



LEARNING GOALS FOR NUCLEAR SCIENCE COURSES

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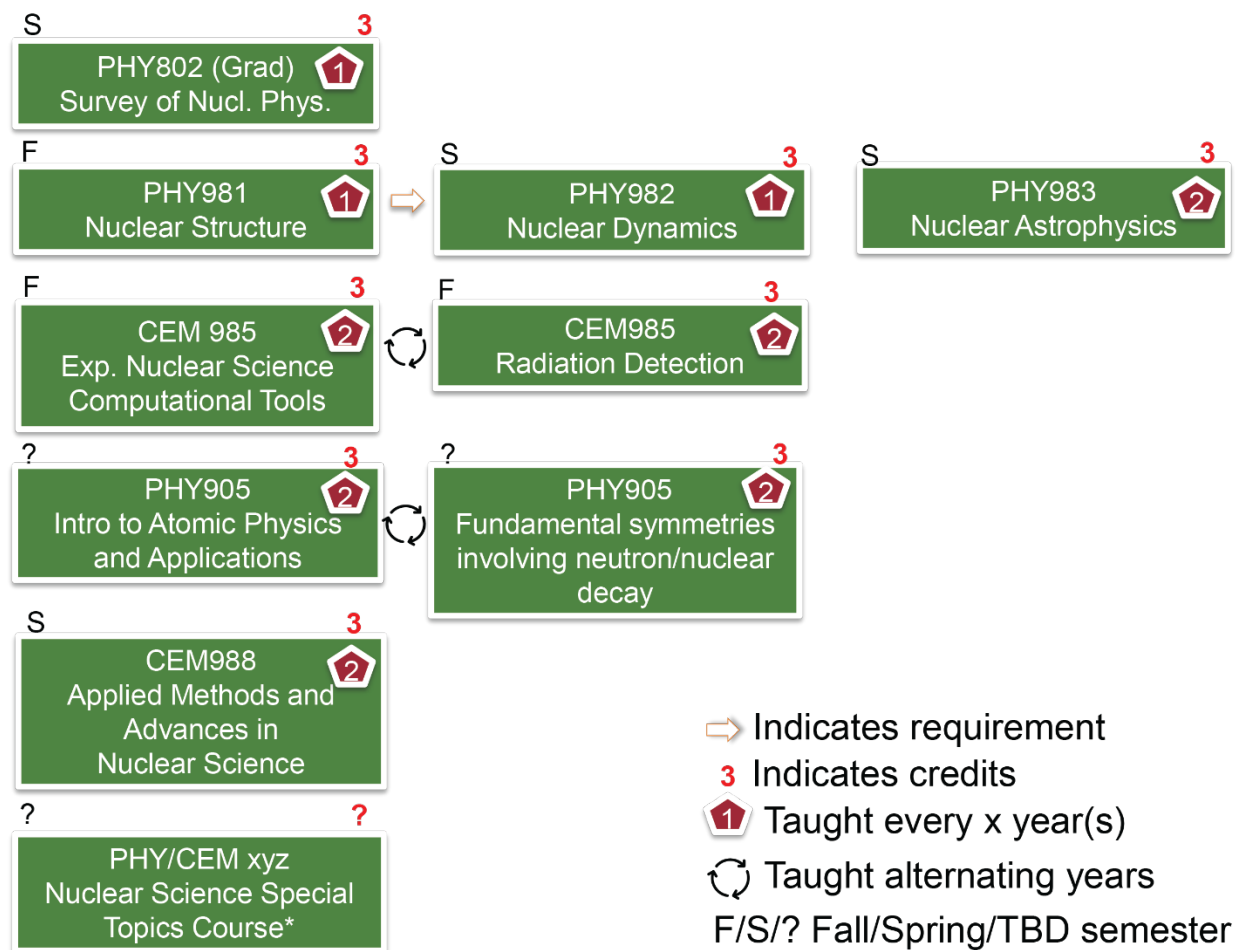
Learning Goals for Nuclear Science Courses

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Overview

An overview of the nuclear science curriculum provided through course work in the Department of Physics and Astronomy and the Department of Chemistry is provided below. This updated structure was developed by the FRIB Curriculum Committee based on a survey amongst nuclear science faculty and graduate students held in AY24. As part of this effort, learning goals for the courses were developed that are documented here.



PHY802 provides an overview of nuclear science for junior graduate students and is preferably taken in the spring semester of the first year in the graduate program. PHY802 was separated from PHY492 (for undergraduate students) in AY2025 to facilitate a better transition to advanced nuclear science course work.

PHY981 (nuclear structure), PHY982 (Nuclear dynamics) are core nuclear science courses. They are preferably taken in Fall and Spring of the second year of the graduate program. PHY981 is a prerequisite course for PHY982. PHY983 (Nuclear astrophysics) is taught once every two years. Especially students pursuing nuclear astrophysics research should preferably take this course in their 2nd or 3rd year in the program.

The CEM985 courses (Experimental nuclear science computational tools and Radiation detection) are taught in alternating years and students pursuing experimental nuclear science are encouraged to take these courses in the earlier years of the graduate program.

The PHY905 courses on atomic physics and applications and fundamental symmetries involving neutron/nuclear decay are new courses. They will be introduced in AY26 and AY27 and it is envisioned that these courses are taught in alternating years. Students pursuing research in these areas should preferably take this course in their 2nd or 3rd in the program. Introduced as special-topics courses, once established, the course numbers will be changed to permanent numbers.

The PHY988 course in applied methods and advances in nuclear science will be introduced in AY25. It will initially be taught as a special topics course. Once established, a permanent course number will be requested. The development of this course was based on a strong interest from students in an application-focused course. Students active in radiochemistry research are encouraged to take this course in the earlier years of the graduate program.

Additional special topic courses can be introduced as necessary. Requests for special topic courses in nuclear science will be reviewed by the FRIB Curriculum committee. The requestor shall prepare a list of topics and learning goals for the curriculum committee as part of the request.

PHY802 Nuclear Survey Goals Learning Goals

Prerequisites

- Undergraduate quantum physics course
- Undergraduate E&M
- Undergraduate modern physics course, including nuclear physics and special relativity

Topics

- The main current nuclear science themes and goals and relationship to other subfields (high and medium energy nuclear physics, neutrino physics), for example based on the most recent NSAC Long Range Plan
- Key Historical nuclear experiments (as part of the covering of various topics)
- The nuclear landscape and basic properties of nuclei, including their decay and underlying interactions, including tools to find these (NNDC/ENDSF etc.)
- Properties of the Nuclear Force
- Basic properties of modern nuclear models
- The liquid drop model
- The shell model
- Evolution and properties of nuclear models, including their use in different areas, strengths and deficiencies
- Quantum numbers and related symmetries
- Fermi Golden Rule
- Nucleosynthesis and the role of nuclei and nuclear reactions in astrophysical phenomena
- Equation of State of nuclear matter
- The main nuclear reactions used to elucidate properties of nuclei and which observables they present
- Two-body relativistic reaction kinematics
- Standard model
- Methods for producing rare isotopes
- Applications of nuclear physics in society

Learning Goals

1. The student will be able to identify the main areas of nuclear physics.
2. The student will be able to describe the global properties of the nuclear landscape using the nuclear liquid drop model.
3. The student will be able to identify the decay modes of atomic nuclei, their typical lifetimes, and underlying interactions.
4. The student will be able to explain the origin and structure of nucleonic shells.
5. The student will be able to identify the quantum numbers characterizing nuclear states and relate them to symmetries (isotropy of space, reflection symmetry, permutation symmetry, isospin).
6. The student will be able to explain the Fermi golden rule.
7. The student will be able to describe the role of the atomic nucleus and their interactions in the Cosmos.
8. The student will be able to identify the building blocks of the Standard Model.

9. The student will be able to classify the hadrons.
10. The student will be able to explain the origin of nuclear mass.
11. The student will be able to describe the main properties of the nuclear force.
12. The student will be able to discuss the basic properties of nuclear matter.
13. The student will be able to describe five nuclear models (liquid drop model, shell model, collective model, density functional theory, ab-initio models) and their domains.
14. The student will be able to identify common nuclear reactions used in low-energy nuclear science (e.g., elastic scattering, inelastic scattering, transfer/knockout, Coulomb excitation, central collisions) and how main observables (such as cross sections, angular distributions) relate to nuclear properties, such as transition strengths, angular momentum transfer, spins etc.
15. The student will be able to use and understand equations for missing mass and invariant mass based on two-body relativistic kinematics.
16. The student will be able to describe the most common techniques for producing rare isotopes in the laboratory and where these different techniques are used for different purposes.
17. The student will be able to identify five societal applications of nuclear physics.

PHY981 Nuclear Structure

Prerequisites

- Nuclear Survey Course PHY802
- Introductory programming experience (ideally python)

Topics

- Nuclear Quantities:
 - Observables vs non-observables
 - Nuclear sizes
 - Nuclear binding (binding, separation, $Q_{\#n}$, thresholds)
 - Alpha-decay and particle decays
 - Gamma-decay
 - Beta-decay and neutrinos
 - Nuclear shapes
 - Fission and fusion
- Models and concepts:
 - Shells / Shell Model
 - Symmetries
 - Tunneling (WKB) and proton emitters
 - (Hartree-)Fock
 - Second quantization and Lipkin Model
- Mathematics:
 - Minimization fundamentals

Learning Goals

1. Students should be able to identify intersections of nuclear structure with other areas of nuclear physics.
2. Students will be able to describe if and how their research program fits into the nuclear structure course.
3. Students should be able to describe the interaction between experiment and theory and the role of uncertainty quantification in this interplay.
4. Students should be able to distinguish between observables and quantities deduced/extracted from these observables.
5. Students will be able to explain the difference between bare and effective nuclear forces and describe their main properties.
6. Students will be able to identify major nuclear models, their domains of applicability, microscopic degrees of freedom (if applicable), and their resolution scales.
7. Students will be able to explain the relation between nuclear binding energy and reaction/decay thresholds.
8. The student will be able to qualitatively predict the properties of selected nuclear states using appropriate schemes/models.

9. Students will understand how nucleonic shells emerge in nuclear structure models, and how they evolve as a function of proton and neutron number.
10. Students will be able to explain the role of symmetries in nuclear structure research.
11. Students will be able to explain the origin of nuclear deformations and the associated collective modes.
12. Students will be able to explain the difference between closed and open quantum systems, in particular for the case of the nucleus.
13. Students will understand how the interplay of weak binding, open decay channels, and continuum effects cause exotic nuclear structure phenomena like clustering and halos.
14. Students will be able to explain the nuclear response to external probes, including giant resonances.
15. Students will understand the impact of nuclear structure on reactions and decay processes.

PHY982 Nuclear Dynamics

Prerequisites

- PHY981 Nuclear Structure

Topics

- Properties and use of nuclear reactions and their dependence on beam energy
- The determination of differential cross sections in experiments and theory
- Relativistic kinematics in reactions
- Direct reactions
- Compound nuclear formation and decay
- Fusion and Fission
- Heavy-ion and central collisions

Learning Goals

1. Understanding different types of reactions, their uses and observables, and the dependence on beam energy (elastic and inelastic scattering, transfer and break-up, Coulomb excitation, capture and fusion/fission, compound nucleus formation, heavy ion (central collisions))
2. Understanding differential cross section (including the concept of solid angle), knowing how to transform to the center-of-mass frame, and how to use relativistic kinematics in reactions.
3. Direct reactions
 - a. Understanding the various reaction mechanisms: elastic and inelastic scattering, transfer and breakup, capture and absorption; and what gets measured in these reactions.
 - b. Solving the single-channel scattering problem with the Schrodinger equation (including Coulomb and optical potentials).
 - c. Understanding the definition of a phase shift and S-matrix.
 - d. Understanding what a resonance is and learning how to estimate its energy and half-width. (include the special case of $l=0$ and the introduction of the scattering length).
 - e. Understanding optical potentials: where they come from and the typical forms.
 - f. Understanding the Lippmann-Schwinger equation and the definition of the T-matrix. Using the two potential formula and the Born expansion in reaction calculations.
 - g. Knowing how to use standard approximations in nuclear reactions and their range of validity (DWBA, Glauber, adiabatic, WKB, etc.)
 - h. Being able to estimate cross sections for specific types of reactions: elastic, inelastic with collective excitations, and single-nucleon transfer reactions.
4. Compound Nucleus Formation and Decay
 - a. Understanding the formation of compound nuclei and their decay
 - b. Understanding the concept of equilibrium based on the description by Weisskopf and Ewing
 - c. Understanding the quantum mechanical implementation by Hauser and Feshbach
5. Fusion and Fission
 - a. Understanding fission in terms of time-evolution in the liquid-drop model
 - b. Understanding the concept of quantum-mechanical barrier tunneling
 - c. Understanding the mass end energy distributions in fission
6. Heavy-ion and central collisions

- a. Understanding the nature of central collisions as evolving with center-of-mass energy
- b. Understanding how central collisions are used for probing the nuclear equation of state
- c. Understanding the concept of Time-dependent Hartree-Fock approaches

PHY983 Nuclear Astrophysics

Prerequisites:

- PHY 410 (Undergraduate Thermal and Statistical Physics), PHY 472 (Undergraduate Quantum Mechanics), and PHY 482 (Undergraduate Electricity and Magnetism), or equivalents. In other words, the course material will be accessible to graduate students of any level with undergraduate degrees in Physics and Astronomy.

List of topics

- Properties and interactions of nuclei
- Survey of astrophysics
- Nuclear reaction rates in stellar environments
- Stellar core and shell burning stages and stellar evolution
- Nucleosynthesis processes
- Stellar transients
- Neutron stars
- Solar neutrinos
- Big Bang nucleosynthesis
- Cosmic-ray nucleosynthesis
- Cosmochronology

Learning Goals

1. By the end of the semester students should be able to explain the following topics:
 - Astronomical observables
 - Birth, evolution, and death of stars
 - Basic nuclear properties
 - Types and roles of nuclear reactions in astrophysics
 - Core/shell burning stages in massive stars
 - Nuclear statistical equilibrium
 - Sites of explosive nucleosynthesis
 - Heavy element nucleosynthesis processes (s, r, i/n, p)
 - Big Bang nucleosynthesis
 - Cosmic-ray nucleosynthesis
 - Common techniques for, and limitations of, nuclear astrophysics experiments
2. By the end of the semester students should be proficient in making simple derivations, predictions, or calculations associated with:
 - Energy release in nuclear reactions and decays

- Spins and parities based on nuclear shell model
 - Gamow window
 - Thermonuclear reaction rates, mean lifetimes, and competition between reactions
 - Thermal excitation and equilibrium
 - Cosmochronology
3. By the end of the semester students should also have developed the following research and professional development skills, which are essential for success in the multidisciplinary field of nuclear astrophysics:
- Be able to independently study topics in Nuclear Astrophysics and discuss them in a group setting
 - Improve comfort level for asking scientific questions
 - Improve presentation skills

CEM985 Radiation Detection

Prerequisites

This course is intended as a graduate level course on radiation detectors and the associated topics. Students should have taken chemistry and physics at the undergraduate level.

Topics

- Interaction of radiation with matter
- Vacuum Systems
- Statistics, background, deadtime
- Radiation detectors
 - Ion Chambers
 - Proportional Counters
 - Scintillators (Organic and Inorganic)
 - PMTs
 - Semiconductors
 - Neutron detectors, fast and slow
- Practical demonstrations
 - Oscilloscope
 - Detectors (semiconductor and scintillator)
 - Vacuum systems
- Electronics
 - Pulse Processing
 - Passive Circuits
 - Active Circuits
 - Noise
 - Linear & Logic signal processing
 - Data Acquisition
 - Analog to Digital Conversion
 - Multidimensional data acquisition

Learning Goals

By the end of the course students should be able to:

1. Demonstrate familiarity with the mechanisms for interaction of the major radiation types (gamma, neutron, charged particles) with matter
2. Demonstrate understanding of the operational principles of each common type of radiation detector (scintillator, semiconductor, gas counters)
3. Identify the most appropriate detector for a given experiment and justify the choice
4. Understand the methods for digitizing signals from detectors
5. Generate a signal from a detector and analyze its properties using an oscilloscope
6. Understand the operational principles and applications of preamplifiers, shaping amplifiers, and other pulse processing circuits, and utilize them to generate linear and logical pulses

7. Perform and interpret calculations using LISE and SRIM (reconcile overlap with CEM 985-003)
8. Explain the operational principle for the most common types of vacuum pumps and recognize different types of vacuum seals
9. Analyze the gas flow from a vacuum system and understand methods to improve pumping speed
10. Analyze detector data and understand the applicability of Poissonian and Gaussian statistics
11. Recognize the sources of noise and ways to mitigate its influence

CEM985 Exp. Nuclear Science Computational Tools

Prerequisites

This course is intended as a graduate level course on radiation detectors and the associated topics. Students should have taken chemistry and physics at the undergraduate level.

Topics

- Introduction to FRIB computational environment
- ROOT
 - Histogram manipulation
 - Tree creation and reading
 - Analysis loops
- Geant4
 - Detector creation
 - Extracting information
 - Defining physics list
- Data Acquisition
- SpecTcl
- LISE/SRIM

Learning goals

1. Students should be able to effectively navigate the laboratory's computational environment and understand what systems are available to them for performing computations. This includes the following subtopics:
 - Students will be able to access Linux clusters and have basic understanding of FRIB computer systems.
 - Students will know how to open and use text editors.
 - Students will have cheat sheet for Linux commands.
 - Students will be able to use containers.
2. Students will demonstrate familiarity with ROOT demonstrated by an ability to create histograms and trees
3. Students will demonstrate an ability to perform simple data analysis with ROOT
4. Students will demonstrate a familiarity with GEANT4 and be able to create a detector environment
5. Students will be able to select and defend an appropriate physics list for a Geant4 simulation
6. Students will be able to extract information from a Geant4 simulation in an appropriate format to compare with experimental data.
7. Students will be able to locate and use user documentation for computational tools provided in the course.
8. Students will demonstrate a basic understanding of SpecTcl and be able to perform a simple analysis using 1D and 2D spectra.

9. Students will understand simple data flows and event building using the FRIB Data Acquisition System.
10. Students will be able to run and interpret a LISE simulation
11. Students will be able to perform simple calculations with SRIM to identify energy loss and range of ions in matter.
12. Students will be able to identify papers relevant to the objectives of given assignments and understand how the technique in the lab was used in the experiment described in the paper, or vice versa.
13. Students will be able to connect the topics within the course to their specific planned thesis experiment.

PHY... Intro to Atomic Physics and Applications

(this is a new course, and a course number is not yet available)

Pre-requisites

- PHY 851 QM1

Topics

1. The interaction of (two-level) atoms with radiation
2. Density Matrix and Decoherence
3. Bloch Sphere & Optical Bloch Equation
4. Spontaneous Emission & Rate Equations
5. Laser & how to home-build an external cavity diode laser
6. laser cooling and trapping
7. Magnetic trapping, evaporative cooling, Bose-Einstein condensation
8. Dipole matrix elements in multi-level atoms (& molecules)
9. Fine structure, hyperfine structure and isotope shifts
10. Diatomic molecules, different Hund's cases
11. Searching for a new particle: the "hidden photon"
12. Effects in atoms from generalized Higgs boson sector
13. Particle dipole moments (magnetic & electric) as probes of particle physics
14. Searching for parity and time-reversal violation with molecules

Learning goals

By the end of the semester, the students will be able to:

1. articulate the idea of spontaneous decay, Rabi oscillation, Bloch sphere, optical dipole force.
2. calculate the quantum state dynamics using optical Bloch equation and transition rate for two level and three level quantum system.
3. understand the principle of laser, how to control, stabilize, and modulate the frequency of a laser in practice.
4. articulate the idea of how to reduce entropy of an atomic/molecular ensemble with lasers and other modern AMO techniques.
5. understand the basics of atomic structures and molecular structures, different Hund's cases of angular momenta couplings in molecules.
6. articulate the idea of how to use atomic and molecular transitions to probe the symmetry-violating interactions in fundamental physics.

PHY... Fundamental symmetries involving neutron/nuclear decay

(this is a new course, and a course number is not yet available)

Prerequisites:

- PHY 852 (QM2)
- PHY802 (Survey of Nuclear Physics) or PHY803 (Survey of Particle Physics)

Topics

- **Introduction**
 - Historical review of the Standard Model
 - The discovery of particles and fundamental bosons
 - Fundamental fermions and bosons in the Standard Model
- **Properties of Fundamental Interactions**
 - Introduction
 - The gravitational interaction
 - The electromagnetic interaction
 - The weak interaction
 - The strong interaction
- **Invariance Principles and Conservation Laws**
 - Introduction
 - Invariance in classical and quantum mechanics
 - Continuous transformations: Translations and Rotations
 - Discrete transformations: Parity, Charge Conjugation, Time Reversal
 - CP and CPT
- **The Electromagnetic Interaction**
 - The interaction between electric charges and the EM coupling constant
 - Concepts of quantum field theory
 - Transition probabilities in perturbation theory (reminder)
 - The bosonic propagator
 - Cross-sections and lifetimes
 - Feynman diagrams
 - Examples of electromagnetic processes
- **The Weak Interaction**
 - Introduction
 - Nuclear beta decay and neutron decay
 - The Fermi coupling constant from muon decay
 - Parity violation in the weak interactions
 - Universality of the weak Interactions
 - The six quarks and the Cabibbo–Kobayashi–Maskawa Matrix
- **Tests of the SM in Neutron and Nuclear Decays**
 - The Vector coupling and the Unitarity of the CKM matrix
 - The neutron lifetime

- Spectrum shape measurements in beta decay
- Searches for deviations from Maximal Parity Violation
- **CP-Violation**
 - The matter-antimatter asymmetry problem
 - Discovery of *CP* violation
 - Formal description of *CP*-Violation
 - CP and T violations
 - *T*-violating correlations in decay processes
- **Double beta decay**
 - Dirac and Majorana neutrinos
 - Lepton and flavor number violation
 - Direct experimental searches for lepton number violation
 - Neutrino-less double beta decay and absolute neutrino mass
 - The role of nuclear theory

Learning Goals

1. Students will receive a gradual introduction to formal aspects of fundamental symmetries in decays
2. Students will get familiar with the application of symmetry transformation properties and apply these to several observables.
3. Students will be able to understand the order of magnitude of EM processes from Feynman diagrams and to identify similarities between processes involving electrons and photons without performing a formal calculation.
4. Students will be able to assess which weak process are allowed or forbidden and to compare common aspects of weak decay, be it in nuclei, the neutron or elementary particles; students will be able to calculate phase space factors to lowest order.
5. Students get familiar with current topics in beta decay and can be invited to select a particular topic to study in more depth and possibly do a short presentation from a literature search.

CEM988 Applied Methods and Advances in Nuclear Science (Selected Topics in Physical Chemistry)

Prerequisites

- None

Topics

The role of radioactivity and radioisotopes and the corresponding applications over a wide range of nuclear sciences and beyond.

- Decay modes
- Radionuclide production, separation, interaction of radiation with matter incl. the biological effects of radiation
- Nuclear imaging and spectroscopy (e.g. Mossbauer spectroscopy, Perturbed Angular Correlation, Image reconstruction)
- Nuclear medicine therapy and imaging/diagnosis
- Radio-tracing for analytical and geological/environmental applications, and nuclear power and waste.

Learning Goals

Students will:

1. Understand radioactive decay in terms of kinetics, decay modes, and emissions.
2. Understand how radioactivity interacts with matter and its biological effects.
3. Become familiar with how radionuclides are produced for applied research and how radionuclides are separated and purified after production.
4. Become familiar with nuclear imaging and spectroscopy, along with their application in imaging and diagnosis and nuclear medicine therapy.
5. Attain a basic understanding of radio-tracing for various scientific fields, nuclear power production and associated nuclear waste.