Lecture 1. Introduction to Nuclear physics

Nuclear physics is the field of physics that studies atomic nuclei and their constituents and interactions. Other forms of nuclear matterare also studied.[1] Nuclear physics should not be confused with atomic physics, which studies the atom as a whole, including its electrons.

Discoveries in nuclear physics have led to applications in many fields. This includes nuclear power, nuclear weapons, nuclear medicineand magnetic resonance imaging, industrial and agricultural isotopes, ion implantation in materials engineering, and radiocarbon datingin geology and archaeology. Such applications are studied in the field of nuclear engineering.

Particle physics evolved out of nuclear physics and the two fields are typically taught in close association. Nuclear astrophysics, the application of nuclear physics to astrophysics, is crucial in explaining the inner workings of stars and the origin of the chemical elements.

Lecture 2. Composition and properties of atomic nuclei

The atomic nucleus is the small, dense region consisting of protons and neutrons at the center of an atom, discovered in 1911 by Ernest Rutherford based on the 1909 Geiger–Marsden gold foil experiment. After the discovery of the neutron in 1932, models for a nucleus composed of protons and neutrons were quickly developed by Dmitri Ivanenko[1] and Werner Heisenberg.[2][3][4][5][6] Almost all of the mass of an atom is located in the nucleus, with a very small contribution from the electron cloud. Protons and neutrons are bound together to form a nucleus by the nuclear force.

The diameter of the nucleus is in the range of 1.75 fm(1.75×10^{-15} m) for hydrogen (the diameter of a single proton)[7] to about 15 fmfor the heaviest atoms, such as uranium. These dimensions are much smaller than the diameter of the atom itself (nucleus + electron cloud), by a factor of about 23,000 (uranium) to about 145,000 (hydrogen).[citation needed]

The branch of physics concerned with the study and understanding of the atomic nucleus, including its composition and the forces which bind it together, is called nuclear physics.

Lecture 3. Nuclear bond energy

Nuclear binding energy is the energy that would be required to disassemble the nucleus of an atom into its component parts. These component parts are neutrons and protons, which are collectively called nucleons. The binding energy of nuclei is due to the attractive forces that hold these nucleons together, and it is always a positive number, since all nuclei would require the expenditure of energy to separate them into individual protons and neutrons. The mass of an atomic nucleus is less than the sum of the individual masses of the free constituent protons and neutrons (according to Einstein's equation $E=mc^2$) and this 'missing mass' is known as the mass defect, and represents the energy that was released when the nucleus was formed.

The term "nuclear binding energy" may also refer to the energy balance in processes in which the nucleus splits into fragments composed of more than one nucleon. If new binding energy is available when light nuclei fuse, or when heavy nuclei split, either process can result in release of this binding energy. This energy may be made available as nuclear energy and can be used to produce electricity as in (nuclear power) or in a nuclear weapon.

When a large nucleus splits into pieces, excess energy is emitted as photons (gamma rays) and as the kinetic energy of a number of different ejected particles (nuclear fission products).

The nuclear binding energies and forces are on the order of a million times greater than the electron binding energies of light atoms like hydrogen.[1]

The mass defect of a nucleus represents the mass of the energy of binding of the nucleus, and is the difference between the mass of a nucleus and the sum of the masses of the nucleons of which it is composed.

Lecture 4. Models of atomic nuclei.

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Lecture 5. General regularities of radioactive decay. Natural and artificial radioactivity. Types of decay

Radioactive decay (also known as nuclear decay or radioactivity) is the process by which an unstable atomic nucleus loses energy (in terms of mass in its rest frame) by emitting radiation, such as an alpha particle, beta particle with neutrino or only a neutrino in the case of electron capture, gamma ray, or electron in the case of internal conversion. A material containing such unstable nuclei is considered radioactive. Certain highly excited short-lived nuclear states can decay through neutron emission, or more rarely, proton emission.

Radioactive decay is a stochastic (i.e. random) process at the level of single atoms, in that, according to quantum theory, it is impossible to predict when a particular atom will decay,[1][2][3] regardless of how long the atom has existed. However, for a collection of atoms, the collection's expected decay rate is characterized in terms of their measured decay constants or half-lives. This is the basis of radiometric dating. The half-lives of radioactive atoms have no known upper limit, spanning a time range of over 55 orders of magnitude, from nearly instantaneous to far longer than the age of the universe.

A radioactive nucleus with zero spin can have no defined orientation, and hence emits the total momentum of its decay products isotropically(all directions and without bias). If there are multiple particles produced during a single decay, as in beta decay, their relative angular distribution, or spin directions may not be isotropic. Decay products from a nucleus with spin may be distributed non-isotropically with respect to that spin direction, either because of an external influence such as an electromagnetic field, or because the nucleus was produced in a dynamic process that constrained the direction of its spin. Such a parent process could be a previous decay, or a nuclear reaction

Lecture 6. Nuclear reactions. Classification.

In nuclear physics and nuclear chemistry, a nuclear reaction is semantically considered to be the process in which two nuclei, or else a nucleus of an atom and a subatomic particle (such as a proton, neutron, or high energy electron) from outside the atom, collide to produce one or more nuclides that are different from the nuclide(s) that began the process. Thus, a nuclear reaction must cause a transformation of at least one nuclide to another. If a nucleus interacts with another nucleus or particle and they then separate without changing the nature of any nuclide, the process is simply referred to as a type of nuclear scattering, rather than a nuclear reaction.

In principle, a reaction can involve more than two particles colliding, but because the probability of three or more nuclei to meet at the same time at the same place is much less than for two nuclei, such an event is exceptionally rare (see triple alpha process for an example very close to a three-body nuclear reaction). "Nuclear reaction" is a term implying an induced change in a nuclide, and thus it does not apply to any type of radioactive decay (which by definition is a spontaneous process).

Natural nuclear reactions occur in the interaction between cosmic rays and matter, and nuclear reactions can be employed artificially to obtain nuclear energy, at an adjustable rate, on demand. Perhaps the most notable nuclear reactions are the nuclear chain reactions in fissionable materials that produce induced nuclear fission, and the various nuclear fusion reactions of light elements that power the energy production of the Sun and stars.

Nuclear reactions may be shown in a form similar to chemical equations, for which invariant mass must balance for each side of the equation, and in which transformations of particles must follow certain conservation laws, such as conservation of charge and baryon number (total atomic mass number).

Lecture 7. Nuclear fission. Thermonuclear reactions.

In nuclear physics, nuclear fusion is a reaction in which two or more atomic nuclei come close enough to form one or more different atomic nuclei and subatomic particles (neutrons or protons). The difference in mass between the reactants and products is manifested as the release of large amounts of energy. This difference in mass arises due to the difference in atomic "binding energy" between the atomic nuclei before and after the reaction. Fusion is the process that powers active or "main sequence" stars, or other high magnitude stars.

A fusion process that produces a nucleus lighter than iron-56 or nickel-62 will generally yield a net energy release. These elements have the smallest mass per nucleon and the largest binding energy per nucleon, respectively. Fusion of light elements toward these releases energy (an exothermic process), while a fusion producing nuclei heavier than these elements will result in energy retained by the resulting nucleons, and the resulting reaction is endothermic. The opposite is true for the reverse process, nuclear fission. This means that the lighter elements, such as hydrogen and helium, are in general more fusible; while the heavier elements, such as uranium and plutonium, are more fissionable. The extreme astrophysical event of a supernova can produce enough energy to fuse nuclei into elements heavier than iron.

In 1920, Arthur Eddington suggested hydrogen-helium fusion could be the primary source of stellar energy. Quantum tunneling was discovered by Friedrich Hund, in 1929, and shortly afterwards Robert Atkinson and Fritz Houtermans used the measured masses of light elements to show that large amounts of energy could be released by fusing small nuclei. Building on the early experiments in nuclear transmutation by Ernest Rutherford, laboratory fusion of hydrogen isotopes was accomplished by Mark Oliphant in 1932. In the remainder of that decade, the theory the main cycle of nuclear fusion in stars were worked out by Hans Bethe. Research into fusion for military purposes began in the early 1940s as part of the Manhattan Project. Fusion was accomplished in 1951 with the Greenhouse Item nuclear test. Nuclear fusion on a large scale in an explosion was first carried out on November 1, 1952, in the Ivy Mike hydrogen bomb test.

Lecture 8. Experiments in high-energy physics.

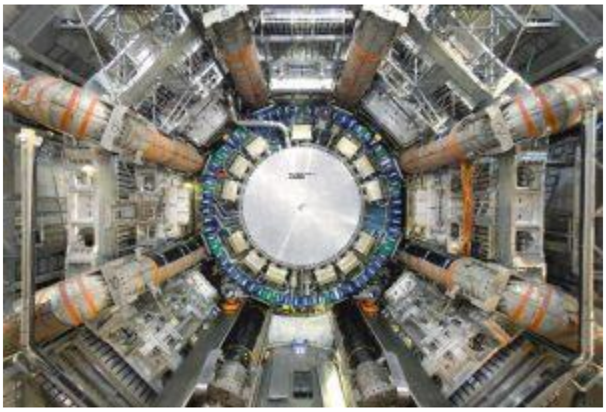
The Wisconsin High Energy Physics group conducts research on the experimental and theoretical frontiers of particle physics. The group works on Energy Frontier at the Large Hadron Collider on ATLAS and CMS experiments (CERN, Geneva), and on the Cosmic Frontier experiment LZ (SURF, South Dakota). Theoretical research encompasses HEP Phenomenology, String Theory and Cosmology.

The objectives for the energy frontier are to explore high energy and luminosity collisions at the LHC using the ATLAS and CMS detectors to lead physics analyses in characterization of the Higgs Boson, to search for its potential partners, to lead searches for Dark Matter and to make extensive studies of Electroweak phenomena.

The objectives for the cosmic frontier are to search for relic cosmic particles, detecting their weak interactions with normal matter, to explain the observed dark matter in the universe (LZ).

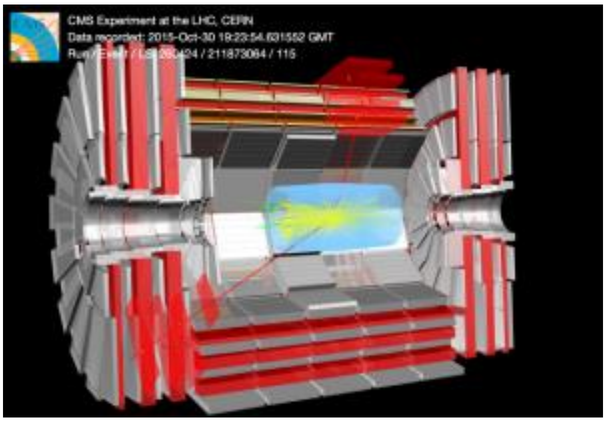
The objectives for the theory frontier are to analyze and interpret the new data (Phenomenology), to investigate new theories of high energy physics extending the standard models of particle physics and cosmology, fundamental issues in gravity, string and quantum field theories, and their phenomenological and cosmological implications (String Theory and Theoretical Cosmology.)

CURRENT EXPERIMENTAL PROGRAM



ATLAS (Photo: CERN)

Wisconsin group in ATLAS, led by Prof. Sau Lan Wu, has experienced major excitement of making outstanding contributions leading to the Higgs boson discovery in 2012 and subsequently the measurement of its properties. Among other recognitions, Prof. Wu’s photo was one of the five physicists on the front page of New York Times. Run 2 of the Large Hadron Collider (LHC) at CERN started in the summer of 2015 at the energy frontier enabling discovery of new physics, in particular, that arising from Dark Matter or hidden sector. Wu’s group is adding its research focus at the LHC from the Higgs particle to another outstanding mystery of Nature: Dark Matter.



CMS Experiment : Dimuon Event (Photo: CERN)

The UW group of Profs Sridhara Dasu, Matt Herndon and Wesley Smith continues its active leadership roles in the Compact Muon Solenoid (CMS) experiment at the LHC, as we explore proton-proton collisions at 13 TeV and prepare for future higher luminosity running. The UW group is leading physics analyses in characterization of the Higgs Boson, searches for its potential partners, searches for particle dark matter, and extensive studies of Electroweak phenomena. The UW group built, commissioned, operates, and upgrades major parts of CMS: the trigger system, including the Level-1 (L1) calorimeter trigger and higher level triggers (HLT), the endcap muon system (EMU), including its infrastructure and new cathode strip chambers (CSCs), software for simulation and event processing, and a leading Tier-2 computing facility.

Lecture 9. Observation, registration and production of elementary particles.

This is a timeline of subatomic particle discoveries, including all particles thus far discovered which appear to be elementary (that is, indivisible) given the best available evidence. It also includes the discovery of composite particles and antiparticles that were of particular historical importance.

More specifically, the inclusion criteria are:

- Elementary particles from the Standard Model of particle physics that have so far been observed. The Standard Model is the most comprehensive existing model of particle behavior. All Standard Model particles including the Higgs boson have been verified, and all other observed particles are combinations of two or more Standard Model particles.
- Antiparticles which were historically important to the development of particle physics, specifically the positron and antiproton. The discovery of these particles required very different experimental methods from that of their ordinary matter counterparts, and provided evidence that all particles had antiparticles—an idea that is fundamental to quantum field theory, the modern mathematical framework for particle physics. In the case of most subsequent particle discoveries, the particle and its anti-particle were discovered essentially simultaneously.
- Composite particles which were the first particle discovered containing a particular elementary constituent, or whose discovery was critical to the understanding of particle physics.

Lecture 10. Classification of elementary particles.

The four fundamental interactions or forces that govern the behavior of elementary particles are listed below.

- The strong force (It holds the nucleus together.)
- The electromagnetic force (It causes interactions between charges.)
- The weak force (It causes beta decay.)
- The gravitational force (It causes interaction between states with energy.)

A given particle may not necessarily be subject to all four interactions. Neutrinos, for example, experience only the weak and gravitational interaction.

The fundamental particles may be classified into groups in several ways. First, all particles are classified into fermions, which obey Fermi-Dirac statistics and bosons, which obey Bose-Einstein statistics. Fermions have half-integer spin, while bosons have integer spin. All the fundamental fermions have spin 1/2. Electrons and nucleons are fermions with spin 1/2. The fundamental bosons have mostly spin 1. This includes the photon. The pion has spin 0, while the graviton has spin 2. There are also three particles, the W^+, W^- and Z_0 bosons, which are spin 1. They are the carriers of the weak interactions.

We can also classify the particles according to their interactions.

Lecture 11. Trends in the development of high-energy physics

The first machines capable of producing mesons were cyclotrons. As accelerators of higher energy were developed, physicists transferred their work to these machines, which enabled the frontiers of small distances and high-mass states to be explored more easily. Today most of the experimental effort in high-energy physics (HEP) is taking place at the large national accelerator laboratories. Paralleling the development of accelerators, instruments for detecting high-energy collisions have evolved. Initially, counters, emulsion stacks, and cloud chambers were used;, but as it became necessary to look at large statistical samples of data with better spatial precision and better knowledge of particle type, these detectors were replaced. At present, for example, the multiwire proportional chamber (MWPC) is widely used. Similarly, owing to new technology, ease of use, and greater availability, man has switched from wood to coal and from coal to oil and gas as primary sources of energy. Marchetti demonstrated that the transition from one source to the next in this series proceeded at a well-defined rate, independent of major events such as war or economic depression.1" 3 Also, Fischer and Pry showed earlier that a smooth transition takes place between competing technologies, such as that between open-hearth and Bessemer steel or between electric arc and open-hearth steel.1* The success of their analyses in the field of energy raises an exciting question; namely, can a similar analysis be employed to describe the use of different particle accelerators and experimental techniques by physicists? Of so, then what are the individual growth and decay rates? Do any patterns emerge? And can extrapolations give us meaningful projections as to future trends? To be able to answer these questions with respect to the community of American experimental high-energy physicists, the papers in Physical Review Letters (PRL) were scanned. The type of machine and the instruments being used for an experiment were recorded. Underlying this approach was the assumption that the number of papers generated by experimenters usiug a given machine and a given type of instrument is representative of the usage of that accelerator and of that instrumentation. PRL was chosen for two reasons: (1) it is the principal journal where frontier research is published in America, and (2) its physical size is small. The latter point was important because the CERN and DESY computer files of HEP papers go back only to 1970, vjhich meant that a manual search was required in order to investigate earlier periods. PRL was first published in July 1958. Because the initial search proved interesting, the Physical Review journal was used to extend the study back to 1953, the year that the Cosraotron began to operate and compete with cyclotrons. In the following, the logistic-substitution model of Marchetti and of Fischer and Pry is briefly described and the results of the scan are presented.

Lecture 12. Nuclear Astrophysics

Nuclear astrophysics is an interdisciplinary branch of physics involving close collaboration among researchers in various subfields of nuclear physics and astrophysics, with significant emphasis in areas such as stellar modeling, measurement and theoretical estimation of nuclear reaction rates, cosmology, cosmochemistry, gamma ray, optical and X-ray astronomy, and extending our knowledge about nuclear lifetimes and masses. In general terms, nuclear astrophysics aims to understand the origin of the chemical elements and the energy generation in stars.

Lecture 13. Nuclear Physics: Present and Future

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Discoveries in nuclear physics have led to applications in many fields. This includes nuclear power, nuclear weapons, nuclear medicineand magnetic resonance imaging, industrial and agricultural isotopes, ion implantation in materials engineering, and radiocarbon datingin geology and archaeology. Such applications are studied in the field of nuclear engineering.

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Lecture 14. The main Equations in Nuclear Physics

Quantity (common name/s)	(Common) symbol/s	Defining equation	SI units	Dimension
Number of atoms	N = Number of atoms remaining at time t N_0 = Initial number of atoms at time t= 0 N_D = Number of atoms decayed at time t		dimensionless	dimensionless
Decay rate, activity of a radioisotope	A		Bq = Hz = s^{-1}	$[T]^{-1}$
Decay constant	λ		Bq = Hz = s^{-1}	$[T]^{-1}$
Half-life of a radioisotope	$t_{1/2}$, $T_{1/2}$	Time taken for half the number of atoms present to decay	s	[T]
Number of half-lives	n (no standard symbol)		dimensionless	dimensionless
Radioisotope	τ (no standard		s	[T]

time constant, mean lifetime of an atom before decay	symbol)			
Absorbed dose, total ionizing dose (total energy of radiation transferred to unit mass)	D can only be found experimentally	N/A	Gy = 1 J/kg (Gray)	$[L]^2[T]^{-2}$
Equivalent dose	H	Q = radiation quality factor (dimensionless)	Sv = J kg^{-1}(Sievert)	$[L]^2[T]^{-2}$
Effective dose	E	W_j = weighting factors corresponding to radiosensitivities of matter (dimensionless)	Sv = J kg^{-1}(Sievert)	$[L]^2[T]^{-2}$

Lecture 15. Sum of the Nuclear Physics

Eighty elements have at least one stable isotope which is never observed to decay, amounting to a total of about 254 stable isotopes. However, thousands of isotopes have been characterized as unstable. These "radioisotopes" decay over time scales ranging from fractions of a second to trillions of years. Plotted on a chart as a function of atomic and neutron numbers, the binding energy of the nuclides forms what is known as the valley of stability. Stable nuclides lie along the bottom of this energy valley, while increasingly unstable nuclides lie up the valley walls, that is, have weaker binding energy.

The most stable nuclei fall within certain ranges or balances of composition of neutrons and protons: too few or too many neutrons (in relation to the number of protons) will cause it to decay. For example, in beta decay a nitrogen-16 atom (7 protons, 9 neutrons) is converted to an oxygen-16 atom (8 protons, 8 neutrons)[23] within a few seconds of being created. In this decay a neutron in the nitrogen nucleus is converted by the weak interaction into a proton, an electron and an antineutrino. The element is transmuted to another element, with a different number of protons.

In alpha decay (which typically occurs in the heaviest nuclei) the radioactive element decays by emitting a helium nucleus (2 protons and 2 neutrons), giving another element, plus helium-4. In many cases this process continues through several steps of this kind, including other types of decays (usually beta decay) until a stable element is formed.

In gamma decay, a nucleus decays from an excited state into a lower energy state, by emitting a gamma ray. The element is not changed to another element in the process (no nuclear transmutation is involved).

Other more exotic decays are possible (see the first main article). For example, in internal conversion decay, the energy from an excited nucleus may eject one of the inner orbital electrons from the atom, in a process which produces high speed electrons, but is not beta decay, and (unlike beta decay) does not transmute one element to another.