Standard Model

Unit: Quantum and Particle Physics

NGSS Standards/MA Curriculum Frameworks (2016): N/A

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 15.8.A.1.ii, 15.8.A.1.iii

Mastery Objective(s): (Students will be able to…)

- Name and describe the particles of the Standard Model.
- Describe interactions between particles, according to the Standard Model.

Success Criteria:

- Descriptions & explanations are accurate and account for observed behavior.

Language Objectives:

- Explain the important features of each model of the atom.

Tier 2 Vocabulary: model, quantum

Notes:

The Standard Model is a theory of particle physics that:

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- identifies the particles that matter is ultimately comprised of
- describes properties of these particles, including their mass, charge, and spin
- describes interactions between these particles

The Standard Model dates to the mid-1970s, when the existence of quarks was first experimentally confirmed. Physicists are still discovering new particles and relationships between particles, so the model and the ways it is represented are evolving, much like atomic theory and the Periodic Table of the Elements was evolving at the turn of the twentieth century. The table and the model described in these notes represent our understanding, as of 2025. By the middle of this century, the Standard Model may evolve into a form that is substantially different from the way we represent it today.

The Standard Model in its present form does not incorporate dark matter, dark energy, or gravitational attraction.

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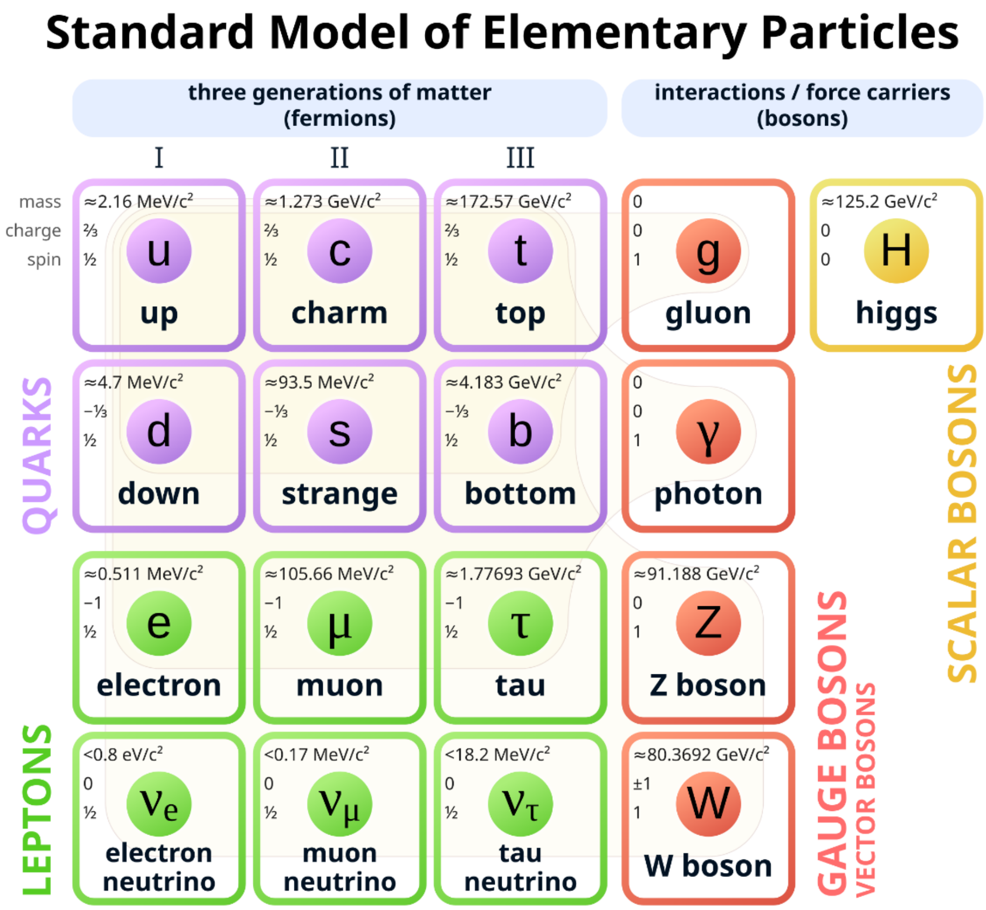
The Standard Model is often presented in a table, with rows, columns, and color-coded sections used to group subsets of particles according to their properties.

As of 2025, the Standard Model is represented by a table similar to this one:



Properties shown in the table include mass, charge, and spin.

- **Mass** is shown in units of electron volts divided by the speed of light squared $\left(\frac{\text{eV}}{c^2}\right)$. An electron volt (eV) is the energy acquired by an electric potential difference of one volt applied to one electron. (Recall that the metric prefix "M" stands for mega (10^6) and the metric prefix "G" stands for giga (10^9).) The c^2 in the denominator comes from Einstein's equation, $E = mc^2$, solved for m.
- **Charge** is the same property that we studied in the electricity unit. The magnitude and sign of charge is relative to the charge of an electron, which is defined to be −1.
- **Spin** is the property that is believed to be responsible for magnetism. (The name is because magnetism was previously thought to come from a magnetic field produced by electrons spinning within their orbitals.)

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Fundamental Particles

Quarks

Quarks are particles that participate in strong interactions (sometimes called the "strong force") through the action of "color charge" (which will be described later). Because protons and neutrons (which make up most of the mass of an atom) are made of three quarks each, quarks are the subatomic particles that make up most of the ordinary matter* in the universe.

- quarks have color charge (*i.e.,* they interact via the strong force)
- quarks have spin of $\pm\frac{1}{2}$
- "up-type" quarks carry a charge of $+\frac{2}{3}$; "down-type" quarks carry a charge of $-\frac{1}{3}$.

There are six flavors† of quarks: up and down, charm and strange, and top and bottom. (Originally, top and bottom quarks were called truth and beauty.)

Leptons

Leptons are the smaller particles that make up most matter. The most familiar lepton is the electron. Leptons participate in "electroweak" interactions, meaning combinations of the electromagnetic and weak forces.

- leptons do not have color charge (*i.e.,* they do not interact via the strong force)
- leptons have spins of $+\frac{1}{2}$
- electron-type leptons have a charge of −1; neutrinos do not have a charge.
- neutrinos (ν) and antineutrinos $(\bar{\nu})$ have no electrical charge, and negligible mass. Moreover, neutrinos oscillate, which makes their mass indefinite. Because neutrinos are leptons (which do not interact with the strong force) and they have no charge, they interact with only the weak and gravitational forces, which means neutrinos have very little interaction with normal matter.

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* Matter that is not "ordinary matter" is called "dark matter", whose existence is theorized but not yet proven.

† Yes, "flavors" really is the correct term.

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Gauge Bosons

Gauge bosons are the particles that carry force—their interactions are responsible for the fundamental forces of nature: the strong force, the weak force, the electromagnetic force and the gravitational force. The hypothetical particle responsible for the gravitational force is the graviton, which has not yet been detected (as of 2025).

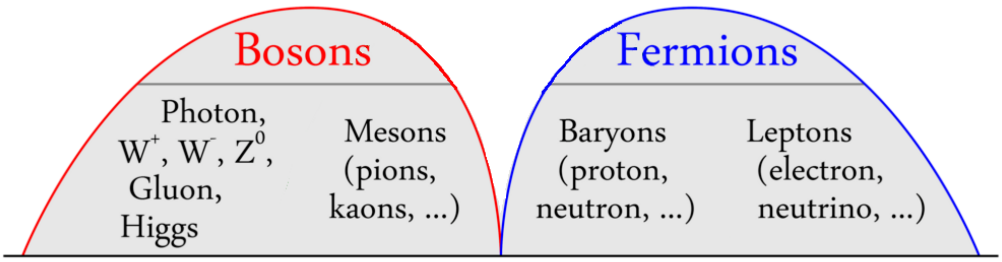
- photons are responsible for the electromagnetic force.
- gluons are responsible for the strong interaction (strong force)
- W and Z bosons are responsible for the weak interaction (weak force)

Scalar Bosons

At present, the only scalar boson we know of is the Higgs boson, theorized in 1964 by Peter Higgs and discovered in 2012, which is responsible for mass.

The Higgs boson interacts with a force field called the Higgs field. The Higgs field causes Higgs bosons to interact with other particles (such as quarks and electrons) to resist changes in their motion. We call this resistance "inertia", which is the basis for Newton's first law (which you studied in Physics 1). The more particles a substance has that can interact with Higgs bosons, the more inertia it has. Recall that translational inertia is the same thing as mass, which is why we say that the Higgs boson is responsible for particles having mass.

Classes of Particles



Bosons

Bosons (the right columns in the table of the Standard Model) are described by Bose-Einstein statistics, have integer spins and do not obey the Pauli Exclusion Principle. Interactions between bosons are responsible for forces and mass.

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Fermions

Quarks and leptons (the left columns in the table of the Standard Model) are fermions. Fermions are described by Fermi-Dirac statistics and obey the Pauli exclusion principle (which states that no two particles in an atom may have the same exact set of quantum numbers—numbers that describe the energy states of the particle).

Fermions are the building blocks of matter. They have a spin of ½, and each fermion has its own antiparticle (see below).

Antiparticles

Each particle in the Standard Model has a corresponding antiparticle. Like chemical elements in the Periodic Table of the Elements, fundamental particles are designated by their symbols in the table of the Standard Model. Antiparticles are designated by the same letter, but with a line over it. For example, an up quark would be designated "u", and an antiup quark would be designated "$\overline{\text{u}}$".

The antiparticle of a fermion has the same name as the corresponding particle, with the prefix "anti-", and has the opposite charge. *E.g.,* the antiparticle of a tau neutrino is a tau antineutrino. (However, for historical reasons an antielectron is usually called a positron.) *E.g.,* up quark carries a charge of $+\frac{2}{3}$, which means an antiup quark carries a charge of $-\frac{2}{3}$.

Each of the fundamental bosons ***is*** its own antiparticle, except for the W^- boson, whose antiparticle is the W^+ boson.

When a particle collides with its antiparticle, the particles annihilate each other, and their mass is converted to energy ($E = mc^2$) and released.

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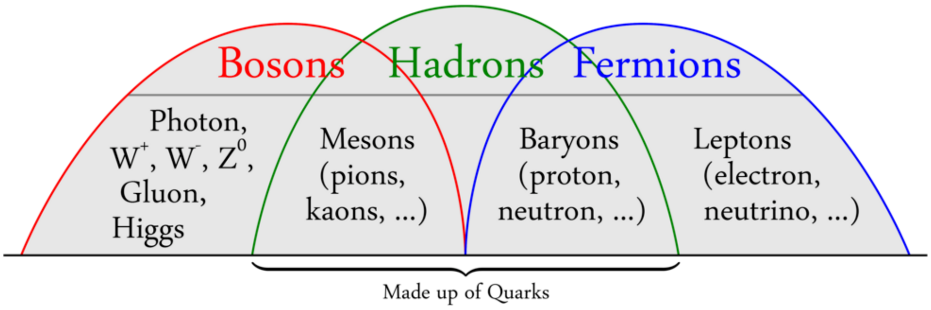
Hadrons (Composite Particles)



Hadrons

Hadrons are a special class of strongly interacting composite particles (meaning that they are comprised of multiple individual particles, specifically quarks). Hadrons can be either bosons or fermions. Hadrons composed of strongly interacting fermions are called baryons; hadrons composed of strongly-interacting bosons are called mesons.

Baryons

The most well-known baryons are protons and neutrons, which are each comprised of three quarks. Protons are made of two up quarks and one down quark ("uud"), and carry a charge of +1. Neutrons are made of one up quark and two down quarks ("udd") and carry a charge of zero.

Some of the better-known baryons include:

- nucleons (protons & neutrons).
- hyperons, *e.g.,* the Λ, Σ, Ξ, and Ω particles. These contain one or more strange quarks and are much heavier than nucleons.
- various charmed and bottom baryons.
- pentaquarks, which contain four quarks and an antiquark.

Mesons

Ordinary mesons are comprised of a quark plus an antiquark. Examples include the pion, kaon, and the J/Ψ. Mesons mediate the residual strong force between nucleons.

Some of the exotic mesons include:

- tetraquarks, which contain two quarks and two antiquarks.
- glueball, a bound set of gluons with no quarks.
- hybrid mesons, which contain one or more quark/antiquark pairs and one or more gluons.

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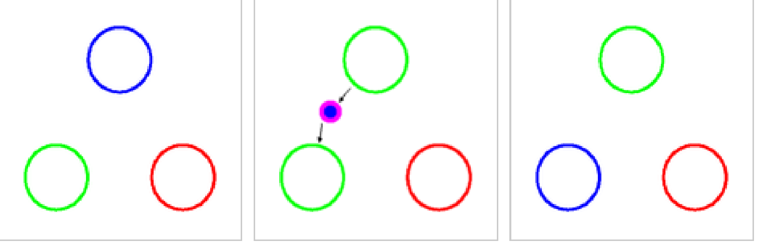
Color Charge and Quantum Chromodynamics (QCD)

Quantum chromodynamics (QCD) is the study of the strong interaction between quarks, which is mediated by gluons. Color charge is the property that is responsible for the strong nuclear interaction. All electrons and fermions (particles that have half-integer spin quantum numbers) must obey the Pauli Exclusion Principle, which states that no two particles within the same larger particle (such as a hadron or atom) can have identical sets of quantum numbers.

For electrons, (as you should have learned in chemistry), if two electrons share the same orbital, they need to have opposite spins. In the case of quarks, all quarks have a spin of $+\frac{1}{2}$, so in order to satisfy the Pauli Exclusion Principle, if a proton or neutron contains three quarks, there has to be some other quantum property that has different values for each of those quarks. This property is called "color charge" (or sometimes just "color*").

The "color" property has three values, which are called "red," "green," and "blue" (named after the primary colors of light). When there are three quarks in a subatomic particle, the colors have to be different and have to add up to "colorless". (Recall that combining each of the primary colors of light produces white light, which is colorless.)

Quarks can exchange color charge by emitting a gluon that contains one color and one anticolor. Another quark absorbs the gluon, and both quarks undergo color change. For example, suppose a blue quark emits a blue antigreen gluon:



You can imagine that the quark sent away its own blue color (the "blue" in the "blue antigreen" gluon). Because it also sent out antigreen, it was left with green, so it became a green quark. Meanwhile, the antigreen part of the gluon finds the green quark and cancels its color. The blue from the blue antigreen gluon causes the receiving quark to become blue. After the interaction, the particle once again has one red, one green, and one blue quark, which means color charge is conserved.

* Just like "spin" is the name of a property of energy that has nothing to do with actual spinning, "color" is a property that has nothing to do with actual color. In fact, quarks couldn't possibly have actual color—the wavelengths of visible light are thousands of times larger than quarks!