

PHYS 5110 — Nuclear and Particle Physics

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Abstract

This course is intended for scientists, engineers, and students completing a Physics minor. An introduction to nuclear physics, including issues related to energy production and radiation safety and to elementary particle physics with emphasis on key discoveries and outstanding questions.

1 General Information

Course name: Introduction to Nuclear and Particle Physics

Course number: PHYS 5110

Number of credits: 3

Class times and location: Mondays, Wednesdays, and Fridays, 3:05 pm to 3:55 pm, in JFB 102

Instructor: Prof. Miguel A. Mostafá; 224 INSCC; 581-4785; mostafa@physics.utah.edu

Office hours: Monday through Friday, 8:30 am to 5:30 pm (except during class hours and when I'm abroad!)

Department: Physics

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Prerequisites

PHYS 5110 is a 3 credit-hour course which fulfills the Quantitative Intensive BS, and has one prerequisite: PHYS 3740 (*“Introduction to Quantum Theory and Relativity”*) or equivalent.

2 Course Objectives

Overview

This is a very interesting and ambitious course. It is designed to provide the students with a solid understanding of the fundamental aspects of low-energy nuclear physics, and an introduction to modern particle physics, incorporating a description of the fundamental particles and their interactions, with the tools to perform kinematic calculations in simple situations.

Objectives

The main objective of this course is to provide an introduction to the fields of nuclear and particle physics at a level such that students should be able to understand how we have arrived at our present description of matter and its interactions, and to have a good idea of the basis of current research.

It is my intention to give the students a solid understanding of the fundamentals of those aspect of nuclear and particle physics that are most important to modern applications (in such areas as nuclear medicine, nuclear engineering, radiochemistry, geosciences, biotechnology, etc.) and current research.

By the end of the course, the student will be able to:

1. have usable knowledge of the physics behind nuclear concepts,
2. calculate the consequences of radioactive growth and decay and nuclear reactions,
3. use nuclear models to:
 - estimate nuclear masses,
 - appreciate why different radioactive decays occur for different isotopes,

- predict levels' structure, energies, spins, and parities,
 - estimate their consequences with respect to radioactive decay,
 - understand the properties of neutron capture and the Breit–Wigner single level formula,
 - calculate cross sections at resonance and thermal energies, and
 - calculate lifetimes of nuclear states that are unstable to alpha, beta and gamma decay, and internal conversion,
4. calculate the kinematics of the interaction of photons with matter and apply stopping power to determine the energy loss rate and ranges of charged particles in matter,
 5. understand the effects and uses of radiation,
 6. calculate binding energies for nuclei and reaction energies for different nuclear decay processes,
 7. calculate the energies of fission fragments and understand the charge and mass distributions of the fission products, and prompt neutron and gamma rays from fission,
 8. understand the principles of power generation via nuclear processes,
 9. investigate different nuclear reactions and reactor designs,
 10. be familiar with experimental techniques and detectors used for studying particle interactions,
 11. understand aspects of how matter is built from elementary particles,
 12. understand the difference between fermions and bosons, and how they behave,
 13. understand the main aspects of the standard model of particle interactions, including:
 - the characteristics of the electromagnetic, strong, and weak interactions,
 - be familiar with the consequences of boson exchange in the mediation of forces,

- the importance of symmetries, and
 - the use of particle quantum numbers and Feynman diagrams for determining what interactions occur, and their approximate strength,
14. understand models that predict the masses of particles, and
 15. be familiar with some of the remaining mysteries of the fundamental interactions of matter and topics currently under active research.

3 Course Content

After a few review lectures on relativistic kinematics, we will start with an outline of basic concepts such as symmetries, conservation laws, and cross sections. Then, we will cover nuclear and particle phenomenology to understand the tools we use to perform experiments in these fields. It is important that theorists and experimentalists at least be able to talk to each other. We need to have some common language and some understanding of each other's techniques and the scope of the problems we are each trying to address.

The nuclear section will be followed by a unified description of particle physics since the experiments that uncovered the atomic structure are similar to the more recent experiments that led us to the discovery of the substructure of protons and neutrons. The components of nucleons, quarks, and the other fundamental components, leptons, are then revealed as the building blocks of all matter. The forces between these building blocks: the electromagnetic, weak, and strong forces and the particles carrying or mediating those forces will be explained. The fundamental particles and their interactions are described by the Standard Model that also includes the mechanism for generating mass.

Even though every measurement that has been made is consistent with the Standard Model, we know that it is not complete. Thus, there has to be a theoretical structure beyond the Standard Model. Leading candidates for extensions of the Standard model will be mentioned as well as current topics in nuclear and particle physics.

The syllabus is divided into eight chapters. Each one lasts two weeks approximately. The topics covered are:

Chapter 1: Basic Concepts

- Review of special relativity
- Introduction to basic concepts such as symmetries and conservation laws
- Observable quantities: cross-sections and decay rates

Chapter 2: Nuclear Phenomenology

- Binding energy
- Radioactive decays
- Semi-empirical mass formula

Chapter 3: Models and Theories of Nuclear Physics

- Fermi gas model
- Shell model
- Non-spherical nuclei
- α - and β -decays
- γ emission and internal conversion

Chapter 4: Applications of Nuclear Physics

- Fission
- Fusion
- Biomedical applications

Chapter 5: Experimental Methods

- Particle accelerators
- Particle interactions with matter
- Particle detectors

Chapter 6: Particle Phenomenology

- Leptons
- Quarks
- Hadrons

Chapter 7: Interactions

- Quark dynamics and color quantum chromodynamics
- Strong coupling constant and asymptotic freedom
- Electroweak interactions
- Unified theory

Chapter 8: Outstanding questions and future prospects

- Quark–gluon plasma, astrophysics, and cosmology
- Nuclear medicine
- Power production and nuclear waste
- The Higgs boson
- Supersymmetry
- Particle astrophysics

4 Evaluation Methods

In addition to the weekly homework assignments, students are required to write two scientific articles during the semester on topics of their own choosing and to lead class discussions based on their research. Students are expected to come to class each week prepared to contribute to the topics of discussion for that week. There are two exams (midterm and final) evenly spaced through the semester. The exact dates will be announced in class and on WebCT. Grades are based on the scientific articles, assignments, and tests, as well as general participation in all class discussions according to the following criteria:

45% - Two in-class exams (20% the mid-term, and 25% the final)

20% - Two scientific articles (10% each)

20% - Weekly homework assignments

15% - Class participation/response system

Reading and Assignments

Assigned readings will be an essential part of 5110. They will be announced in class and appear on WebCT, and include: articles from newspapers, published scientific papers, web logs, and articles from different books and magazines.

Homework

There will be weekly homework assignments. They will be posted each week on WebCT. Although students can work in groups, they must solve the problems individually and write up not only the final answer but also show the work involved to get full credit.

Scientific Articles

There will be two scientific articles assigned for this course. The due dates for these papers will be posted on WebCT. (Typically, the first article is due right after the Spring break, and the second one the week before the final exam.) You can choose

any topic related to nuclear or particle physics. You may get inspiration from the list of suggested topics below. If the topic of your choice was already covered in class, your report must go deeper into the matter. The only constraints on the choice of topic are the following:

1. each student must choose a different topic, and
2. the presentation should be at the level of the course.

The topic must be researched and then certain questions answered in detail with quantitative analysis.

The papers should be typed. The first page of the paper should begin with the “*Title of the Paper*” followed by the author’s name. A short abstract on the first page is optional. The body of the paper follows immediately after the title and author’s name and the optional abstract. The length of the paper should be between 1500 and 2000 words, which works out to roughly between 4 and 5 typed double-spaced pages using standard 10 or 12 point fonts. You can include formulas in your papers, if you want to, provided you explain them in words in the text (textbook-style). At the end of the body of the papers should be the list of citations to any material or resource you used. Throughout the text you should use these citations to indicate which resource provided which information in the paper (*e.g.*, if a paragraph is based on information in resource 3, put a note [3] after the main sentence in the paragraph). References must be included and all written work in the article must be your own or properly cited¹. **Any example of plagiarism will result in a failing score.**

Since this is a scientific paper, you should maintain a certain style. You should write simply and clearly but not colloquially. Avoid shortened words like can’t, don’t, etc. References, figures, and/or tables should be included at the end and are not counted as part of the total number of pages. Not conforming to this format will result in a returned paper.

The grade of the written reports will be based on the following criteria:

- 20 points for meeting the deadlines;
- 30 points for correct physics that demonstrates a clear understanding of the concepts involved;

¹A good example of style preferences is the **Physical Review Style and Notation Guide**, available on the web site of the American Physical Society at <http://authors.aps.org/STYLE/>.

- 30 points for the quality of writing, *i.e.*, organization of ideas, coherence, clarity, style, and grammar; and
- 20 points for the quality and extent of research, *i.e.*, evidence of use of library databases, library books, and professional journals. (You will not get full credit if you limit yourself to the internet.)

Suggested subjects

This is a list of topics that I find interesting or important. This list is not exhaustive, and more topics may be added in the future. Thus, the subjects you choose for your research articles are not limited to the ones in this list. If you have some other idea for a topic, please let me know. If you want to know what some of these topics are, just ask me.

- Medical applications of particle and nuclear physics: magnetic resonance imaging, positron emission tomography, proton therapy, etc.
- Applications of nuclear physics: fission, fusion, radioactive dating, etc.
- Nuclear models
- Quark–gluon plasma
- Super–heavy elements (*i.e.* beyond $Z = 116$)
- Super–deformed nuclei
- Radiation therapy using neutrons and heavy ions
- Functional MRI
- Nuclear fusion
- “*Burning*” nuclear waste with particle accelerators
- Rubbia’s Energy Amplifier
- Structure of hadrons
- Bound states: positronium, quarkonium, etc.

- Relativistic effects in the hydrogen atom
- Magnetic moments of elementary particles
- Technicolor and/or compositeness
- Quark confinement
- Quantum chromodynamics on a computer (lattice QCD)
- Pentaquarks
- The search for the Higgs boson
- Techniques and/or recent results from the Tevatron
- Techniques and/or goals of the Large Hadron Collider
- Techniques and/or goals of the International Linear Collider
- Techniques and/or goals of a (proposed) Muon Collider
- Techniques and/or goals of a (proposed) Neutrino Beam
- Neutrino masses (solar neutrinos, neutrino oscillations, tritium endpoint)
- Neutrino astronomy (Amanda, Ice Cube)
- Gamma-ray astronomy (GLAST, VERITAS)
- Ultra-high energy cosmic rays (Pierre Auger Observatory, Telescope Array)
- Nuclear astrophysics (supernovae, nucleosynthesis)
- CP violation (in B sector, relationship to baryogenesis)
- Electroweak unification
- Grand unified theories
- Supersymmetry
- Superstring theories

- Nuclear and particle physics in cosmology
- Dark matter – Dark energy
- Matter–antimatter asymmetry
- Glueballs
- Deconfinement

Participation in class

Students are expected to actively participate in class so they can learn from each other. We know that active involvement in learning increases what is remembered, how well it is assimilated, and how the learning is used in new situations. In making statements to peers about their own thoughts on a class topic, students must articulate those thoughts and also submit them to (hopefully constructive) examination by others. In listening to their peers, students hear many different ways of interpreting and applying class material, and thus are able to integrate many examples of how to use the information. Especially in a course that stresses application of material, extensive participation in class discussions is an essential element of students' learning. Participation will be graded on a scale from 0 (lowest) through 4 (highest), using the criteria described in table 1. Criteria focus on what you demonstrate and do not presume to guess at what you know but do not demonstrate. This is because what you offer to the class is what you and others learn from. I expect the average level of participation to satisfy the criteria for a 3.

Table 1: Criteria to evaluate participation in class.

Grade	Criteria
0	Absent.
1	Present, not disruptive. Tries to respond when called on but does not offer much. Demonstrates very infrequent involvement in discussion.
2	Demonstrates adequate preparation: knows basic case or reading facts, but does not show evidence of trying to interpret or analyze them. Offers straightforward information (e.g., straight from the case or reading), without elaboration or very infrequently (perhaps once a class). Does not offer to contribute to discussion, but contributes to a moderate degree when called on. Demonstrates sporadic involvement.
3	Demonstrates good preparation: knows case or reading facts well, has thought through implications of them. Offers interpretations and analysis of case material (more than just facts) to class. Contributes well to discussion in an ongoing way: responds to other students' points, thinks through own points, questions others in a constructive way, offers and supports suggestions that may be counter to the majority opinion. Demonstrates consistent ongoing involvement.
4	Demonstrates excellent preparation: has analyzed case exceptionally well, relating it to readings and other material (e.g., readings, course material, discussions, experiences, etc.). Offers analysis, synthesis, and evaluation of case material, e.g., puts together pieces of the discussion to develop new approaches that take the class further. Contributes in a very significant way to ongoing discussion: keeps analysis focused, responds very thoughtfully to other students' comments, contributes to the cooperative argument-building, suggests alternative ways of approaching material and helps class analyze which approaches are appropriate, etc. Demonstrates ongoing very active involvement.

Extra Credit

Periodically through out the semester there will be short extra credit assignments announced in class and posted on WebCT. There is no penalty for not completing those assignments.

5 Texts and references

This is the second time I teach this course. I hope we can continue to make changes to the curriculum, which address topics that students want to learn about. First of all, I ordered a different text book: “*Nuclear and Particle Physics*,” by B. R. Martin. It should be in the book store by the start of classes. This book is up to date. It is at a somewhat lower level than some of the material I will cover. However, I think it is probably helpful to read about some of these subjects in a simpler form. It covers both nuclear and particle physics. There is also a chapter on what exciting developments we can look forward to in these fields. There is a chapter on nuclear power, and one on biomedical applications. We will cover these in class, and I hope your interest is piqued enough to read about some of these topics. We will also make heavy use of network resources for providing documentation and guides to various forms of current technologies and research.

This semester, the student response system (clickers) will be provided by the manufacturer as a test. (We will probably have to set up a deposit because we will have to return the clickers at the end of the class.)

Related textbooks

There are hundreds of titles available under the subjects of *Nuclear* and *Particle Physics*. The list below covers most subjects, but is certainly not complete. I provide the **Call No.** for those titles that are available in the Marriott Library.

- “*The Physics of Nuclei and Particles*,” R. A. Dunlap, Thomson Learning — Brooks/Cole, 2004
This is a concise readable introduction, although the particle physics part is very short — just 50 pages. This book is exclusively about theory, and the only one in this list that is not available in the Marriott Library.
- “*Introduction to Nuclear and Particle Physics*,” A. Das and T. Ferbel, John Wiley and Sons, QC776.D37 1994
This book covers most of the material that I plan to go over in this course. When I did the book order, a new edition had not yet come out. I thought that the book by Martin would be more readable and up to date, and would be a better companion to my notes. Unlike the previous title, it also discusses experimental methods.

- “*Nuclear and Particle Physics*,” W. S. C. Williams, Oxford University Press, QC776.W55 1991
This book is fairly comprehensive and was the course text up until 2005. In its day, it was a really good book. However, it has got a bit out of date, and the style is rather discursive.
- “*Nuclear and Particle Physics*,” W. E. Burcham and M. Jobes, Longman Scientific and Technical, QC793.3.S8 B87 1995
This book is also comprehensive but, although it goes further than the one by Martin, it treats nuclear and particle physics as almost independent subjects.
- “*Particles and Nuclei*,” B. Povh *et al.*, 5th ed., Springer, QC776.T4513 2006
This is the closest in its coverage to the book by Martin and at a similar level, but the experimental methods are only discussed in a brief appendix. Although it also treats nuclear and particle physics as independent subjects, this book is worth looking at.

Titles in Nuclear Physics:

- “*An introduction to nuclear physics*,” W. Cottingham and D. Greenwood, Cambridge University Press, QC776.C63 2001
- “*Fundamentals of nuclear physics*,” N. Jelley, Cambridge University Press, QC776.J45 1990
- “*Introductory Nuclear Physics*,” K. Krane, John Wiley and Sons, QC777.K73 1987
- “*Introductory Nuclear Physics*,” P. Hodgson, E. Gadioli, and E. Gadioli Erba, Oxford University Press, QC777.H585 1997
- “*Nuclear Physics*,” E. Fermi, University of Chicago Press, QC173.F44 1950
This is a unique set of lecture notes (compiled by Jay Orear, A. Rosenfeld, and R. Schluter) of a course given by Enrico Fermi at the University of Chicago. Although old, these notes are still well worth reading.

Titles in Particle Physics:

- “*Subatomic physics*,” E. Henley and A. García, World Scientific, 2007,
On order

- “*Introduction to high energy physics*,” D. Perkins, Cambridge University Press, QC793.2.P47 2000
- “*Introduction to elementary particles*,” D. Griffiths, John Wiley and Sons, QC793.2.G75 1987

6 Students with Disabilities

The University of Utah seeks to provide equal access to its programs, services and activities for people with disabilities. If you will need accommodations in the class, reasonable prior notice needs to be given to the Center for Disability Services, 162 Union Building, 581-5020 (V/TDD). CDS will work with you and the instructor to make arrangements for accommodations.

All written information in this course can be made available in alternative format with prior notification to the Center for Disability Services.

7 Accommodations Policy

Some of the writings, lectures, films, or presentations in this course may include material that conflicts with the core beliefs of some students. Please review the syllabus carefully to see if the course is one that you are committed to taking. If you have a concern, please discuss it with me at your earliest convenience.

For more information, please consult the University of Utah’s Accommodations Policy, which appears at www.admin.utah.edu/facdev/accommodations-policy.pdf.

8 Rights and responsibilities

Faculty

Responsibilities of faculty are spelled out in Rights and Responsibilities, which can be found on the web at: <http://www.admin.utah.edu/ppmanual/8/8-12-4.html>. The instructor’s responsibilities include the following:

- Convene classes unless valid reason and notice given.

- Perform and return evaluations in a timely manner.
- Inform students at beginning of class of:
 1. General content and course activities
 2. Evaluation methods and grade scale
 3. Schedule of meetings, topics, due dates.
- Ensure environment conducive to learning.
- Enforce student code.

Students

The mission of the University of Utah is to educate the individual and to discover, refine, and disseminate knowledge. The University supports the intellectual, personal, social, and ethical development of members of the University community. These goals can best be achieved in an open and supportive environment that encourages reasoned discourse, honesty, and respect for the rights of all individuals. Students at the University of Utah are encouraged to exercise personal responsibility and self-discipline and engage in the rigors of discovery and scholarship.

The Code of Student Rights and Responsibilities has seven parts. The full text is available on the web at <http://www.admin.utah.edu/ppmanual/8/8-10.html>, and also in Student Affairs.

All students are expected to maintain professional behavior in the classroom setting, according to the Student Code, spelled out in the Student Handbook. Students have specific rights in the classroom as detailed in Article III of the Code. The Code also specifies proscribed conduct (Article XI) that involves cheating on tests, plagiarism, and/or collusion, as well as fraud, theft, etc. Students should read the Code carefully and know they are responsible for the content. According to Faculty Rules and Regulations, it is the faculty responsibility to enforce responsible classroom behaviors, and I will do so, beginning with verbal warnings and progressing to dismissal from the class and a failing grade. Students have the right to appeal such action to the Student Behavior Committee.