. Use basic quantum mechanical formalism, such as the time-independent Schrodinger equation in free space, to calculate charge densities and expectation values.

6. Use advanced quantum mechanical concepts, such as ladder operators, to calculate the Clebsch-Gordan coefficients for simple examples of angular momentum addition.

Nuclear Structure (NS)

1. Use basic quantum mechanical formalism, such as the time-independent Schrodinger equation in free space, to solve for the Deuteron wavefunction and to calculate the charge and current densities

2. Use advanced quantum mechanics concepts, such as partial wave expansion to describe the scattering between nucleons and solve the quantum mechanical scattering problem.

3. Explain the formation a bound deuteron state from the findings of the neutron-proton, proton-proton and neutron-neutron scattering experiments using the concepts of scattering length and effective range.

4. Explain the properties of the nuclear force and describe the various contributions to the nuclear potential and the exchange force model.

Models of Nucleus (MoN)

1. Explain the underlying principles and assumptions taken in the formulation of the different models of the nucleus (e.g., Liquid Drop Model) as well as their strengths and limitations.

2. Use statistical mechanics to determine the density of states and solve for the Fermi energy and derive an expression of the total binding energy in the Fermi Gas model and relate to the asymmetry term in the Liquid Drop Model.

3. Describe the significance of the nuclear spin orbit term in determining the magic numbers in the shell model.

4. Determine the nuclear spin and parity assignments of the ground state of nuclei using the Shell Model as well as to interpret the spin and parity assignments of low-lying excites states of nuclei.

5. Describe how the features of low-lying excited states in even N - even Z nuclei are associated with collective behavior of the nucleons in the nucleus.

Radioactivity (R)

1. Explain the key concepts of the decay law, half-life, decay constants and activity as well as the application of radioactive dating methods.

2. Explain the key concepts in alpha decay and apply the spin and parity selection rules to determine the spin and parity assignments following alpha decay. Determine the energetics in the decay and calculate the Q value. Use basic quantum mechanical formalism to derive the transition probabilities in alpha decays and calculate the half-life.

3. Explain the key concepts in beta decay and the discovery of the neutrino. Determine the energetics in the decay and calculate the Q value. Use basic quantum mechanical formalism to derive the transition probabilities in beta decay. Explain the concept of comparative half-life.

4. Apply the spin and parity selection rules to determine the spin and parity assignments following beta decay. Explain the concepts of allowed and forbidden decays. Describe the parity violation experiment in Beta decay and the KATRIN experiment to determine the mass of the neutrino.

5. Describe the key concepts in alpha decay and apply the spin and parity selection rules to determine the spin and parity assignments following alpha decay. Determine the energetics in the decay and calculate the Q value. Use electromagnetic concepts to derive the transition probabilities in gamma decay; and calculate the half-life. Explain the concept of Weisskopf estimates.

Detection of Radiation (DoR)

1. Describe the interaction of alpha, beta and gamma radiation with matter and explain their energy loss mechanisms.

2. Explain the concepts of range, mean range, straggling, and stopping power.

3. Use of the Monte-Carlo software SRIM and CASINO to calculate the ranges of ions and electrons in matter.

4. Describe the basic operating principles of various detectors e.g., ionization chambers, scintillation detectors, solid state detectors, cloud chambers, bubble chambers, photographic emulsions, multiwire proportional counters, time of flight detectors, Cherenkov detectors, layered detectors.

Particle Accelerators (PA)

1. Describe the main features and basic operating principles of various particle accelerators: Cockcroft Walton, Van de Graaff, Tandem accelerator, Cyclotron, Synchrocyclotron, Isochronous Cyclotron, Synchrotron, Linear accelerator.

2. Describe the applications of accelerators in medical physics, materials characterization, and high energy physics and explain concepts like Bragg peak for on therapy.

Nuclear Fission & Fusion (NF)

1. Explain why nuclear fission occurs and determine the energetics and the probability of spontaneous fission.

2. Describe the insights gained from the liquid drop model and calculate the energy released.

3. Describe the properties induced fission and the related concepts of prompt neutrons, delayed neutrons, fission cross-sections.

4. Calculate the rates for chain reaction.

5. Describe the operation of Nuclear Power Stations & Uranium Enrichment and the development of fission weapons (little boy and fat man).

6. Explain why nuclear fusion occurs and determine the energetics and the probabilities of various fusion reactions.

7. Explain why the D-T reaction is chosen for realizing commercial fusion on earth.

8. Describe the properties fusion and the related concepts of Coulomb barrier, fusion cross-section and reaction rates; as well as the processes in Solar Fusion

9. Derivation of Lawson's criteria.

10. Describe the main features and basic operating principles of the tokamak (ITER), spherical tokamaks, Wendelstein stellerator and inertial confinement fusion (Laser Mégajoule and National Ignition Facility); and the development of thermonuclear weapons

Course Content

Nuclear Properties & Nuclear Structure	Properties of nuclei: radii, masses, abundances, binding energies, spins and electromagnetic moments, Rutherford scattering, deuteron, nucleon-nucleon scattering in terms of an exchange force.
Models of Nucleus	Semi-empirical mass formula, the Fermi gas model, shell model, liquid drop model with vibrational and rotational excitations, collective structure.
Radioactivity	Half-life; Alpha decay: Geiger-Nuttal Rule, selection rules; Beta decay: Selection rules, parity violation, Fermi theory, neutrinos; Gamma decay: Selection rules, multipole transitions, Weisskopf estimates.
Detection of Radiation	interaction of alpha, beta and gamma radiation with matter; ionization chambers, scintillation detectors, solid state detectors, cloud chambers, bubble chambers, photographic emulsions, multiwire proportional counters, time of flight detectors, Cherenkov detectors, layered detectors.
Particle Accelerators	Cockcroft Walton, Van de Graaff, Cyclotron, Synchrocyclotron, Synchrotron, Linear accelerator.
Nuclear Fission & Fusion	Nuclear fission energetics, Nuclear fission reactors and nuclear power; Nuclear Fusion energetics, experimental Fusion reactors and inertial confinement.

Assessment (includes both continuous and summative assessment)

Component	Course ILO Tested	Related Programme LO or Graduate Attributes	Weighting	Team/Individual	Assessment rubrics
1. Final Exam	All	Competency (1,3,4)	60%	Individual	Point-based marking (not rubric based)
2. CA1: Pre-lecture Reading & Learning Activity Management System (LAMS) Quizzes	All	Competency (1,2,3,4), Character (1,2,3)	20%	Individual	Point-based marking (not rubric based)
3. CA2 weekly homework	All	Competency (1,3,4) Character (1,2,3)	10%	Individual	Point-based marking (not rubric based)
4. CA3: Midterm Test	From Nuclear Properties to Radioactivity	Competency (1,3,4)	10%	Individual	Point-based marking (not rubric based)
Total			*100%*		

Formative feedback

Formative feedback is given weekly through assignments marking and tutorial lessons. A weekly TA meeting discusses the progress, pace, and difficulty level of lectures. Formative feedback on the midterm exam is given as a midterm check of students' understanding of learned contents, including feedback on common mistakes. Past exam questions and examiner's report are made available for students. Finally, your lecturer will try and make himself available for fast turn-around feedback on a one-on-one basis, through email or personal discussions after lecture, tutorials, or during consultation.

Learning and Teaching approach

Approach	**How does this approach support you in achieving the learning outcomes?**
Pre-Lecture Reading & Learning Activity	To encourage learners to take a more active role in the teaching and learning process. Background reading and short quizzes will help guide and assess the conceptual understanding of related fundamental content to

Management System (LAMS) Quizzes	enhance the teaching and learning in the lectures.
Lectures	Content and derivations, examples of problem solving and discussion of conceptual understanding.
Tutorial	Review and discussion of key concepts from lectures with TAs, by working through problems. The TAs will monitor and provide timely feedback.
Homework	Homework comprises of problems and standard textbook practice questions that are discussed during lectures allowing for formative assessment and feedback.

Reading and References

- K. S. Krane, Introductory Nuclear Physics, John Wiley & Sons (ISBN: 978-0-471-80553-3)
- D. J. Griffiths, **Introduction to Quantum Mechanics**, Benjamin Cummings (**ISBN-10:** 0131118927, **ISBN-13:** 978-0131118928)

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / Mid-terms, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-terms.
2. Submit the original Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (*subject to availability*) and make-up mid-terms.

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

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

Collaboration is encouraged for your homework because peer-to-peer learning helps you understand the subject better and working in a team trains you to better communicate with others. As part of academic integrity, crediting others for their contribution to your work promotes ethical practice.

You **must write up your solutions by yourself and understand anything that you hand in.**

If you do collaborate, **you must write on your solution sheet the names of the students you worked with. If you did not collaborate with anyone, please explicitly write, "No collaborators."** Failure to do so constitutes plagiarism.

Use of materials outside the course is strongly discouraged. If you use outside source, you must reference it in your solution.

Course Instructors

Instructor	Office Location	Phone	Email
Prof Sum Tze Chien	SPMS-PAP-04-01	6316 2971	tzechien@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course ILO	Readings/ Activities
1	Lecture 0 (1h): Introduction to Nuclear Physics and Course Administration Lecture 1 (1h): Nuclear Radius Lecture 2 (1h): Rutherford Scattering	 **NP** 1 **NP** 2	Textbook, Reading Materials and LAMS Quizzes
2	Lecture 3 (1h): Nuclear Mass and Binding Energy Lecture 4 (1h): Nuclear Properties Tutorial 1 (1h)	**NP** 3 **NP** 4-6	Textbook, Reading Materials and LAMS Quizzes
3	Lecture 5 (1h): The Deuteron Lecture 6 (2h): Nucleon-Nucleon scattering I	**NS** 1 **NS** 2	Textbook, Reading Materials and LAMS Quizzes
4	Lecture 7 (2h): Nucleon-Nucleon scattering II Tutorial 2 (1h)	**NS** 3	Textbook, Reading Materials and LAMS Quizzes
5	Lecture 8 (1h): Properties of the Nuclear Force Lecture 9 (1h): Nuclear Models I – Semi-empirical Mass Model & Fermi Model Lecture 10 (1h): Nuclear Models II – Shell Model	**NS** 4 **MoN** 1-2 **MoN** 3-4	Textbook, Reading Materials and LAMS Quizzes
6	Lecture 11 (1h): Nuclear Models III – Collective Model Lecture 12 (1h): Decay Law Tutorial 3 (1h)	**MoN** 5 **R** 1	Textbook, Reading Materials and LAMS Quizzes
7	Lecture 13 (2h): Alpha Decay Lecture 14 (1 h): Beta Decay I	**R** 2 **R** 2	Textbook, Reading Materials and LAMS Quizzes

Recess Week			
8	Lecture 15 (2h): Recap of Key Concepts (Week 1-7) and Beta Decay II Tutorial 4 (1h)	**R** 4	Textbook, Reading Materials and LAMS Quizzes
9	Lecture 16 (1.5h): Gamma Decay Lecture 17 (1.5h): Detection of Nuclear Radiation	**R** 5 **DoR** 1-3	Textbook, Reading Materials and LAMS Quizzes
10	Lecture 18 (2h) Detectors I Tutorial 5 (1h)	**DoR** 4	Textbook, Reading Materials and LAMS Quizzes
11	Lecture 19 (1h): Detectors II Lecture 20 (1h): Accelerators I Lecture 21 (1h): Accelerators II	**DoR** 4 **PA** 1 – 2	Textbook, Reading Materials and LAMS Quizzes
12	Lecture 22 (2h): Nuclear Fission Tutorial 6 (1h):	**NF** 1 – 5	Textbook, Reading Materials and LAMS Quizzes
13	Lecture 23 (2h): Nuclear Fusion Lecture 24 (1h): Revision (recap of key concepts)	**NF** 6 – 10	Textbook, Reading Materials and LAMS Quizzes
Examination Week			

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

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

Competency	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 [PHMA 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;
	3	make educated guesses / estimations of physical quantities in general;
	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.

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

Communication	1	describe physical phenomena with scientifically sound principles;
	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.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	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.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.