

12.S: Nuclear Physics (Summary)

Key Terms

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| 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 (β) 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 |

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| gamma (γ) 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 |

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| 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

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| Atomic mass number | $A = Z + N$ |
| Standard format for expressing an isotope | ${}_Z^A X$ |
| Nuclear radius, where r_0 is the radius of a single proton | $r = r_0 A^{1/3}$ |
| Mass defect | $\Delta m = Zm_p + (A - Z)m_n - m_{nuc}$ |
| 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) | $\ln A = -\lambda t + \ln A_0$ |
| Alpha decay | ${}_Z^A X \rightarrow {}_{Z-2}^{A-4} X + {}_2^4 He$ |
| Beta decay | ${}_Z^A X \rightarrow {}_{Z+1}^A X + {}_{-1}^0 e + \bar{\nu}$ |
| Positron emission | ${}_Z^A X \rightarrow {}_{Z-1}^A X + {}_{+1}^0 e + \nu$ |
| Gamma decay | ${}_Z^A X^* \rightarrow {}_Z^A X + \gamma$ |

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 (λ) 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 α decay symbolically by ${}^A_Z X \rightarrow {}^{A-4}_{Z-2} X + {}^4_2 \text{He}$. 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.

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