Physics 2018: Great Ideas in Science: The Physics Module Particle Physics Lecture Notes

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Edition 1.0

Abstract

These class notes are designed for use of the instructor and students of the course Physics 2018: Great Ideas in Science. This edition was last modified for the Fall 2007 semester.

II. Particle Physics

A. Matter, Energy, and Forces.

1. As we saw in the last section on quantum mechanics (see page I-7), there are 4 field (*i.e.*, natural) forces in nature:

    a) The **strong force** is a nuclear force that binds the nucleons (*i.e.*, protons and neutrons) together. This force is *released* in thermonuclear fusion reactions.

    b) The **electromagnetic (E/M) force** is the force that binds matter together (*e.g.*, atoms → molecules → solids). This force is *released* in chemical reactions and photon/matter interactions.

    c) The **weak force** is another nuclear force that causes radioactivity. This force is *released* in nuclear fission reactions.

    d) The **gravitational force** is the force that binds large objects together (*e.g.*, planets, stars, galaxies, and the Universe as a whole). This force is *released* in gravitational interactions (*i.e.*, trajectories, orbits, etc.)

2. But how do these forces propagate in nature?

    a) Newton never described a mechanism for how gravity works.

    b) Faraday described the natural forces that were known in the 1800s (*i.e.*, gravitational, electrical, and magnetic) as a (vector) *field* that permeates all of space $\Longrightarrow$ these forces propagate in space via the field.

    c) Modern physics has come up with a new mechanism by

which the natural forces propagate $\implies$ via particle exchanges.

3. As technology progressed in the 20th century, particle accelerators were built. These devices accelerate particles to speeds near the speed of light and have these fast moving particles crash into each other.

    a) Fermi lab near Chicago has a large particle accelerator.

    b) The European Organization for Nuclear Research (in French, the Organisation Europèenne pour la Recherche Nuclèaire), commonly known as CERN, is the world's largest particle physics laboratory, situated just northwest of Geneva on the border between France and Switzerland. It currently has the largest particle accelerator on the planet.

    c) As the accelerators achieved higher and higher energies, more and more types of elementary particles were being created. The world of particle physics was getting quite complicated.

4. However in the early 1970s, a new idea was put forth that only 12 types of elementary particles exist and all the particles that were being created in the labs were combinations of these particles $\implies$ the **Standard Model** of particle physics.

B. Spin and Particle Families

1. In *classical* mechanics, a rigid body admits two kinds of angular momentum:

    a) **Orbital**: $\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$, associated with the motion *of* the center of mass. Here, $\boldsymbol{L}$ is the angular momentum vector, $\boldsymbol{r}$ is the radial distance that the object is with respect to

the center of the orbit, and $p = mv$ is the linear momentum of the orbiting object of mass m. Such motion is referred to as a **revolution** about the center of mass.

b) **Spin**: $S = I\omega$, associated with the motion _about_ the center of mass. Here, S is the spin angular momentum, I is the moment of inertia (in units of mass times length squared), and ω is the angular velocity of the spinning object. Such motion is referred to as a **rotation** about an axis.

c) One then talks about the **total angular momentum**: orbital (L) + spin (S) angular momenta.

2. By analogy, we have the same description on the microscopic level for _quantum_ mechanics:

a) **Orbital**: The motion of an electron about the nucleus of an atom as described by _spherical harmonics_ with the orbital angular momentum quantum number ℓ and the magnetic (or azimuthal) quantum number m. This is sometimes referred to as the _extrinsic_ angular momentum (L).

b) **Spin**: Unlike the classical case, this isn't the spin of the electron about an axis, since the electron is a point particle (even though we describe electron spin about an axis in elementary physics). Here "spin" is nothing more than the _intrinsic_ angular momentum (S) of the electron. Since this is intrinsic, spin angular momentum is independent of spatial coordinates (r, θ, ϕ).

3. The spin angular momentum vectors are *not* spherical harmonics (they are not functions of θ and ϕ at all). The Schrödinger equation forces the ℓ quantum number to be integers for spherical harmonic functions (*i.e.*, orbital angular momentum). Meanwhile the spin quantum number s can be both integers and half-integers. (You'll have to trust me on this, the mathematics that prove these statements are beyond the scope of this class.)

a) It so happens that every elementary particle has a *specific and immutable* value of s which we call the **spin** of that particular species.

b) Particles with *half-integer* spins are called **fermions**. Fermions are said to have **anti symmetric** wave functions. These 1/2-integer spin particles are called fermions since their population distributions follow **Fermi-Dirac** statistics instead of the Maxwell-Boltzmann statistics of classical physics.

c) Particles with *integer* spins are called **bosons**. Bosons are said to have **symmetrical** wave functions. These integer spin particles are called bosons since their population distributions follow **Bose-Einstein** statistics.

d) The convolution (*i.e.*, joining together) of anti symmetric wave functions go to zero as two identical particles approach each other. As a result, two fermions in the same quantum state exhibit mutual repulsion to avoid their combined wave functions going to zero. This effect is known as the **Pauli Exclusion Principle**.

e) Bosons have no such exclusion principle since the convolution of symmetric wave functions do not go to zero as two identical particles approach each other.

4. In modern physics, there are two main groups of particles that make up all matter and energy:

a) Elementary particles: These are particles that make up matter. They are subdivided into 3 groups:
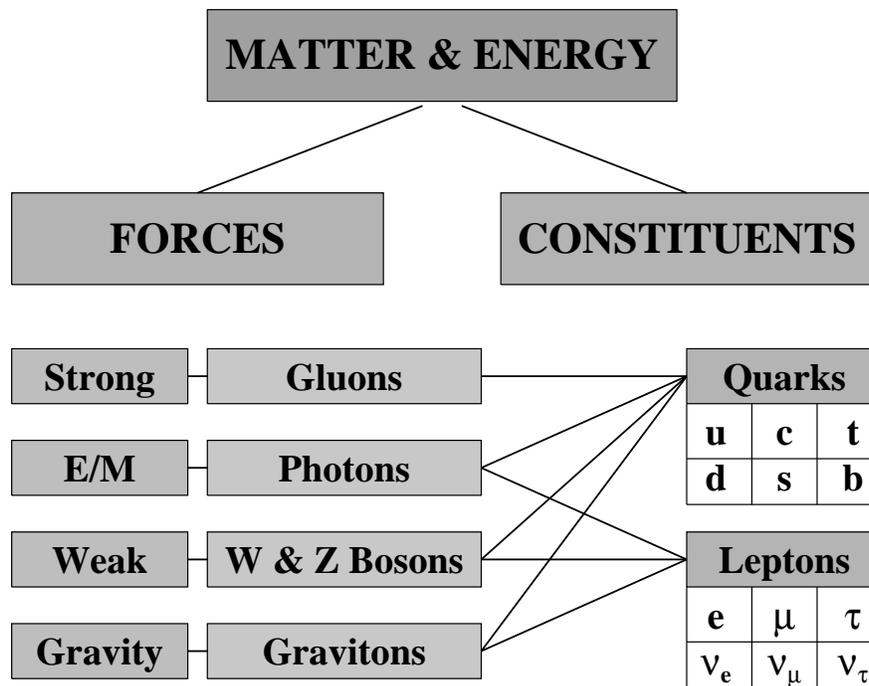
i) Leptons (*light* particles) include the *electron* (e^-, $m_e = 511$ keV, 1 keV $= 1000$ eV, 1 eV $= 1.60 \times 10^{-19}$ Joules), *muon* (μ, $m_\mu = 107$ MeV), and *tau particle* (τ, $m_\tau = 1784$ MeV), each with a negative charge; their respective neutrinos: *electron neutrino* (ν_e, $m_{\nu-e} < 30$ eV), *muon neutrino* (ν_μ, $m_{\nu-\mu} < 0.5$ MeV), and *tau neutrino* (ν_τ, $m_{\nu-\tau} < 250$ MeV), each with no charge; and the antiparticles of each: e^+ (called a *positron*), $\overline{\mu}, \overline{\tau}, \overline{\nu_e}, \overline{\nu_\mu}$, and $\overline{\nu_\tau}$ (the "bar" over the symbol indicates these are anti-particles). These particles do **not** participate in the strong interactions. All leptons have spin of 1/2, hence are fermions.

ii) Mesons are particles of intermediate mass that are made of quark-antiquark pairs and include *pions*, *kaons*, and *η-particles*. All are unstable and decay via weak or E/M interactions. All mesons have either 0 or integer spin, hence are bosons.

iii) Baryons (*heavy* particles) include the nucleons n (*neutrons* — neutral particles) and p (*protons* — positive charged) and the more massive *hyperons* (*i.e.*, Λ, Σ, Ξ, and Ω). Baryons are composed of a triplet of quarks. Each baryon has an antibaryon associated with it and has a spin of either 1/2 or 3/2, hence are fermions.

b) **Field particles**: These particles mediate the 4 natural forces and are sometimes referred to as the *energy* particles — all are bosons. Here they are listed in order from strongest to weakest:

i) **Gluons**: Mediate the strong [nuclear] force. Strength of this force is described by the **color charge**.

ii) **Photons**: Mediate the electromagnetic force. Strength of this force is described by the **electric charge**.

iii) **Intermediate vector [W & Z] bosons** (sometimes referred to as **weakons**): Mediate the weak [nuclear] force. Strength of this force is described by the **weak charge**.

iv) **Gravitons**: Mediate the force of gravity. Strength of this force is described by the **mass**.

5. From the above list of elementary particles, there seems to be only 2 types of basic particles: *leptons* which do not obey the strong force and *quarks* which do obey the strong force. Particles that participate in the strong force are also called **hadrons** — so obviously, the hadrons are those particles composed of quarks (*i.e.*, the mesons and baryons). All quarks have a spin of 1/2. There are 6 *flavors* of leptons (as describe above). As such, it was theorized and later observed, 6 types of quarks (and an additional 6 antiquarks) must exist:

a) **Up** (u) quark has a rest energy of 360 MeV (1 MeV = 10^6 eV) and a charge of $+\frac{2}{3}\,e$.

b) **Down** (d) quark has a rest energy of 360 MeV and a charge of $-\frac{1}{3}\,e$.

c) Charmed (c) quark has a rest energy of 1500 MeV and a charge of $+\frac{2}{3}e$.

d) Strange (s) quark has a rest energy of 540 MeV and a charge of $-\frac{1}{3}e$.

e) Top (t) quark has a rest energy of 170 GeV (1 GeV $= 10^9$ eV) and a charge of $+\frac{2}{3}e$.

f) Bottom (b) quark has a rest energy of 5 GeV and a charge of $-\frac{1}{3}e$.

6. Note that a proton is composed of 2 u and a d quark and a neutron composed of an u and 2 d quarks.

7. The theory on how quarks interact with each other is called **quantum chromodynamics** (in analogy with quantum mechanics). One interesting result of this theory is that quarks cannot exist in isolation, they must always travel in groups of 2 to 3 quarks.

8. As described above, the four forces in relativistic quantum mechanics are mediated by the exchange of integer-spin particles (bosons).

a) Of the four forces, only gravity gives rise to attractive forces between *like* particles (same type of color charge, electric charge, weak charge, or mass).

b) This difference arises because the graviton is spin 2, whereas the gluon, photon, and weakon are spin 1 (see Table II-1).

MATTER & ENERGY

FORCES **CONSTITUENTS**

Strong	Gluons
E/M	Photons
Weak	W & Z Bosons
Gravity	Gravitons

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

The Standard Model of Particle Physics

Figure II–1: The Standard Model is the current best description of the subatomic world.

9. This description of elementary and field particles is called the **Standard Model**. A graphical representation of this model is shown in Figure II-1.

10. Getting back to angular momentum, *spin* can take on any half-integer or integer value for s. As mentioned above, each particle has its own specific spin (see Table II-1) that remains *fixed*. In contrast, the *orbital* angular momentum quantum number ℓ can take on any (integer) value you please, and will change from one to another when the system is perturbed (via a photon interaction or from the electromagnetic field of a passing charged particle).

11. In the science of quantum mechanics, particles with $s = 1/2$ (*i.e.*, fermions) are the most important, since these are the particles that make up ordinary matter (protons, neutrons, and electrons), as well as all quarks and leptons. There are just *two* quantum states for these type of fermions:

Table II–1: Spin quantum numbers for a sample of elementary and field particles.

Common Name	Symbol†	Particle Type	Spin (s)	Spin Family
Pion	π^+	meson	0	boson
	π^0	meson	0	boson
Electron	e^-	lepton	$\frac{1}{2}$	fermion
Muon	μ^-	lepton	$\frac{1}{2}$	fermion
Neutrino	ν_e	lepton	$\frac{1}{2}$	fermion
Proton	p	baryon	$\frac{1}{2}$	fermion
Neutron	n	baryon	$\frac{1}{2}$	fermion
Gluon	G	field	1	boson
Photon	γ	field	1	boson
Weakon	W	field	1	boson
Delta	Δ^+	baryon	$\frac{3}{2}$	fermion
Graviton	g	field	2	boson

† – The superscript in the symbol corresponds to the charge of the particle: '+' = positive, '–' = negative, '0' = neutral. Symbols with no superscript are neutral, except for the proton which is positively charged, and the weakons which can have a +, –, or no electric charge.

a) $+\frac{1}{2}$: the **spin up** (↑) state.

b) $-\frac{1}{2}$: the **spin down** (↓) state.

12. Bound electrons can carry out a **spin-flip transition**. When an electron in the ground state has a "spin" *parallel* to the proton's "spin" (*i.e.*, both are spinning in the same direction), it has a slightly higher energy than when the spins are *antiparallel* (*i.e.*, the electron is spinning in the opposite direction with respect to the proton).

a) For hydrogen, an electron in the parallel state can spontaneously decay to the antiparallel state giving rise to an emission line at 21-cm at radio wavelengths.

b) The probability of this transition occurring is very low however (that is, it has a very low *oscillator strength*) with an Einstein A-value of $A_{21} = 2.85 \times 10^{-15}$ sec^{-1}. Note that the average lifetime that an electron will stay excited depends on the reciprocal of the Einstein A-value. For comparison, the Lyman-α transition (level $n = 2$ to level $n = 1$) in hydrogen has an Einstein A-value of $A_{21} = 6.62 \times 10^8$ sec^{-1}).

c) Such a transition is called a **hyperfine** transition $\Longrightarrow$ transitions involving electron spin-flips.

d) Of course, hydrogen can also absorb a 21-cm photon producing an absorption line at this wavelength.

e) Much of the interstellar medium (*i.e.*, the gas in between the stars) is composed of cold hydrogen gas. As such, the structure of the Milky Way Galaxy has been mapped via this 21-cm line (note that photons at this wavelength are unaffected by dust, and as such, can travel great distances through the galactic plane which is a very dusty place).

C. The Details of the Standard Model.

1. The Standard Model is a grouping of two major theories:

a) The **quantum electroweak** theory which describes the electromagnetic and the weak forces as one set of equations.

b) The **quantum chromodynamics** theory which describes the strong force.

c) Both of these provide an internally consistent theory describing interactions between all experimentally observed particles.

d) Technically, **quantum field theory** provides the mathematical framework for the Standard Model. The Standard Model describes each type of particle in terms of a mathematical field.

e) Currently physicists are working on a new theory which will merge the electroweak force and the strong force into one "super" force. When validated, this new theory will be called the **Grand Unified Theory**.

f) Note however that the Grand Unified Theory will not yet include the gravitational force. When (and if) the gravitational force is merged into this Grand Unified Theory, the new theory will be called the **Theory of Everything**.

2. Even though a "place-holder" has been assigned for gravity in the Standard Model, **relativistic quantum mechanics**, which uses the Standard Model does not have the physics of the gravitational force built into this model.

a) That is, we have never observed the **graviton** force carrying particle.

b) Such a theory, when developed, will likely be called **quantum gravity**. Whenever (and if ever) quantum gravity is realized, the Theory of Everything will be realized.

3. The distinguishing characteristic that separates an elementary particle from a filed particle is that an elementary particle possesses *mass* whereas a field particle is a pure-energy particle.

4. One thing that the Standard Model cannot yet explain is why the elementary particles possess mass.

5. One idea that has been put on the table to describe the origin of mass is called the **Higgs mechanism**. This mechanism involves one additional particle to be included in Figure II-1, called the **Higgs boson**, and one additional force type to be included, mediated by exchanges of this boson.

  a) The Higgs particle has not yet been observed. Today we can only say that if it exists, it must have a mass greater than about 80 GeV/c^2.

  b) Searches for a more massive the Higgs boson are beyond the scope of the present facilities at CERN, Fermi Lab, or SLAC (the Stanford University Linear Accelerator).

  c) Future facilities, such as the **Large Hadron Collider** currently being designed at CERN, may have energies high enough to detect this Higgs boson.

6. The particle called Higgs boson is the quantum of one of the components of a **Higgs field**. In empty space, the Higgs field acquires a non-zero value, which permeates every place in the Universe at all times.

  a) The Higgs field is analogous to the **vacuum field energy** described by the general theory of relativity.

  i) "Virtual particles" (matter-antimatter pairs) continuously come into existence from this vacuum energy (the energy of the space-time continuum), then quickly destroy themselves.

  ii) The pressure of these virtual particles is what gives rise to the **Casimir Effect** first observed in 1948.

b) The vacuum expectation value (VEV) of the Higgs field is constant and equal to 246 GeV (246×10^9 eV). The existence of this non-zero VEV plays a fundamental role — it gives mass to every elementary particle, including to the Higgs boson itself.

i) In technical terms, the acquisition of a non-zero VEV spontaneously breaks the electroweak gauge symmetry, a phenomenon known as the Higgs mechanism.

ii) This is the simplest mechanism capable of giving mass to the gauge bosons that is also compatible with gauge theories. We can't go any further here since gauge theory is a graduate-level physics course and the math is far too complicated for an undergraduate class like this one.

c) Since the Higgs field is a scalar field, the Higgs boson has spin zero and hence has no intrinsic angular momentum. The Higgs boson is also its own antiparticle.