Physics 1214 — Chapter 30: Nuclear and High-Energy Physics

1 Properties of Nuclei

nuclei: core of the atom; consists of protons and neutrons.
atomic number: Z; the number of protons in a nucleus.
neutron number:N; the number of neutrons in a nucleus.
nucleon number or mass number:$A = Z + N$; the number of nucleons in the nucleus.

Radii of nuclei

The radii of nuclei are given approximately by the formula

$$R = R_0 A^{1/3},$$

where R_0 is an empirical constant:

$$R_0 = 1.2 \times 10^{-15}\,\mathrm{m} = 1.2\,\mathrm{fm}.$$

All nuclei have approximately the same density.

nuclide: a single nuclear species having specific values of both Z and N.
isotopes: nuclei of a given element with different mass numbers; different isotopes have slightly different physical properties.
mass of proton: $m_p = 1.672621777x10^{-27}$ kg
mass of neutron: $m_n = 1.674927351x10^{-27}$ kg
unified atomic mass unit: 1 u = $1.660538921x10 - 27$ kg ; one-twelfth of the mass of the neutral carbon atom with mass number $A = 12$.

Mass of p, n, e in u	
$m_p =$	1.007276466812 u
$m_n =$	1.00866491600 u
$m_e =$	$5.4857990946 \times 10^{-4}$ u

Energy equivalent of 1 u from $E = mc^2$

$$\boxed{E = (1.66054 \times 10^{-27}\mathrm{kg})(2.99792 \times 10^{8}\mathrm{m/s})^2 = 1.49242 \times 10^{-10}\mathrm{J} = 931.494\mathrm{MeV}}$$

binding energy: magnitude of the total potential energy of the nucleus.

Mass defect

The mass defect ΔM for a nucleus with mass M containing Z protons and N neutrons is defined as

$$\Delta M = Zm_p + Nm_n - M.$$

Mass defect is the mass difference. The total mass of a nucleus is always less than the total mass of its constituent parts due to the ***mass equivalent*** *($E = mc^2$).*

deuterium: the isotope of hydrogen with mass number 2. The nucleus consists of a proton and a neutron bound together called the *deuteron.*
nuclear spin: the total angular momentum of a nucleus; generally associated with both orbital and spin angular momentum of the protons and neutrons.

2 Nuclear Stability

nuclear force or strong force:

- does not depend on charge; same for p and n.
- has a short range on the order of nuclear dimensions $\sim 10^{-15}$ m.
- a particular nucleon interacts only with those few nucleons in its immediate vicinity (versus all other nucleons).
- favors the binding of pairs of p or n with opposite spins ($p\uparrow$-$p\downarrow$ or $n\uparrow$-$n\downarrow$) and of pairs of pairs (p-p with n-n).

3 Radioactivity

radioactivity: the spontaneous disintegration of nuclides that are not stable.
alpha decay: decay of a nucleus emitting alpha (α) particles
alpha particle: identical to the ^{4}He nucleus: 2 p and 2 n bound together; 0 total spin.
beta-minus (β^-) particle: a free n that decays into a p and an e with an average lifetime of about 15 minutes.
neutrino: ν; note: the book has ν_e, but there exist ν_e, ν_τ, ν_μ neutrinos and all their anti-particles.
anti-neutrino: $\bar{\nu}$; $\bar{\nu}_e$, $\bar{\nu}_\tau$, $\bar{\nu}_\mu$
gamma: γ, as in gamma radiation can be emitted from an excited nucleus after an emission of an α or a β^- particle.

Rate of decay of radioactive nuclei

$$\frac{\Delta N}{\Delta t} = -\lambda N.$$

The constant λ is called the decay constant. It has different values for different nuclides.

Number of radioactive nuclei remaining after time t

If there are N_0 nuclei with decay constant λ at time $t = 0$, the number N remaining after time t is

$$N = N_0 e^{-\lambda t}.$$

half-life: $T_{1/2}$ of a radioactive substance is the time required for the number of radioactive nuclei to decrease to half the original number N_0.

Decay constant and half-life

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}.$$

In particle physics, the life of an unstable nucleus or particle is usually described by the lifetime, not the half-life. The **lifetime** (or mean lifetime) T_{mean} is the average time for a nucleus or particle to decay:

$$T_{mean} = \frac{1}{\lambda} = \frac{T_{1/2}}{\ln 2} = \frac{T_{1/2}}{0.693}.$$

activity: of a specimen is the number of decays per unit time.
curie: Ci, common unit of activity; 1 Ci $= 3.70 \times 10^{10}$ decays/s.
becquerel: Bq, SI unit of activity; 1 Bq = 1 decay/s; and 1 Ci $= 3.70 \times 10^{10}$ Bq.
radiocarbon dating: the dating of archeological and geological specimens by measuring the concentration of radioactive isotopes.

4 Radiation and the Life Sciences

radiation: includes radioactivity (α, β, γ, n) and electromagnetic radiation such as x rays and gamma rays. As these particles pass through matter, they lose energy, breaking molecular bonds and creating ions–*ionizing radiation*.
radiation dosimetry: quantitative description of the effect of radiation on living tissue.
absorbed dose: the energy delivered to the tissue, per unit mass of tissue.
gray: Gy, SI unit of absorbed dose of radiation.
rad: common unit of absorbed radiation.

Definition of unit of absorbed radiation dose

$$1 \text{ Gy} = 1 \text{ J/kg}, \; 1 \text{ rad} = 0.01 \text{ J/kg} = 0.01 \text{ Gy} = 1 \text{ cGy}$$

relative biological effectiveness (RBE): a numerical factor weighting the type (energy) of radiation dose with x rays of 200 keV have 1 RBE.

Radiation	**RBE**
x rays and γ rays	1
e	1
p	5
α particles	20
heavy ions	20
slow n	5-20
	(energy dependent)

Sievert: Sv, SI unit of equivalent dose for humans.

Units of equivalent dose

$$\text{equivalent dose (Sv)} = \text{RBE} \times \text{absorbed dose (Gy)}.$$

A more common unit, corresponding to the rad, for equivalent dose for humans is the **rem**:

$$\text{equivalent dose (rem)} = \text{RBE} \times \text{absorbed dose (rad)}.$$

thus, 1 rem = 0.01 Sv.

5 Nuclear Reactions

nuclear reaction: nuclear particles are rearranged as a result of the bombardment of a nucleus by a particle, rather than through a spontaneous natural process; obey classical conservation principles for electric charge, momentum, angular momentum, and energy *plus* conservation of the total number of nucleons.
reaction energy: the difference between the rest masses before and after the reaction. $Q = (M_A + M_B - M_C - M_D)c^2$ where reaction energy Q, particles A and B $\longrightarrow$ particles C and D.
exoergic reaction or exothermic reaction: $Q > 0$, the total mass decreases and the total kinetic energy increases.
endoergic or endothermic: $Q < 0$, the total mass increases and the total kinetic energy decreases.
threshold energy: the energy required for an endoergic reaction: $E \geq |Q|$.

6 Nuclear Fission

nuclear fission: a decay process in which an unstable nucleus splits into two fragments of comparable mass instead of emitting an α or β particle.
fission fragments: products of fission.
induced fission: fission resulting from neutron absorption.
spontaneous fission: fission occurring without initial neutron absorption.
chain reaction: fission that induces more fission events.
nuclear reactor: a system in which a controlled nuclear chain reaction is used to liberate energy.

7 Nuclear Fusion

nuclear fusion: two or more small light nuclei combine to form a larger nucleus.
thermonuclear reactions: fusion chain reactions
cold fusion: fusion not requiring high temperatures; hypothetical.

8 Fundamental Particles

positron: β^+ or e^+
anti-particles: particle with same mass but charge is equal and opposite of partner.
pair production: products of high-energy collisions of charged particles or gamma rays with matter.
muons: μ^- and it's antiparticle μ^+; charge equal to electron; mass $207m_e$.
pions: $\pi^{\pm}$; mass $273m_e$; charge $e^{\pm}$

9 High-Energy Physics

Four Forces

- the strong interaction: gluons
- the electromagnetic interaction: photons
- the weak interaction: W & Z bosons
- the gravitational interaction: gravitons

antiproton: $\bar{p}$
hadrons: have strong interactions; include baryons and mesons;
leptons: do not have strong interactions; $e^{\pm}$,$\mu^{\pm}$, $\tau^{\pm}$, $\nu_{e,\tau,\mu}$; obey conservation principle
bosons: zero or integer spins;
fermions: half-integer spins;
baryons: fermions; nucleons and more massive particles that resemble nucleons; hyperons: Λ, Σ, Ξ, Ω;
mesons: spin 0 or 1; boson; $\pi^{\pm}$, K mesons or kaons, η mesons;
conservation of baryon number: all baryons have a baryon number of ±1 and in all interactions, the total baryon number is conserved.
strangeness: a quantity or property of mesons; conserved in production processes, but not in individual decay processes.
absolute conservation laws: always true such as baryon number conservation.
conditional conservation law: conservation laws that are conditional such as strangeness.
quarks: fundamental particles (for the time being) that make up baryons (3), mesons
gluons: force mediators involved in strong force; massless spin-1 bosons.
quantum chromodynamics: theory of the strong interactions.
standard model: the current scheme of 6 quarks, 6 leptons, and the force mediators and our understanding of their behavior.
electroweak theory: theory that treats the weak and electromagnetic forces as two aspects of a single interaction at sufficiently high energies.
grand unified theories or GUTs: comprehensive theory of strong, weak, and electromagnetic interactions.
theory of everything: GUTs plus gravity.

10 Cosmology

red shifts: longer wavelengths of distant galaxies that indicate expansion of the universe.
Hubble's law: the speed of recession, ν, of a galaxy is approximately proportional to its distance r from us.
Big Bang: the hypothesis, suggested by Hubble's law, that at some time in the past, all the matter in the universe was concentrated in a very small space and was blown apart in an immense explosion–the Big Bang, giving all observable matter more or less the velocities observed today.
dark matter: about 26.8% of energy in the universe of unknown content. CMB
dark energy: about 69% of the energy in the universe. universe. CMB

These values for *dark energy* and *dark matter* are different from your text. This happens in REAL science...values change as we know more and theories are refined! Keep your mind open, keep questioning, keep thinking.

11 Links

Particle Poster jpg
Pdfs
Fermions
Bosons
Baryons
Mesons
Atomic Structure
Properties of Interactions
Particle Processes
Unsolved Mysteries
History of the Universe Images
Particle Overview Simple
Awesome Sites
The Particle Adventure
The Official String Theory Web Site
The Particle Zoo