11.S: Particle Physics and Cosmology (Summary)

Key Terms

antiparticle	subatomic particle with the same mass and lifetime as its associated particle, but opposite electric charge
baryon number	baryon number has the value $B=+1$ for baryons, -1 for antibaryons, and 0 for all other particles and is conserved in particle interactions
baryons	group of three quarks
Big Bang	rapid expansion of space that marked the beginning of the universe
boson	particle with integral spin that are symmetric on exchange
color	property of particles and that plays the same role in strong nuclear interactions as electric charge does in electromagnetic interactions
cosmic microwave background radiation (CMBR)	thermal radiation produced by the Big Bang event
cosmology	study of the origin, evolution, and ultimate fate of the universe
dark energy	form of energy believed to be responsible for the observed acceleration of the universe
dark matter	matter in the universe that does not interact with other particles but that can be inferred by deflection of distance star light
electroweak force	unification of electromagnetic force and weak-nuclear force interactions
exchange symmetry	property of a system of indistinguishable particles that requires the exchange of any two particles to be unobservable
fermion	particle with half-integral spin that is antisymmetric on exchange
Feynman diagram	space-time diagram that describes how particles move and interact
fundamental force	one of four forces that act between bodies of matter: the strong nuclear, electromagnetic, weak nuclear, and gravitational forces
gluon	particle that that carry the strong nuclear force between quarks within an atomic nucleus
grand unified theory	theory of particle interactions that unifies the strong nuclear, electromagnetic, and weak nuclear forces
hadron	a meson or baryon
Hubble’s constant	constant that relates speed and distance in Hubble’s law
Hubble’s law	relationship between the speed and distance of stars and galaxies
lepton	a fermion that participates in the electroweak force
lepton number	electron-lepton number L_e, the muon-lepton number L_μ, and the tau-lepton number L_τ are conserved separately in every particle interaction
mesons	a group of two quarks
nucleosynthesis	creation of heavy elements, occurring during the Big Bang

particle accelerator	machine designed to accelerate charged particles; this acceleration is usually achieved with strong electric fields, magnetic fields, or both
particle detector	detector designed to accurately measure the outcome of collisions created by a particle accelerator; particle detectors are hermetic and multipurpose
positron	antielectron
quantum chromodynamics (QCD)	theory that describes strong interactions between quarks
quantum electrodynamics (QED)	theory that describes the interaction of electrons with photons
quark	a fermion that participates in the electroweak and strong nuclear force
redshift	lengthening of the wavelength of light (or reddening) due to cosmological expansion
Standard Model	model of particle interactions that contains the electroweak theory and quantum chromodynamics (QCD)
strangeness	particle property associated with the presence of a strange quark
strong nuclear force	relatively strong attractive force that acts over short distances (about \(10^{−15}) m) responsible for binding protons and neutrons together in atomic nuclei
synchrotron	circular accelerator that uses alternating voltage and increasing magnetic field strengths to accelerate particles to higher and higher energies
synchrotron radiation	high-energy radiation produced in a synchrotron accelerator by the circular motion of a charged beam
theory of everything	a theory of particle interactions that unifies all four fundamental forces
virtual particle	particle that exists for too short of time to be observable
W and Z boson	particle with a relatively large mass that carries the weak nuclear force between leptons and quarks
weak nuclear force	relative weak force (about 10^{-6} the strength of the strong nuclear force) responsible for decays of elementary particles and neutrino interactions

Key Equations

Momentum of a charged particle in a cyclotron	$p = 0.3Br$
Center-of-mass energy of a colliding beam machine	$W^2 = 2[E_1E_2 + (p_1c)(p_2c)] + (m_1c^2)^2 + (m_2c^2)^2$
Approximate time for exchange of a virtual particle between two other particles	$\Delta t = \frac{h}{E}$
Hubble's law	$v = H_0 d$
Cosmological space-time metric	$ds^2 = c^2dt^2 - a(t)^2 d\sum^2$

Summary

11.1 Introduction to Particle Physics

- The four fundamental forces of nature are, in order of strength: strong nuclear, electromagnetic, weak nuclear, and gravitational. Quarks interact via the strong force, but leptons do not. Both quark and leptons interact via the electromagnetic, weak, and gravitational forces.
- Elementary particles are classified into fermions and boson. Fermions have half-integral spin and obey the exclusion principle. Bosons have integral spin and do not obey this principle. Bosons are the force carriers of particle interactions.
- Quarks and leptons belong to particle families composed of three members each. Members of a family share many properties (charge, spin, participation in forces) but not mass.
- All particles have antiparticles. Particles share the same properties as their antimatter particles, but carry opposite charge.

11.2 Particle Conservation Laws

- Elementary particle interactions are governed by particle conservation laws, which can be used to determine what particle reactions and decays are possible (or forbidden).
- The baryon number conservation law and the three lepton number conversation law are valid for all physical processes. However, conservation of strangeness is valid only for strong nuclear interactions and electromagnetic interactions.

11.3 Quarks

- Six known quarks exist: up (u), down (d), charm (c), strange (s), top (t), and bottom (b). These particles are fermions with half-integral spin and fractional charge.
- Baryons consist of three quarks, and mesons consist of a quark-antiquark pair. Due to the strong force, quarks cannot exist in isolation.
- Evidence for quarks is found in scattering experiments.

11.4 Particle Accelerators and Detectors

- Many types of particle accelerators have been developed to study particles and their interactions. These include linear accelerators, cyclotrons, synchrotrons, and colliding beams.
- Colliding beam machines are used to create massive particles that decay quickly to lighter particles.
- Multipurpose detectors are used to design all aspects of high-energy collisions. These include detectors to measure the momentum and energies of charge particles and photons.
- Charged particles are measured by bending these particles in a circle by a magnetic field.
- Particles are measured using calorimeters that absorb the particles.

11.5 The Standard Model

- The Standard Model describes interactions between particles through the strong nuclear, electromagnetic, and weak nuclear forces.
- Particle interactions are represented by Feynman diagrams. A Feynman diagram represents interactions between particles on a space-time graph.
- Electromagnetic forces act over a long range, but strong and weak forces act over a short range. These forces are transmitted between particles by sending and receiving bosons.
- Grand unified theories seek an understanding of the universe in terms of just one force.

11.6 The Big Bang

- The universe is expanding like a balloon—every point is receding from every other point.
- Distant galaxies move away from us at a velocity proportional to its distance. This rate is measured to be approximately 70 km/s/Mpc. Thus, the farther galaxies are from us, the greater their speeds. These “recessional velocities” can be measure using the Doppler shift of light.
- According to current cosmological models, the universe began with the Big Bang approximately 13.7 billion years ago.

11.7 Evolution of the Early Universe

- The early universe was hot and dense.
- The universe is isotropic and expanding.
- Cosmic background radiation is evidence for the Big Bang.

- The vast portion of the mass and energy of the universe is not well understood.