7.S: Nuclear Physics (Summary)

Key Terms

activity	magnitude of the decay rate for radioactive nuclides
alpha (α) rays	one of the types of rays emitted from the nucleus of an atom as alpha particles
alpha decay	radioactive nuclear decay associated with the emission of an alpha particle
antielectrons	another term for positrons
antineutrino	antiparticle of an electron's neutrino in β−β− decay
atomic mass	total mass of the protons, neutrons, and electrons in a single atom
atomic mass unit	unit used to express the mass of an individual nucleus, where $1u = 1.66054 \times 10^{-27} kg$
atomic nucleus	tightly packed group of nucleons at the center of an atom
atomic number	number of protons in a nucleus
becquerel (Bq)	SI unit for the decay rate of a radioactive material, equal to 1 decay/second
beta (ββ) rays	one of the types of rays emitted from the nucleus of an atom as beta particles
beta decay	radioactive nuclear decay associated with the emission of a beta particle
binding energy (BE)	energy needed to break a nucleus into its constituent protons and neutrons
binding energy per nucleon (BEN)	energy need to remove a nucleon from a nucleus
breeder reactor	reactor that is designed to make plutonium
carbon-14 dating	method to determine the age of formerly living tissue using the ratio $^{14}C/^{12}C$
chart of the nuclides	graph comprising stable and unstable nuclei
critical mass	minimum mass required of a given nuclide in order for self-sustained fission to occur
criticality	condition in which a chain reaction easily becomes self-sustaining
curie (Ci)	unit of decay rate, or the activity of 1 g of ^{226}Ra, equal to $3.70 \times 10^{10} Bq$
daughter nucleus	nucleus produced by the decay of a parent nucleus
decay	process by which an individual atomic nucleus of an unstable atom loses mass and energy by emitting ionizing particles
decay constant	quantity that is inversely proportional to the half-life and that is used in equation for number of nuclei as a function of time
decay series	series of nuclear decays ending in a stable nucleus
fission	splitting of a nucleus

gamma (γγ) rays	one of the types of rays emitted from the nucleus of an atom as gamma particles
gamma decay	radioactive nuclear decay associated with the emission of gamma radiation
half-life	time for half of the original nuclei to decay (or half of the original nuclei remain)
high dose	dose of radiation greater than 1 Sv (100 rem)
isotopes	nuclei having the same number of protons but different numbers of neutrons
lifetime	average time that a nucleus exists before decaying
liquid drop model	model of nucleus (only to understand some of its features) in which nucleons in a nucleus act like atoms in a drop
low dose	dose of radiation less than 100 mSv (10 rem)
mass defect	difference between the mass of a nucleus and the total mass of its constituent nucleons
mass number	number of nucleons in a nucleus
moderate dose	dose of radiation from 0.1 Sv to 1 Sv (10 to 100 rem)
neutrino	subatomic elementary particle which has no net electric charge
neutron number	number of neutrons in a nucleus
nuclear fusion	process of combining lighter nuclei to make heavier nuclei
nuclear fusion reactor	nuclear reactor that uses the fusion chain to produce energy
nucleons	protons and neutrons found inside the nucleus of an atom
nucleosynthesis	process of fusion by which all elements on Earth are believed to have been created
nuclide	nucleus
parent nucleus	original nucleus before decay
positron	electron with positive charge
positron emission tomography (PET)	tomography technique that uses β^+ emitters and detects the two annihilation γ rays, aiding in source localization
proton-proton chain	combined reactions that fuse hydrogen nuclei to produce He nuclei
radiation dose unit (rad)	ionizing energy deposited per kilogram of tissue
radioactive dating	application of radioactive decay in which the age of a material is determined by the amount of radioactivity of a particular type that occurs
radioactive decay law	describes the exponential decrease of parent nuclei in a radioactive sample
radioactive tags	special drugs (radiopharmaceuticals) that allow doctors to track movement of other drugs in the body
radioactivity	spontaneous emission of radiation from nuclei
radiopharmaceutical	compound used for medical imaging

radius of a nucleus	radius of a nucleus is defined as $r = r_0 A^{1/3}$
relative biological effectiveness (RBE)	number that expresses the relative amount of damage that a fixed amount of ionizing radiation of a given type can inflict on biological tissues
roentgen equivalent man (rem)	dose unit more closely related to effects in biological tissue
sievert (Sv)	SI equivalent of the rem
single-photon-emission computed tomography (SPECT)	tomography performed with γ-emitting radiopharmaceuticals
strong nuclear force	force that binds nucleons together in the nucleus
transuranic element	element that lies beyond uranium in the periodic table

Key Equations

Atomic mass number	$A = Z + N$
Standard format for expressing an isotope	${}^A_Z X$
Nuclear radius, where r_0 is the radius of a single proton	$r = r_0 A^{1/3}$
Mass defect	$\Delta m = Z m_p + (A - Z) m_n - m_{nuc}$
Binding energy	$E = (\Delta m) c^2$
Binding energy per nucleon	$BEN = \frac{E_b}{A}$
Radioactive decay rate	$-\frac{dN}{dt} = \lambda N$
Radioactive decay law	$N = N_0 e^{-\lambda t}$
Decay constant	$\lambda = \frac{0.693}{T_{1/2}}$
Lifetime of a substance	$\bar{T} = \frac{1}{\lambda}$
Activity of a radioactive substance	$A = A_0 e^{-\lambda t}$
Activity of a radioactive substance (linear form)	$lnA = -\lambda t + lnA_0$
Alpha decay	${}^A_Z X \rightarrow {}^{A-4}_{Z-2} X + {}^4_2 He$
Beta decay	${}^A_Z X \rightarrow {}^A_{Z+1} X + {}^0_{-1} e + \bar{v}$
Positron emission	$A^Z_X \rightarrow {}^A_{Z-1} X + {}^0_{+1} e + v$
Gamma decay	${}^A_Z X* \rightarrow {}^A_Z X + \gamma$

Summary

10.1 Properties of Nuclei

- The atomic nucleus is composed of protons and neutrons.
- The number of protons in the nucleus is given by the atomic number, Z. The number of neutrons in the nucleus is the neutron number, N. The number of nucleons is mass number, A.
- Atomic nuclei with the same atomic number, Z, but different neutron numbers, N, are isotopes of the same element.
- The atomic mass of an element is the weighted average of the masses of its isotopes.

10.2 Nuclear Binding Energy

- The mass defect of a nucleus is the difference between the total mass of a nucleus and the sum of the masses of all its constituent nucleons.

- The binding energy (BE) of a nucleus is equal to the amount of energy released in forming the nucleus, or the mass defect multiplied by the speed of light squared.
- A graph of binding energy per nucleon (BEN) versus atomic number A implies that nuclei divided or combined release an enormous amount of energy.
- The binding energy of a nucleon in a nucleus is analogous to the ionization energy of an electron in an atom.

10.3 Radioactive Decay

- In the decay of a radioactive substance, if the decay constant (λλ) is large, the half-life is small, and vice versa.
- The radioactive decay law, $N = N_0 e^{-\lambda t}$, uses the properties of radioactive substances to estimate the age of a substance.
- Radioactive carbon has the same chemistry as stable carbon, so it mixes into the ecosphere and eventually becomes part of every living organism. By comparing the abundance of ^{14}C in an artifact with the normal abundance in living tissue, it is possible to determine the artifact's age.

10.4 Nuclear Reactions

- The three types of nuclear radiation are alpha (α) rays, beta (β) rays, and gamma (γ) rays.
- We represent αα decay symbolically by $^A_Z X \rightarrow ^{A-4}_{Z-2} X + ^4_2 He$. There are two types of β decay: either an electron (β^-) or a positron (β^+) is emitted by a nucleus. γ decay is represented symbolically by $^A_Z X* \rightarrow ^A_Z X + \gamma$.
- When a heavy nucleus decays to a lighter one, the lighter daughter nucleus can become the parent nucleus for the next decay, and so on, producing a decay series.

10.5 Fission

- Nuclear fission is a process in which the sum of the masses of the product nuclei are less than the masses of the reactants.
- Energy changes in a nuclear fission reaction can be understood in terms of the binding energy per nucleon curve.
- The production of new or different isotopes by nuclear transformation is called breeding, and reactors designed for this purpose are called breeder reactors.

10.6 Nuclear Fusion

- Nuclear fusion is a reaction in which two nuclei are combined to form a larger nucleus; energy is released when light nuclei are fused to form medium-mass nuclei.
- The amount of energy released by a fusion reaction is known as the Q value.
- Nuclear fusion explains the reaction between deuterium and tritium that produces a fusion (or hydrogen) bomb; fusion also explains the production of energy in the Sun, the process of nucleosynthesis, and the creation of the heavy elements.

10.7 Medical Applications and Biological Effects of Nuclear Radiation

- Nuclear technology is used in medicine to locate and study diseased tissue using special drugs called radiopharmaceuticals. Radioactive tags are used to identify cancer cells in the bones, brain tumors, and Alzheimer's disease, and to monitor the function of body organs, such as blood flow, heart muscle activity, and iodine uptake in the thyroid gland.
- The biological effects of ionizing radiation are due to two effects it has on cells: interference with cell reproduction and destruction of cell function.
- Common sources of radiation include that emitted by Earth due to the isotopes of uranium, thorium, and potassium; natural radiation from cosmic rays, soils, and building materials, and artificial sources from medical and dental diagnostic tests.
- Biological effects of nuclear radiation are expressed by many different physical quantities and in many different units, including the rad or radiation dose unit.
