THE WRIGHT CENTER FOR SCIENCE EDUCATION

Innovative Curriculum Series,
Edited by Cathleen Banister-Marx

Beyond the 1930s Atom

Pamela Perry, Physics & Astronomy

Lewiston High School
Lewiston, ME

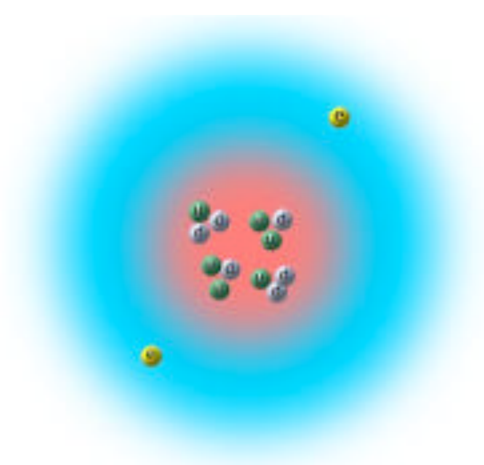
Tufts University
Massachusetts Space Grant Consortium
Fondation H. Dudley Wright
Commonwealth of Massachusetts
Foundation for the Future

Tufts University, 4 Colby Street, Medford, MA 02155
(617) 627-5394 • FAX (617)627-3995 • wright_center@tufts.edu
http://www.tufts.edu/as/wright_center

Beyond the 1930s Atom

Pamela Perry, physics and astronomy
Lewiston High School
Lewiston, Maine

Table of Contents



Introduction

Even as children, most of us wonder about the Universe, its beginning, its end and its size. These fundamental questions are difficult to answer, but are ones that underlie modern cosmology. **Cosmology** is the field of study that brings together the natural sciences, particularly astronomy and physics, in an effort to understand the structure and evolution of the Universe.

Particle physics concepts are important in astrophysics, especially in trying to determine how conditions during the first few minutes of the Big Bang could have governed the formation and nature of matter today. Amazingly, to understand such large scale objects as galaxy clusters, one must start with the smallest fundamental particles of matter and the rules governing their interactions. The activities in this unit provide an introduction to the **Standard Model**, a current theoretical framework that describes these interactions.

Most students are familiar only with the view of the atom that was developed in the mid-1930s. Research by Hendrik Antoon Lorentz, Pieter Zeeman and J.J. Thompson led to the idea of a negatively charged particle even smaller than the atom, called the electron. Ernest Rutherford showed that atoms had massive positively charged nuclei. James Chadwick's discovery of the nucleus made sense of isotopes, and Neils Bohr and quantum theory showed why electrons could only occupy certain energy levels and what produced atomic spectra.

Since this time, physicists have found that the world of particles is much more extensive than just the proton, neutron and electron. In 1912, Victor Hess discovered cosmic rays when he found that an electroscope discharged more quickly as he rose in altitude in a balloon. Originally thought to be part of the electromagnetic spectrum, in the 1930s cosmic rays were found to be made of charged particles affected by Earth's magnetic field. Before modern high energy particle accelerators, these cosmic rays led to the detection of new particles such as positrons and muons. By the 1960s, accelerator experiments had produced hundreds of proton- and neutron-like particles called baryons and a new family of particles called mesons.

In 1964, two physicists, Murray Gell-Mann and George Zweig, independently came up with the idea for building blocks even smaller than neutrons and protons called quarks which could provide the structure for all of these new particles.

Project 2061's Benchmarks says that by the 12th grade students should know that: *"Increasingly sophisticated technology is used to learn about the universe...accelerators give subatomic particles energies that simulate conditions in the stars and in the early history of the universe before stars formed."* From studies of cosmic rays, supernovae and black holes to the origin and fate of the universe, high energy astrophysicists are working to answer the largest yet most basic questions about our Universe.

This unit introduces students to the **Standard Model of Fundamental Particles and Interactions** and conservation laws which govern the consistent patterns in physical processes. The unit ends with a card game on particle physics as well as guidelines that students may use to create learning games of their own on various topics.

Rationale and Standards

This unit will

a) introduce students to current models of the atom.

b) give background that will aid students in understanding cosmological research and particle physics - incredible amounts of current research are being done in both fields.

c) let students discover and apply conservation laws

c) model the development of theories by indirect observation.

d) model the development of a game to teach scientific concepts so that students can develop their own games on other topics.

The following standards are from the **Maine Learning Results**, but closely follow similar national standards.

E. STRUCTURE OF MATTER
Students will understand the structure of matter and the changes it can undergo. Students will be able to:

1. Trace the development of models of the atom to the present and describe how each model reflects the scientific understanding of their time.

G. THE UNIVERSE
Students will gain knowledge about the universe and how humans have learned about it, and about the principles upon which it operates. Students will be able to:

1. Describe how scientists gather data about the universe.

J. INQUIRY AND PROBLEM SOLVING
Students will apply inquiry and problem-solving approaches in science and technology. Students will be able to:

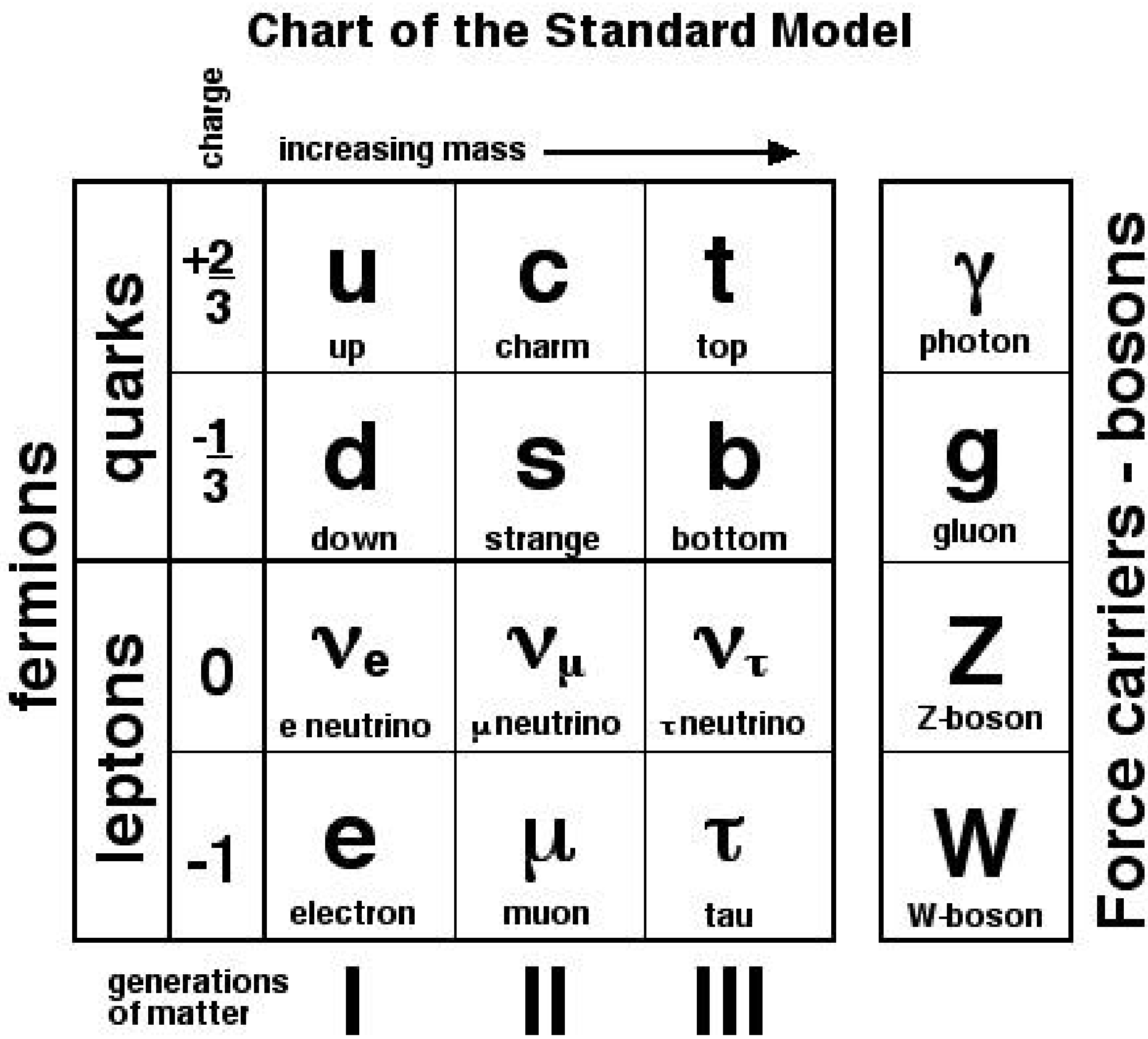
2. Verify, evaluate, and use results in a purposeful way. This includes analyzing and interpreting data, making predictions based on observed patterns, testing solutions against the original problem conditions, and formulating additional questions.

K. SCIENTIFIC REASONING
Students will learn to formulate and justify ideas and to make informed decisions. Students will be able to:

3. Develop generalizations based on observations.

Summary of the Standard Model

Physicists have identified twelve fundamental particles (**fermions**) that make up matter: six **quarks** and six **leptons** as shown in the following chart.



Ordinary matter is made up of just three of these, the up and down quarks composing the proton and neutron, and the electron which is a lepton. Notice that these particles are in generation I, the least massive. articles in generations II and III have rapid decay rates and, therefore, very short life times.

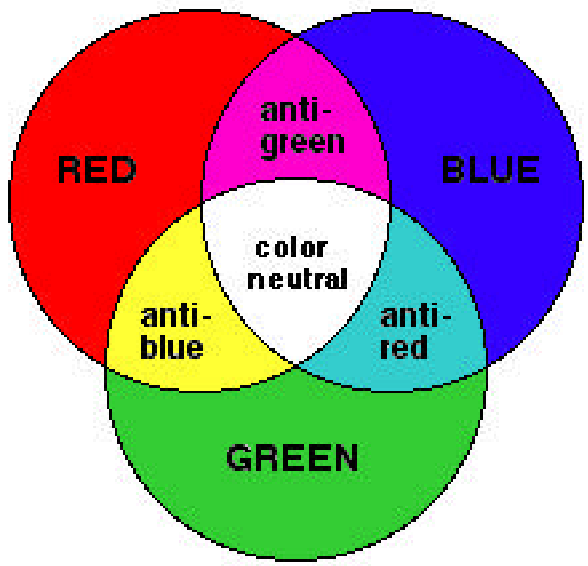
Matter/antimatter

For every particle, there is a corresponding anti-particle. The anti-particle has the same mass, but an opposite charge. Anti-particles can be denoted with a bar over the symbol or by its charge. For example, the symbol for a proton is “p” and the anti-proton is a “p” with a bar over it. The symbol for an electron is “e^-” and its anti-matter particle the positron is “e^+”. When matter and anti-matter particles meet, they annihilate in a flash of energy (give off photons).

Hadrons (particles made of quarks, have integer charges)

Baryons - made of three quarks (ex. **proton** - uud and **neutron** - ddu)
Mesons - made of one quark and one anti-quark

Quarks have a quantum number or characteristic which is whimsically called ‘color’. This governs why quarks must combine in threes or as quark/anti-quark pairs. A particle composed of quarks must be ‘color neutral’. Since the primary colors of light combine to form white light, red, blue and green were chosen to represent quark colors and the complimentary colors (magenta=anti-green, cyan=anti-red, and yellow=anti-blue) to represent anti-quarks. Baryons must consist of a red, blue and green quark to be color neutral. A meson can be color neutral if the quark is one color and the anti-quark is its anti-color.



Leptons

Leptons, unlike quarks, can exist alone. Muons and taus are more massive cousins of electrons.

Neutrinos have very small masses and no charges. They are necessary to preserve certain conservation laws in particle interactions and were first detected in 1956 by Clyde Cowan and Frederick Reines.

Four fundamental interactions or forces

All forces can be attributed to four types of interactions between particles:

a) **electromagnetic** - works between charged particles, binds electrons to positive nuclei
b) **strong** - holds together quarks to form hadrons and is responsible for nuclear binding
c) **weak** - involved in the decay of one particle to a less massive one
d) **gravitational** - not yet incorporated into the Standard Model, works on large scales rather than subatomic ones

Particles interact by transmitting or exchanging force carrying particles called **bosons**. The strong force is mediated by **gluons**, the weak force by massive **W** or **Z bosons** and the electro-magnetic force by **photons**. Physicists hypothesize that the gravitational force or interaction is also mediated by bosons called **gravitons**.

Conservation laws

Particle interactions and decays are governed by certain conservation laws. First let's use the analogy of a chemical reaction (combining hydrogen and oxygen to make water). A balanced equation would have the same number of each type of atom on either side.

	H_2	+	O_2	---->	H_2O
# of H atoms	2		0		2
# of O atoms	0		2		1

To balance the equation, one must do as follows:

	$2H_2$	+	O_2	---->	$2H_2O$
# of H atoms	4		0		4
# of O atoms	0		2		2

In particle interactions, other quantities must be conserved on either side of the interaction or decay. We will be considering conservation of color–charge (in constructing baryons and mesons), baryon number, electric–charge, electron number, muon number and tau number in these activities. See below:

	n	---->	p	+	e-
baryon #	1		1		0
electric-charge	0		+1		-1
electron #	0		0		1
muon #	0		0		0
tau #	0		0		0

In the above interaction, baryon # and electric charge is conserved but not electron number. The following interaction (neutron beta decay) takes care of the conservation of electron number.

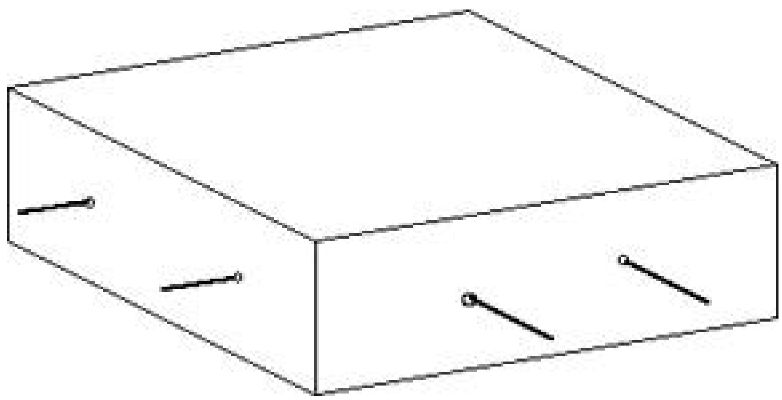
	n	---->	p	+	e-	+	$\bar{\nu}_e$
baryon #	1		1		0		0
electric-charge	0		+1		-1		0
electron #	0		0		1		-1
muon #	0		0		0		0
tau #	0		0		0		0

Name____________________________________ **Period**_____ **Date**________

The Black Box

Background:
Often scientists form hypotheses about the structure of an object they cannot actually see by how it interacts with other things. An example of this is Ernest Rutherford's studies from 1909-1911 where he fired alpha particles at gold foil. By the way the alpha particles were deflected, he theorized that an atom consisted of a small but massive positively charged nucleus with electrons orbiting the space around it. You can read more about Rutherford's experiment and try a computer simulation at

Atom: The Incredible World: Rutherford's Experiment
http://library.thinkquest.org/19662/low/eng/exp-rutherford.html?tqskip=1



Purpose:
To determine the objects comprising the interior of a 'black box' and their configuration by indirect observation.

Procedure:

1. Your teacher will give you a 'black box'. Do not open the box.

2. By shaking and tilting the box, form an hypothesis about what is inside. Be specific about what you think the objects are and also about the arrangement of the objects.

3. Record what you do and your observations. For example: "I tilted the box to the left and heard..."

Observations:

Conclusions:

1. Describe the objects inside the box, being as specific as possible (what are the objects, how many are there, how are they arranged, etc.) Also draw a picture of the inside of the box. How do your observations support these conclusions?

2. What made this experiment difficult? How sure are you of your conclusions? Could there be another explanation besides the one you gave about the objects inside?

3. Your teacher may or may not let you verify your conclusions by opening the box. Why would not opening the box better simulate experiments such as Rutherford's?œœ

The Black Box

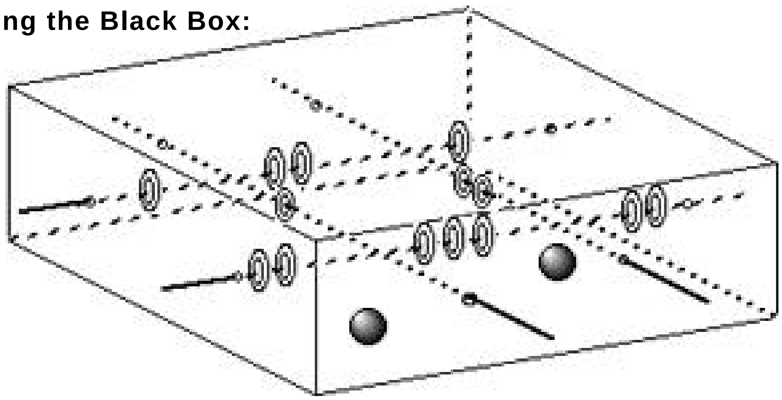
Teacher Pages

Optional Introductory Activity:

You may wish to introduce students to a unit on the Standard Model and particle physics by giving each student or pair of students a different article to read on current research in the field. They can then present a short summary of their article to the class. You can find such articles under "Particle News!' at:

The Particle Adventure
http://particleadventure.org/

Instructions for making the Black Box:



Black boxes can be made for this activity by using small cardboard boxes (I used postal mailing boxes), bamboo skewers, and washers. Thread four skewers through the sides of the box as shown, slipping washers on them in any position. Wrapping masking tape around the ends of the skewers on the outside of the box will help them from slipping through. Tape the boxes shut.

By tilting and shaking the boxes, students will be able to hear the washers sliding on the skewers and determine the number and placement of them. You could also place loose washers in the box and/or marbles which would roll rather than slide along the bottom, producing a different sound.

An alternative to this box would be to make simple mazes or shapes inside the box with strips of cardboard and to put one or more marbles in them. Students would then determine the placement of the walls and the number of objects in the box. You can also buy 'black box' type experiments from scientific supply companies such as **Lab-Aid No.100** from:

Lab-aids, Inc.
17 Colt Court Ronkonkoma, New York 11779
Phone: 631-737-1133 - Fax 631-737-1286 http://www.lab-aids.com/catalog.cfm?Id=88

Students will want to open the boxes to see if their hypotheses are correct. Scientists can rarely 'open' the boxes and must rely on indirect observation so not letting them might be a more authentic experience.
Supplemental activity:

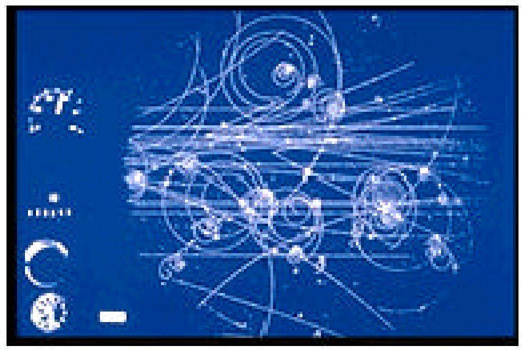
A complete time line of the development of the atom can be found at:
http://particleadventure.org/other/historyAndex.html

Have students make a comic strip, a children’s book, or an illustrated time line of the most important developments in atomic theory over time.

Name____ Period_____ Date________

Basic Building Blocks and Interactions

Background:
To understand the structure of matter, scientists have to determine what the basic building blocks are and also how those components interact. In accelerators, physicists collide particles together at high energies in order to unravel the forces acting between them. Noting events that do not happen is as important as observing ones that do occur in determining a set of 'rules' that govern interactions between particles.



Top: Photograph of interacting elementary particles taken in a bubble chamber.
Left: Aerial view of the Fermi National Accelerator Laboratory site.
http://tuhepa.phy.tufts.edu/page2.html

Purpose:
To examine sets of observed and unobserved events to determine the basic building blocks and their interactions.

Procedure:

Do the activity found at:

How Does the Universe Work:
http://www-ed.fnal.gov/samplers/hsphys/activities/unipuzzlestud.html

Basic Building Blocks and Interactions **Teacher Page**

The teacher page, student page, and answer key for this activity can be found at:

How Does the Universe Work? A Puzzle Analogy

http://www-ed.fnal.gov/samplers/hsphys/activities/unipuzzle.html

You can print out the student page and photocopy it. A computer is not needed for this activity

Name ______________________________ **Period** _____ **Date** _______

The Standard Model

Background:
The Standard Model is the theory of fundamental particles and their interactions. It is widely tested and is accepted as correct by particle physicists. The following activities serve as an introduction to this theory.

Purpose:
To understand the basics of the Standard Model.

Procedure:

You will be given either a passage to read or an online game or simulation to play. You will then answer the questions that follow.

A. Introduction: Read **"The science of matter, space and time"** http://www.fnal.gov/pub/inquiring/matter/index.html

1. Are atoms the smallest units of matter? If not, what are the fundamental building blocks?

2. Why isn't empty space really empty?

3. What might be a reason why our universe consists mostly of matter and not antimatter?

4. About how much of the universe consists of matter we can see? What question does this bring up for astrophysicists?

B. Introductory Activity: Open the "**Atom Builder"** and construct a carbon atom.

http://www.pbs.org/wgbh/aso/tryit/atom/#

1. What particles make up a proton?

2. What particles make up a neutron?

3. What particles make up an electron?

4. What makes an atom unstable?

5. What makes an atom ionized?

6. What makes an atom radioactive?

7. When does an atom change into another element?

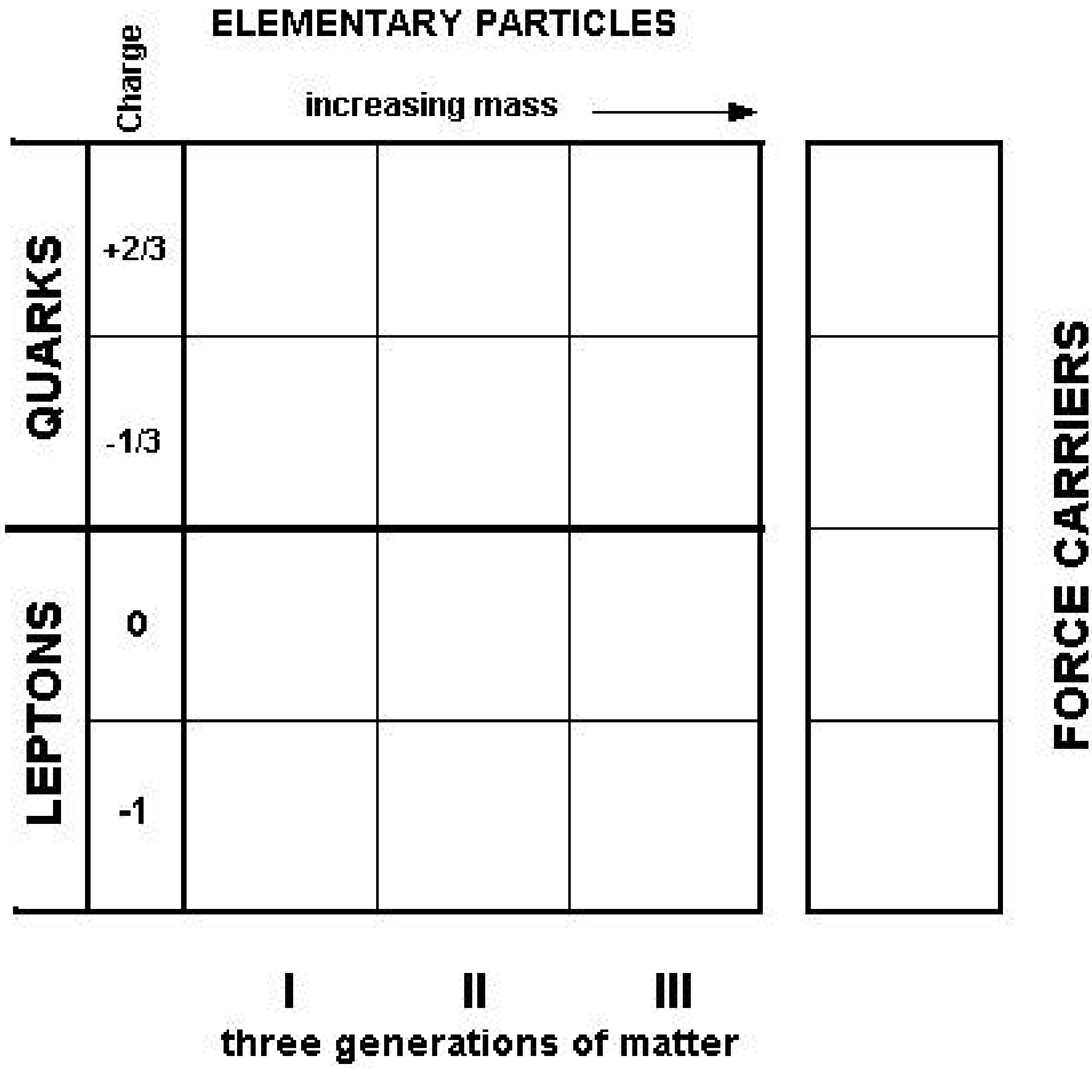
C. Read: **"What is the world made of?"**
http://www.fnal.gov/pub/inquiring/matter/madeof/index.html

"A Summary of Particle Physics"
http://particleadventure.org/other/proj_sum.html

1. How many building blocks have been identified that are the fundamental constituents of matter?

2. Fill in the symbols and names of the particles in the Standard Model chart below. You can find a bigger chart to use as a reference at:

   http://www-sldnt.slac.stanford.edu/alr/images/simplemodel2.gif



3. How many fundamental particles make up the matter of our everyday world and what are they? Why isn't this matter made up of the other particles?

4. What is **antimatter**? What happens when antimatter meets matter?

5. If a proton consists of uud quarks, what would an anti proton consist of? What would be the charge of an anti proton?

6. What is another name for an antielectron? What charge does it have?

7. Can **quarks** be found by themselves? Can **leptons**?

D. Play: "**Four Forces**"

http://www-ed.fnal.gov/projects/labyrinth/games/lawnorder/four_forces/intro.html

or Read: "**Forces and Interactions"**

http://www2.slac.stanford.edu/vvc/theory/interactions.html

1. Fill in the chart below for the four elementary forces from strongest to weakest (a **boson** is a force-carrying particle).

Force	Range	Boson	Acts on

2. Name the elementary force responsible for ______________________________

a. atoms combining to form crystals and molecules ______________________

b. the moon orbiting the earth ______________________________

c. beta decay (neutron decaying into a proton) ______________________

d. binding electrons to atomic nuclei ______________________________

e. a quark changing into another kind of quark
(or a lepton into another kind of lepton) ______________________

f. the binding of protons and neutrons in the nucleus ______________________

g. friction ______________________________

h. our weight on earth ______________________________

i. the gluing together of quarks to form hadrons ______________________

j. nuclear fission producing alpha particles

The Standard Model

If your students do not have internet access, you can print out the following pages for them to read:

“The science of matter, space and time”
http://www.fnal.gov/pub/inquiring/matter/index.html

“What is the world made of?”
http://www.fnal.gov/pub/inquiring/matter/madeof/index.html

“A Summary of Particle Physics“
http://particleadventure.org/other/proj_sum.html

“**Forces and Interactions”**
http://www2.slac.stanford.edu/vvc/theory/interactions.html

“Strong Interactions”
http://www2.slac.stanford.edu/vvc/theory/stronginteract.html

“Electromagnetic Interactions”
http://www2.slac.stanford.edu/vvc/theory/eminteract.html

“Weak Interactions”
http://www2.slac.stanford.edu/vvc/theory/weakinteract.html

“Gravitational Interactions”
http://www2.slac.stanford.edu/vvc/theory/gravity.html

You will have to skip “**B. Introductory Activity”**

Answers:

Part A

1. No, quarks and leptons.

2. Quantum effects constantly produce particles and antiparticles "out of nothing", only to have them disappear a few moments later.

3. There are some small differences in the way that matter and anti-matter behave.

4. Less than 10%; what is the dark matter that makes up the rest of the universe?

Part B

1. two up and one down quarks

2. one up and two down quarks

3. just an electron

4. when the net charge is not zero or the atom has too few or too many neutrons

5. an uneven number of protons and electrons

6. too many or too few neutrons

7. when the number of protons changes

Part C

1. 12

2. See the chart in the “Summary” at the beginning of this unit.

3. 3, the up and down quarks and the electron; the other generations of matter are more massive and decay rapidly

4. antimatter has the same mass as matter but the opposite charge; they annihilate, disappearing in a flash of energy

5. $\bar{u}\,\bar{u}\,\bar{d}$; -1

6. positron; +1

7. no; yes

Part D

1.

Force	Range	Boson	Acts on
strong	nuclear distances	gluon	quarks, gluons, particles made of quarks
electromagnetic	all distances	photon	all electrically charged particles
weak	subnuclear distances	W and Z bosons	quarks, leptons, particles made of quarks
gravity	all distances	graviton	all particles

2. a. electromagnetic

b. gravity

c. weak

d. electromagnetic

e. weak

f. strong

g. electromagnetic

h. gravity

i. strong

j. strong

Name ________________________________ **Period** _____ **Date** ________

Colorful Quarks

Background:
Quarks exist only inside composite particles called **hadrons**. Quarks have a quantum number or characteristic which is whimsically called 'color' that determines how they can combine. Just as particles have electric charges which are denoted by integers such as +1, 0 or -1, one can think of quarks as having **color charge** denoted by the primary (red, blue and green) and complimentary (cyan, yellow and magenta) colors of light.

Purpose:
To determine the rules for the way quarks can combine to form hadrons and also to differentiate between the two different families of hadrons, baryons and mesons.

Materials:

3 flashlights with the lights covered with theater gel (attach with a rubber band), **Or** three lamps with colored light bulbs (one each of red, blue, and green)

white wall or screen

Procedure (Part 1):

1. In a darkened room, shine all three lamps or flashlights so that the light overlaps. Record the color of the combined light.

2. Repeat #1 using the red and blue lights, the red and green lights, and the green and blue lights.

Observations:

red + blue + green = ________ **light**
red + blue = ________ **light**
red + green = ________ **light**
green + blue = ________ **light**

Conclusions:

1. What color would you expect for each of the following and why?

   red + cyan (blue green) = ________ **light**
   green + magenta = ________ **light**
   blue + yellow = ________ **light**
   cyan + magenta + yellow = ________ **light**

2. What are two ways you could get white light by using three lights?

3. What are three ways you could get white light by using two lights?

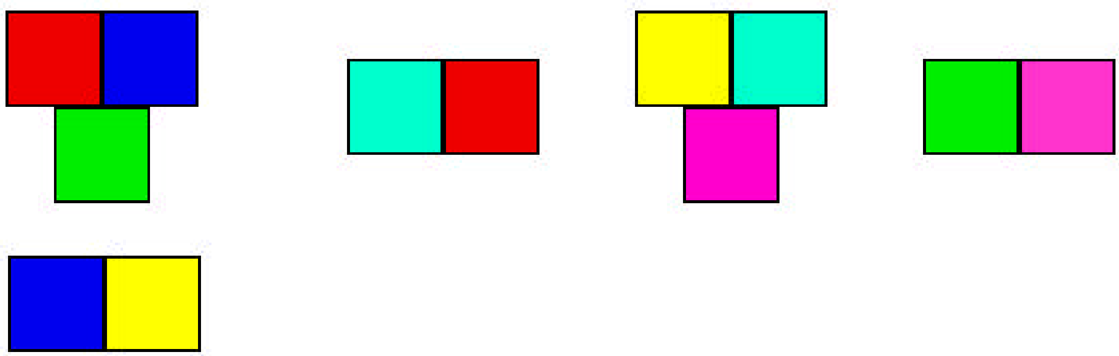
Procedure (Part 2): copy for color printers

1. In the following pictures, a square represents a quark (R = red, B = blue, G = green, C = cyan, M= magenta and Y = yellow). Looking at the "Combinations Observed" and "Combinations Not Observed", determine rules for the ways that quarks can combine.

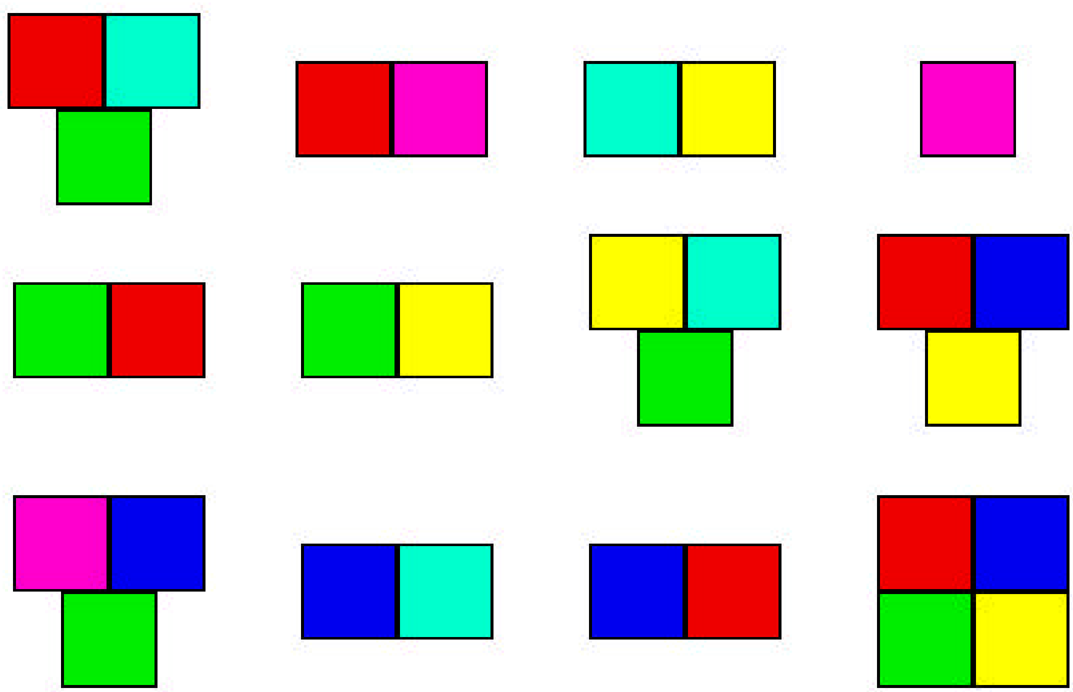
2. In student groups of three or four, combine your lists into one master list that fits "Combinations Observed" and "Combinations Not Observed".

3. Each group will present its results to the class to again be combined into a master list agreed upon by all.

COMBINATIONS OBSERVED



COMBINATIONS NOT OBSERVED



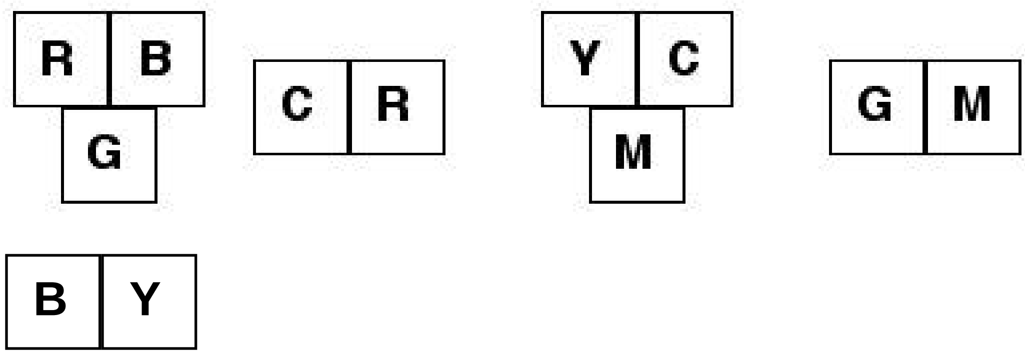
Procedure (Part 2): To be copied if a color copier is not available

1. In the following pictures, a square represents a quark (R = red, B = blue, G = green, C = cyan, M = magenta and Y = yellow). Looking at the "Combinations Observed" and "Combinations Not Observed", determine rules for the ways that quarks can combine.

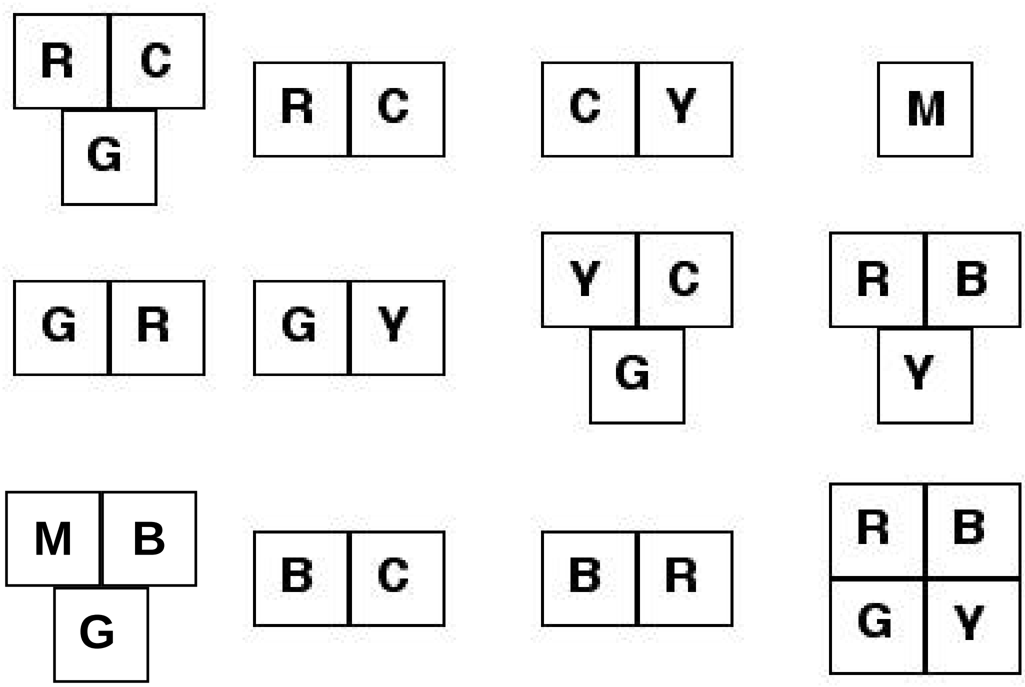
2. In student groups of three or four, combine your lists into one master list that fits "Combinations Observed" and "Combinations Not Observed".

3. Each group will present its results to the class to again be combined into a master list agreed upon by all.

COMBINATIONS OBSERVED



COMBINATIONS NOT OBSERVED



Conclusions:

1. Your rules for how quarks can combine (explain your reasoning):

2. Your group's rules for how quarks can combine:

3. The class' rules for how quarks can combine:

4. **Baryons** are hadrons consisting of three quarks. **Mesons** consist of one quark and one anti-quark. Under each hadron in "Combinations Observed", label it as a meson or a baryon.

5. Why do you suppose physicists chose the primary colors of light to represent quarks and the complimentary colors to represent anti-quarks? What do you think is meant by the requirement that a hadron be **color neutral**?

6. Quarks have a charge of either $^{+}2/3$ or $^{-}1/3$ and the corresponding anti-quarks have charges of $^{-}2/3$ or $^{+}1/3$. Hadrons must have whole integer charges. Show why this condition also would govern why baryons must consist of three quarks (and anti-baryons, three anti-quarks) and mesons and anti-mesons must be composed of a quark and an anti-quark.

Colorful Quarks

Teacher Pages

Please note that page two of the student pages can be found in two versions: one for those with color printers or photocopiers and also a black and white version.

Part 1:
Observations:

red + blue + green = white light
red + blue = magenta light
red + green = yellow light
green + blue = cyan light

Conclusions:

1. red + cyan (blue green) = white light
   green + magenta = white light
   blue + yellow = white light
   cyan + magenta + yellow = white light

2. red + blue + green or cyan + magenta + yellow

3. red + cyan, green + magenta, or blue + yellow

Part 2:
Conclusions:

3. 3 quarks:
   red + blue + green
   cyan + magenta + yellow

   2 quarks:
   red + cyan
   blue + yellow
   green + magenta

4. any consisting of 3 squares is a baryon and 2 squares is a meson

5. These colors can be combined to make white. Hadrons must be color neutral (colors combined = white or color neutral).

6. all possible combinations:

   baryons:

   $^{+}2/3 + {}^{+}2/3 + {}^{+}2/3 = {}^{+}6/3 = {}^{+}2$

   $^{+}2/3 + {}^{+}2/3 + {}^{-}1/3 = {}^{+}3/3 = {}^{+}1$

   $^{+}2/3 + {}^{-}1/3 + {}^{-}1/3 = 0/3 = 0$

   $^{-}1/3 + {}^{-}1/3 + {}^{-}1/3 = {}^{-}3/3 = {}^{-}1$

   anti-baryons:

   $^{-}2/3 + {}^{-}2/3 + {}^{-}2/3 = {}^{-}6/3 = {}^{-}2$

   $^{-}2/3 + {}^{-}2/3 + {}^{-}1/3 = {}^{-}3/3 = {}^{-}1$

   $^{-}2/3 + {}^{+}1/3 + {}^{+}1/3 = 0/3 = 0$

   $^{+}1/3 + {}^{+}1/3 + {}^{+}1/3 = {}^{+}3/3 = {}^{+}1$

   mesons/anti-mesons

   $^{+}2/3 + {}^{+}1/3 = {}^{+}3/3 = {}^{+}1$

   $^{+}2/3 + {}^{-}2/3 = 0/3 = 0$

   $^{-}1/3 + {}^{-}2/3 = {}^{-}3/3 = {}^{-}1$

   $^{-}1/3 + {}^{+}1/3 = 0/3 = 0$

Name______________________________________ **Period**______ **Date**_________

Conservation: It's the Law

Background:

If you have taken chemistry, you know that for a chemical equation to be balanced, the same number of each kind of atom must be present on both sides of the equation. During a chemical reaction, atoms may be separated and rearranged, but not created or destroyed. This is an example of a **conservation law** (the conservation of matter).

Let's look at a reaction of hydrogen and oxygen. A balanced equation would have the same number of each type of atom on either side.

	H_2	+	O_2	---->	H_2O
# of H atoms	2		0		2
# of O atoms	0		2		1

To balance the equation, one must do as follows:

	$2H_2$	+	O_2	---->	$2H_2O$
# of H atoms	4		0		4
# of O atoms	0		2		2

The most common type of observation in particle physics is called an **event**. An event is similar to the chemical reactions above, because one set of particles is formed from another. Particle interactions and decays are also governed by certain conservation laws. These laws explain why certain interactions or events occur but not others.

Purpose:

To determine conservation laws for particle interactions based upon observed and unobserved events.

Procedure:

1. Examine the "Events Observed" and "Events Not Observed" on the last page and determine rules for the ways that particles can interact. You will wa nt to count different kinds of particles on each side (example: baryons, mesons, types of leptons), electric charge, etc. to see if that quantity is conserved. Make a list of your conservation laws.

   NOTE: Antimatter particles are denoted either with a bar over the symbol (for baryons and neutrinos) or by using the same symbol with opposite charge (for mesons and leptons).

   EX**:** **p** is a proton and $\bar{\mathbf{p}}$ is an antiproton

   $\mathbf{D^+}$ and $\mathbf{D^-}$ are particle and antiparticle

2. In groups of three or four, combine your laws into one master list that fits "Events Observed" and "Events Not Observed".

3. Each group will present its results to the class to again be combined into a master list of conservation laws agreed upon by all.

Table of Symbols:

Baryons:

p, n, Λ^{o}**,** Σ^{+}**,** Σ^{o}**,** Σ^{-}**,** Δ^{++}**,** Δ^{++}**,** Δ^{+}**,** Δ^{o}**,** Δ^{-}**,** Ξ^{o}**,** Ξ^{-}**,** Ω^{-}

Mesons:

π^{+}**,** π^{o}**, K⁺, K°,** η^{o}**,** ρ^{+}**,** Φ^{o}**,** D^{+}**,** D^{o}**,** J/Ψ^{o}

Leptons:

e^{-}**,** μ^{-}**,** τ^{-}**,** ν_{e}**,** ν_{μ}**,** ν_{τ}

Conclusions:

1. Your conservation laws for particle interactions:

2. Your group's conservation laws for particle interactions:

3. The class' conservation laws for particle interactions:

4. Under each "Event Not Observed" explain which conservation law is violated.

EVENTS OBSERVED

$n \dashrightarrow p + e^- + \overline{\nu}_e$	$\Lambda^0 \dashrightarrow p + \pi^-$
$\pi^+ + n \dashrightarrow p + \pi^0$	$\pi^- + p \dashrightarrow n + \pi^- + \pi^+$
$\pi^0 \dashrightarrow e^- + e^+ + \gamma$	$\Lambda^0 \dashrightarrow p + \pi^-$
$K^- \dashrightarrow \pi^0 + \mu^- + \overline{\nu}_\mu$	$e^- + e^+ \dashrightarrow D^+ + D^-$
$K^+ \dashrightarrow \pi^+ + \pi^0$	$K^0 \dashrightarrow \pi^+ + \pi^- + \pi^0$
$\gamma + p \dashrightarrow D^+ + \overline{D}^0 + n$	$e^- + e^+ \dashrightarrow \gamma + \gamma$
$D^+ \dashrightarrow K^- + \pi^+ + \pi^+$	$K^- + p \dashrightarrow \Omega^- + K^+ + K^0$
$\Omega^- \dashrightarrow \Xi^0 + \pi^-$	$\Xi^0 \dashrightarrow \Lambda^0 + \gamma + \gamma$
$\mu^- \dashrightarrow e^- + \nu_\mu + \overline{\nu}_e$	$\tau^- \dashrightarrow e^- + \nu_\tau + \overline{\nu}_e$

EVENTS NOT OBSERVED

$n + p \dashrightarrow p + p$	$p \dashrightarrow \pi^+ + \pi^0$
$p \dashrightarrow \pi^+ + \pi^-$	$\pi^+ + n \dashrightarrow K^+ + K^0$
$n \dashrightarrow p + e^-$	$\Delta^0 \dashrightarrow K^+ + K^-$
$\pi^0 + n \dashrightarrow \pi^+ + \pi^-$	$\Delta^0 \dashrightarrow n + \pi^0 + \nu_e$
$\pi^- \dashrightarrow e^- + \gamma$	$n \dashrightarrow p + e^- + \overline{\nu}_\mu$
$\tau^- \dashrightarrow e^- + \nu_\tau$	$\mu^+ \dashrightarrow e^+ + \nu_\mu + \overline{\nu}_e$

Conclusions:

3. conservation of:

electric charge
(charges are given as superscripts)

baryon number
(baryons have a baryon # of 1, antibaryons have a baryon # of -1)

electron number
(electrons have an electron # of 1, and positrons have an electron # of -1,
electron neutrinos have an electron # of 1, anti-electron neutrinos have an electron # of -1)

muon number
(muons have a muon # of 1, and anti-muons have a muon # of -1,
muon neutrinos have a muon # of 1, anti-muon neutrinos have an muon # of -1)

tau number
(taus have a tau # of 1, and anti-taus have a tau # of -1,
tau neutrinos have a tau # of 1, anti-tau neutrinos have a tau # of -1)

4.

EVENTS NOT OBSERVED

$n + p \dashrightarrow p + p$
electric charge not conserved

$p \dashrightarrow \pi^+ + \pi^-$
electric charge and
baryon # not conserved

$n \dashrightarrow p + e^-$
electron # not conserved

$\pi^0 + n \dashrightarrow \pi^+ + \pi^-$
baryon # not conserved

$\pi^- \dashrightarrow e^- + \gamma$
electron # not conserved

$\tau^- \dashrightarrow e^- + \nu_\tau$
electron # and
tau # not conserved

$p \dashrightarrow \pi^+ + \pi^0$
baryon # not conserved

$\pi^+ + n \dashrightarrow K^+ + K^0$
baryon # not conserved

$\Delta^0 \dashrightarrow K^+ + K^-$
baryon # not conserved

$\Delta^0 \dashrightarrow n + \pi^0 + \nu_e$
electron # not conserved

$n \dashrightarrow p + e^- + \overline{\nu}_\mu$
electron # and
muon # not conserved

$\mu^+ \dashrightarrow e^+ + \nu_\mu + \overline{\nu}_e$
electron # not conserved

Name ________________________________ **Period** ______ **Date** ________

We All Have Our Quarks!!!

Object of the game:

Collect quarks of different colors to make baryons and mesons to score points. Combine these particles with leptons and photons to produce particle interactions or events that obey conservation laws. The game ends when one player constructs two such events or runs out of cards.

# of players: 2 to 4

Learning objectives:

1. To demonstrate the rules for the construction of hadrons. (Baryons are composed of three quarks, anti-baryons three anti-quarks and mesons one quark and one anti-quark. All must be color neutral.)

2. To use conservation laws to construct possible particle events. (Particle events must obey conservations laws like conservation of electric charge, baryon number, electron number, muon (m) number and tau (t) number.)

Materials:
(found at http://www.geocities.com/lewiston_stargazer/cardgame.html)

one deck of particle cards (quark cards are in color, lepton cards are black-and-white)

one score sheet per player

Rules for play:

1. The youngest player deals 10 cards to each player in a clockwise fashion. The remaining cards are placed face down to become the **draw** pile. Turn over the top card to start the **discard** pile.

2. The player to the dealer's left begins by taking the top card from either the discard pile or the draw pile.

3. During a turn a player may make as many **hadrons** as he/she can (see choice #1) **OR** produce one **particle event** (see choice #2).

Choice #1: Making hadrons

The player can make **baryons** or **mesons** from colored quark cards following the rules of color-charge conservation.

baryon:	3 quarks:	red/blue/green
anti-baryon:	3 anti-quarks:	anti-red/anti-blue/anti-green
meson/anti-meson:	1 quark, 1 anti-quark	red/anti-red blue/anti-blue green/anti-green

When a baryon or meson is made, the symbol for this particle is entered in the correct spot on the first page of the score sheet. Make sure the charge of the particle is given as a superscript.

The player then puts the used quark cards face-up on the bottom of the discard pile and takes that many cards from the draw pile.

A player continues until he/she can no longer make baryons or mesons.

Choice #2: Producing a particle event

Players may also use a turn to use the baryons and mesons they have made and their lepton cards (black-and-white) to produce a particle interaction or **event**. Also, two **photon** cards may be used as the products of the interaction (annihilation) of a particle and an anti-particle. You may also use photon cards in events as shown under "Events Observed" table in Activity 5. The event is recorded on the second page of the score sheet using the symbols for the particles involved. Events must obey conservation of charge, baryon #, e lepton #, m lepton # and t lepton #. Other players may challenge an event if they do not think it meets these conservation rules. If the majority of players determine the event invalid, the player's turn is terminated. Any baryons or mesons used must be crossed off on the front side of the score sheet.

4. The turn ends with a card being placed face-up on the discard pile. Play proceeds to the next player on the left.

5. When the draw pile is gone, the cards in the discard pile (with the exception of the top one) are shuffled to become the draw pile.

6. The game ends when a player has two correct events or when a player runs out of cards.

7. Points on the front and back of the score sheet are totaled. The player with the most points wins the game.

Questions to answer after the game is played:

1. By playing this game, did you meet the learning objectives? Why or why not?

2. What made this game successful or unsuccessful in helping you to meet the learning objectives?

3. If you were to design a game around a science topic like "The Life of a Star", what steps would you need to follow to develop a game that is a useful learning tool?

4. List characteristics that would make a game a useful learning tool.

Activity 6: We All Have Our Quarks!!! teacher page

You will need to print one score sheet per pupil and cards for one deck for every four students. See the student page for the location of these materials.

This card game summarizes the material from this unit. I tried to make a game whose rules mimicked those of hadron formation and particle interactions or events.

As a teacher, I have had my students make board and card games on a variety of topics. They have made these games either as an evaluation of what they had just learned in a unit or as introduction and research into a topic which was new to them.

Some games were wonderful and others not so good. I realized that for students to develop a better game, they should see a completed one as a model. A game that is a useful learning tool should:

1. have clearly stated learning objectives.
2. have rules for play that are clear and understandable and also that have some connection to actual scientific processes that fit the topic.
3. help the players achieve the learning objectives.
4. have game pieces, cards or a game board that has eye appeal and are related to the topic.
5. be fun and interesting to play.

After this unit, you may wish to have students make their own games. Peer evaluation is invaluable in judging the quality or usefulness of a game. Let groups exchange games with each other. After playing a game, have each student rate the clarity of the instructions, how fun the game was, and how much the game taught them.

Name____________________________________ **Period**_____ **Date**________

Strangeness

Background:
The strange quark was discovered when “strange particles” were first observed in cosmic rays. These particles decayed radioactively giving “strange” patterns in a cloud chamber, a particle detector. Much more recently it was learned that strange particles like the lambda baryon, contain at least one strange quark.

The strange quark is the partner of the charm quark. Its electric charge is -1/3, or 1/3 that of an electron and is equal to the charge on a down quark. The mass of a strange quark is about one-half the mass of a proton.

Purpose:
To understand the basics of the strange quark.

Procedure:

Assign each particle a total strangeness quantum number (-1 for each strange quark, +1 for each anti-strange quark, 0 for all other quarks).

particle family	name	symbol	quarks	strange-ness
Mesons	pion	π^+ π^0 π^-	$d\bar{u}$ $q\bar{q}$ $u\bar{d}$	
	kaon	K^+ K^0 K^-	$s\bar{u}$ $d\bar{s}$ $u\bar{s}$	
Baryons	neutron	n	udd	
	proton	p	uud	
	lambda	Λ^0	uds	
	sigma	Σ^- Σ^+	dds uus	
	xi	Ξ^- Ξ^0	dss uds	

Questions to answer

1. Consider the following strong interactions. Is strangeness conserved in strong interactions?

   $p + p \rightarrow p + n + \pi^+$

   $p + p \rightarrow p + \Lambda^o + K^+$

   $\Lambda^o + p \rightarrow n + p + \overline{K^o}$

   $\overline{K} + p \rightarrow K^+ + \Xi^-$

2. Is strangeness conserved in kaon decay?

   $K^o \rightarrow \pi^+ + \pi^-$

3. Is strangeness conserved in lambda decay?

   $\Lambda^o \rightarrow p + \pi^-$

4. If rapid decays are strong interactions, while slower decays are weak interactions, what might account for the "strange" (unusually long) lifetimes of lambda baryons and kaons?

5. What other quantum numbers have you found that are conserved in particle interactions? Do these rules hold for all of the interactions above?

Supplemental Activity: Strangeness **Teacher Page**

Answers:

1. yes
2. no
3. no
4. Lambda baryons and kaons decay via weak interactions.
5. Conservation of baryon #, electron #, tau #, muon #, and electric charge, yes

Glossary

***Antimatter**
A material made from antiparticles. The particles that are common in our universe are defined as matter and their antiparticles as antimatter. In the particle theory there is almost no a priori distinction between matter and antimatter. Their interactions are almost identical. The asymmetry of the universe between these two classes of particles is a deep puzzle which is yet to be fully understood

***Antiparticles**
In particle physics every particle with any type of charge or fermion label has a corresponding antiparticle type. Any particle and its antiparticle have identical mass and spin but opposite charges. For example the antiparticle of an electron is a positron. It has exactly the same mass as an electron but has appositive charge.

Some particles are their own antiparticles, the antiparticle of a photon is a photon for instance. Conserved quantities such as baryon number and lepton number are further types of "charges" that are reversed for particle and antiparticle. Thus an electron and an electron neutrino both have electron number +1 while their antiparticles the positron and the anti-electron-neutrino have electron number -1.

***Baryon**
A hadron made from a basic structure of three quarks. The proton and the neutron are both baryon. The antiproton and the antineutron are antibaryons

***Boson**
The general name for any particle with a spin of an integer number (0,1 or 2...) of quantum units of angular momentum. (named for Indian physicist S.N. Bose). The carrier particles of all interactions are bosons.

***Bottom Quark or B Quark**
The fifth flavor of quark (in order of increasing mass), with electric charge -1/3.

***Charge**
A quantity carried by a particle that determines its participation in an interactions process. A particle with electric charge has electrical interactions; one with strong charge (or color charge) has strong interactions, etc.

***Charm**
The fourth flavor of quark (in order of increasing mass), with electric charge -+2/3. Also known as the C quark.

***Color Charge**
The charge associated with strong interactions. Quarks and gluons have color charge and consequently participate in strong interactions. Leptons, photons and W and Z bosons do not have color charge and therefore do not participate in strong interactions.

****Conservation law**
A general statement that a physical quantity, such as energy, momentum, or mass, is unchanged (conserved) in an interaction occurring within a closed system.

****Cosmology**
1. the study of the universe's origin, structure, and evolution. 2. a theory of the origin and structure of the universe.

***Down Quark or D Quark**
The second flavor of quark (in order of increasing mass), with electric charge -1/3.

***Electromagnetic Interaction**
The interaction due to electric charge; this includes magnetic effects that have to do with moving electric charges.

***Electron**
The least massive electrically charged particle, therefore is absolutely stable. It is the most common lepton with a charge -1. An electron is one of the fundamental particles in nature. Fundamental means that, as far as we know, an electron cannot be broken down into smaller particles. (This concept is one of the things SLAC physicists always challenge by looking for other particles.) Electrons are responsible for many of the phenomena that we observe in everyday life. Mutual repulsion between electrons in the atoms of the floor and those within your shoes keeps you from sinking and disappearing into the floor!!! Electrons carry electrical current and successful manipulation of electrons allows electronic devices, such as the one you are using, to function

***Fermion**
General name for a particle that is a matter constituent, characterized by spin in odd half integer quantum units (1/2,3/2,5/2...). Named for Italian physicist Enrico Fermi. Quarks, leptons and baryons are all fermions.

***Flavor**
The name used for the different quark types and the different lepton types. The six flavors of quarks are: up, down, strange, charm, bottom, top, in increasing order of mass. The flavors of charged leptons are: electrons, muon and tau, again in increasing order of mass. For each charged lepton flavor there is a corresponding neutrino flavor.

***Fundamental Interaction**
The known fundamental interactions are the strong, electromagnetic, weak and gravitational interaction. These interactions explain all observed physical processes but do not explain particle masses. Any force between two objects is due to one or another of these interactions. All known particle decays can be understood in terms of these strong, electromagnetic or weak interactions.

***Fundamental Particle**
A particle with no internal substructure. In the Standard Model, the quarks, leptons, photons, gluons, W-boson and Z-bosons are fundamental. All other objects are made from these particles.

****Gluon**
A massless particle that carries the strong force from one quark to another. Gluons can also interact among themselves and form particles consisting only of gluons bound together.

***Gravitational Interaction**
An attractive force between any two objects or particles. The “charge” that determines the strength of the gravitational interaction is energy. For a static object it is mass-energy but in fact all forms of energy both cause and feel gravitational effects.

****Graviton**
A theoretically deduced particle that is the quantum of gravitational fields, having zero mass, zero charge, and a spin of 2.

***Hadron**
Any particle made of quarks and gluons, i.e. a meson or a baryon. All such particles have no strong charge (i.e. are strong charge neutral objects) but participate in residual strong interactions due to the strong charges of their constituents.

***High-Energy Physics**
A branch of science that tries to understand the interactions of the fundamental particles, such as electrons, photons, neutrons and protons (and many others than can be created). These particles are the basic building blocks of everyday matter, making up the human body as well as the entire universe. This type of physics is called high-energy because very powerful machines, such as the Two-Mile Accelerator at SLAC, are created to make these particles go very fast so that they can probe deeply into other particles and try to understand what they are made of.

***Lepton**
A fundamental matter particle that does not participate in strong interactions. The charge leptons are the electron, the muon, the tau and their antiparticles. Neutral leptons are called neutrinos

***Matter**
We call the commonly observed particles such as protons, neutrons and electrons matter particles, and their antiparticles are then antimatter.

***Meson**
A hadron with the basic structure of one quark and one antiquark.

***Muon**
The second lepton (in order of increasing mass), with an electric charge -1.

***Neutrino**
A lepton with no electric charge. Neutrinos participate only in weak (and gravitational) interactions and therefore are very difficult to detect. There are three known types of neutrino, all of which have very low or possibly even zero mass.

***Neutron**
A baryon with electric charge zero. Its basic structure is two down quarks and one up quark.

***Pair Production and Annihilation**
Whenever sufficient energy is available to provide the mass-energy, a particle and its matching antiparticle can be produced (pair production). When a particle collides with its matching antiparticle they may annihilate—which means they both disappear and their energy appears as some other particles—with balanced number of particles and antiparticles for each type. All conservation laws are obeyed in these processes.

***Particle**
In “particle physics”, a subatomic object with definite mass and charge

****Particle accelerator**
A device designed to accelerate charged particles to high energies.

***Photon**
The carrier particle of the electromagnetic interaction. Depending on its frequency (and therefore its energy) photons can have different names such as visible light, X-rays and gamma rays. We describe light in several ways. When we talk about “photons” we generally think of uncharged particles without mass that carry energy (but be careful, there are other particles like this!). Photons of light are known by other names too, such as gamma rays and x-rays. Low-energy forms are called ultraviolet rays, infrared rays, even radio waves! A photon is one of the fundamental particle in nature and it plays an important role involving electron interactions. Photons are the most familiar particles in everyday existence. The light we see, the radiant heat we feel, and microwaves we cook with make use of photons of different energies. An X-ray is simply a name given to the most energetic of these particles.

***Pion**
The lightest type of mesons. They are copiously produced in high energy particle collisions.

***Positron**
Antiparticle of the electrons.

***Proton**
A baryon with electric charge +1. Protons contain a basic structure of two up quarks and one down quark. The nucleus of a hydrogen atom is a proton. A nucleus with atomic number Z contains Z protons; therefore the number of protons is what distinguishes the different chemical elements.

***Quark**
A fundamental matter particle that has strong interactions. Quarks have an electric charge of either +2/3 (up, charm and top) or -1/3 (down, strange and bottom) in units where the proton charge is 1.

***Standard Model**
Physicists' name for the current theory of fundamental particles and their interactions.

***Strange Quark**
The third flavor of quark (in order of increasing mass), with electric charge -1/3.

***Strong Interaction**
The interaction responsible for binding quarks and gluons to make hadrons. Residual strong interactions provide the nuclear binding force. In nuclear physics the term “strong interaction” is also used for this residual effect. (As a parallel, the force between electrically charged particles is an electromagnetic interaction, the force between neutral atoms that leads to the formation of molecules is a residual electromagnetic effect.)

***Tau**
The third charged lepton (in order of increasing mass), with electric charge -1.

***Top Quark**
The sixth flavor of quark (in order of increasing mass) with electric charge +2/3.

***Up Quark**
The first flavor of quark (in order of increasing mass), with electric charge +2/3.

***W Boson**
A carrier particle of the weak interaction.

***Weak Interaction**
The interactions responsible for all processes in which flavor changes; hence for the instability of heavy leptons and quarks, and particles that contain them. Weak interactions that do not change flavor have also been observed.

***Z Boson**
Also known as a Z Particle. A carrier particle of weak interactions. It is involved in weak processes that do not change flavor.

*from the **SLAC Virtual Visitor Center Glossary of Terms**
http://www2.slac.stanford.edu/vvc/glossary.html

from the **Harcourt Academic Press Dictionary of Science and Technology
http://www.harcourt.com/dictionary/def/6/4/7/6/647600.html

References

The Standard Model:

- **The Particle Adventure: the Fundamentals of Matter and Force**
  home page: http://www.particleadventure.org/
  in-depth: http://www.particleadventure.org/frameless/startstandard.html
  summary: http://particleadventure.org/particleadventure/other/proj_sum.html
  student activities: http://particleadventure.org/particleadventure/other/othersites.html

- **Fermi National Accelerator Laboratory: Inquiring Minds:**
  http://www.fnal.gov/pub/inquiring/matter/index.html

- **CERN: Explore the Atom**
  http://public.web.cern.ch/Public/SCIENCE/Welcome.html

- **Stanford Linear Accelerator Center: Probing the Structure of Matter**
  home page: http://www2.slac.stanford.edu/vvc/
  theory: http://www2.slac.stanford.edu/vvc/theory.html
  conservation laws: http://www2.slac.stanford.edu/vvc/theory/conserv.html
  color charge: http://www2.slac.stanford.edu/vvc/theory/colorchrg.html
  cosmic rays: http://www2.slac.stanford.edu/vvc/cosmicrays/crdatacenter.html

- **Hyperphysics: Particles**:
  http://hyperphysics.phy-astr.gsu.edu/hbase/particles/parcon.html

Games:

- **Fermilabyrinth -** web based games (under "Law and Order" try 'Baryron Bonanza', 'Particle Families' and 'Four Forces')
  http://www-ed.fnal.gov/projects/labyrinth/

- **The Sci-Tech Quark Machine** http://scitech.mus.il.us/qmachine/index.html

- **PBS: The Atom Builder** http://www.pbs.org/wgbh/aso/tryit/atom/#

Misc:

- **Live From CERN: Antimatter: Mirror of the Universe**
  http://livefromcern.web.cern.ch/livefromcern/antimatter/index.html

- **Imagine the Universe: Cosmic Rays**
  http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html

- **The Wright Center: Cosmic Evolution**
  http://www.tufts.edu/as/wright_center/cosmic_evolution/

- **Life in the Universe**
  http://www.lifeinuniverse.org/

SCORE SHEET

Enter particles by using the symbol given in parentheses with its total charge (add together the charges of the quarks) as a superscript. The proton and neutron are exceptions, denoted by just **p** and **n** (for anti-protons and anti-neutrons put a bar over these symbols).

BARYONS (3 quarks) - score **ANTIBARYONS** (3 anti-quarks) the same way **total points**

ALL are **u**'s and/or **d**'s	**proton (p)** - uud **neutron (n)** - udd **delta (Δ)** - uuu, ddd	5					
2 are **u**'s and/or **d**'s	**sigma (Σ)** - uus, dds, uuc, ddc **lambda (Λ)** - uds, udc	10					
1 is **u** OR **d**	**xi (Ξ)** - uss, dss, ucc, dcc, ucs, dcs	20					
NONE are **u**'s OR **d**'s	**omega (Ω)** - sss, ccc, ccs, css	40					

MESONS (1 quark and 1 anti-quark) - score **ANTIMESONS** the same way **total points**

ALL **u**'s, **d**'s, **anti-u**'s, **anti-d**'s	**pion (π)** - $u\underline{d}$, $u\underline{u}$, $d\underline{d}$, $\underline{u}d$	3					
ONE **u**, **d**, **anti-u**, or **anti-d**	**kaon (K)** - $u\underline{s}$, $d\underline{s}$, $\underline{u}s$, $\underline{d}s$ **D-meson (D)** - $c\underline{d}$, $c\underline{u}$, $\underline{c}d$, $\underline{c}u$	5					
NO **u**'s, **d**'s, **anti-u**'s, **anti-d**'s	**D-meson (D_s)** - $c\underline{s}$, $\underline{c}s$ **phi (Φ)** - $s\underline{s}$ **J/Psi (J/Ψ)** - $c\underline{c}$	10					

TOTAL SCORE FROM ABOVE ____________

EVENT #1						→					
charge						→					
baryon #						→					
e lepton #						→					
μ lepton #						→					
τ lepton #						→					

SCORE (10 points per particle or photon) = __________

EVENT #2						→					
charge						→					
baryon #						→					
e lepton #						→					
μ lepton #						→					
τ lepton #						→					

SCORE (10 points per particle or photon) = __________

Total Score from above __________

Total Score from front + __________

TOTAL SCORE __________

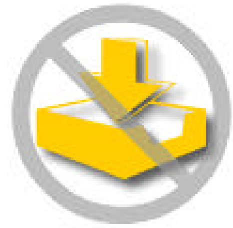
anti-down
anti-red
+1/3

anti-down
anti-red
+1/3

anti-down
anti-green
+1/3

anti-down
anti-green
+1/3

anti-down
anti-blue
+1/3



anti-down
anti-blue
+1/3

anti-down
anti-red
+1/3

anti-down
anti-red
+1/3

anti-down
anti-green
+1/3

anti-down
anti-green
+1/3

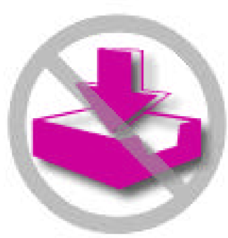
anti-down
anti-blue
+1/3

anti-down
anti-blue
+1/3

anti-down
anti-red
+1/3

anti-down
anti-red
+1/3

anti-down
anti-green
+1/3



anti-down
anti-green
+1/3

anti-down
anti-blue
+1/3

anti-down
anti-blue
+1/3

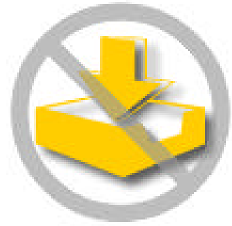
anti-down
anti-red
+1/3

+1/3
anti-red
anti-down

anti-down
anti-green
+1/3

+1/3
anti-green
anti-down

anti-down
anti-blue
+1/3



+1/3
anti-blue
anti-down

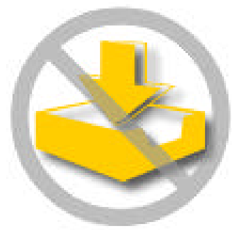
anti-down
anti-red
+1/3

+1/3
anti-red
anti-down

anti-down
anti-green
+1/3

+1/3
anti-green
anti-down

anti-down
anti-blue
+1/3

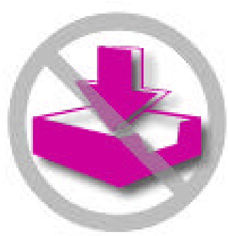


+1/3
anti-blue
anti-down

anti-down
anti-red
+1/3

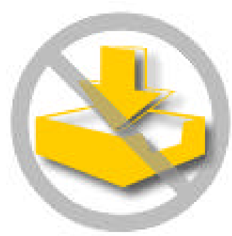
+1/3
anti-red
anti-down

anti-down
anti-green
+1/3

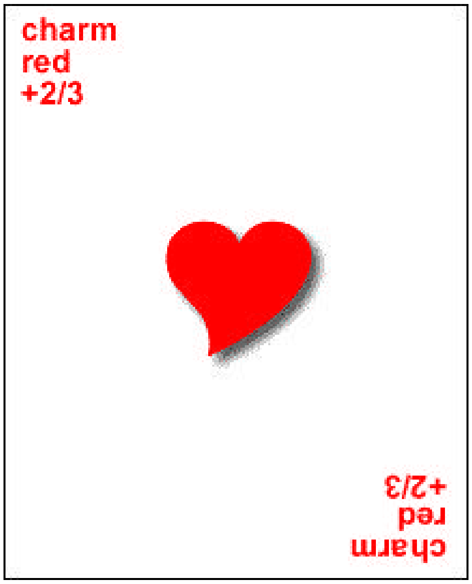


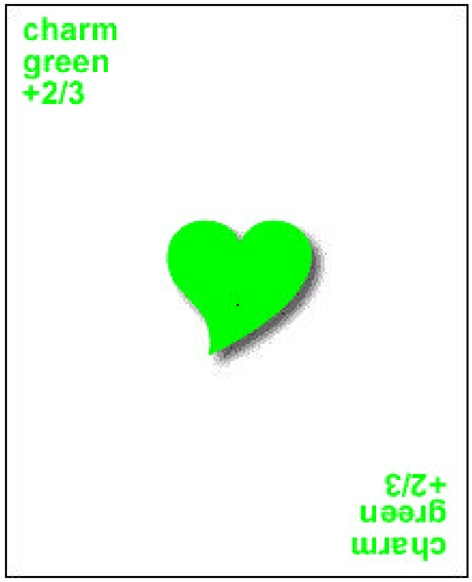
+1/3
anti-green
anti-down

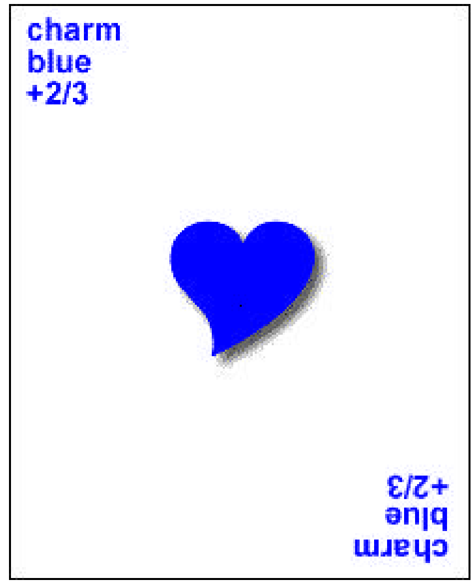
anti-down
anti-blue
+1/3



+1/3
anti-blue
anti-down

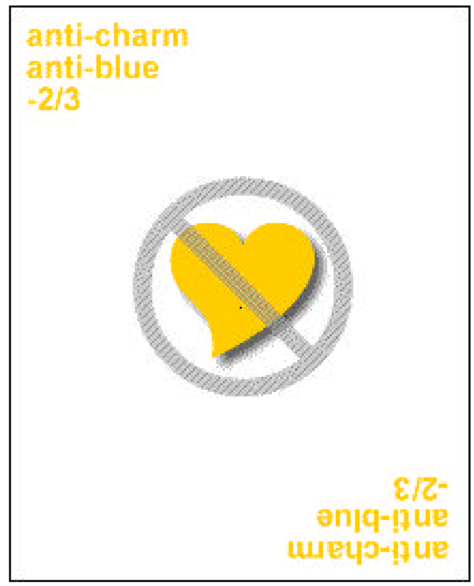

charm
red
+2/3
charm
red
+2/3


charm
green
+2/3
charm
green
+2/3


charm
blue
+2/3
charm
blue
+2/3


anti-charm
anti-red
-2/3
anti-charm
anti-red
-2/3

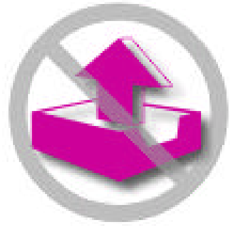

anti-charm
anti-green
-2/3
anti-charm
anti-blue
-2/3


anti-charm
anti-blue
-2/3
anti-charm
anti-blue
-2/3

anti-up
anti-red
-2/3

anti-up
anti-red
-2/3

anti-up
anti-green
-2/3



anti-up
anti-green
-2/3

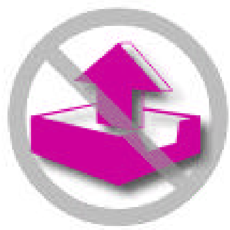
anti-up
anti-blue
-2/3

anti-up
anti-blue
-2/3

anti-up
anti-red
-2/3

anti-up
anti-red
-2/3

anti-up
anti-green
-2/3



anti-up
anti-green
-2/3

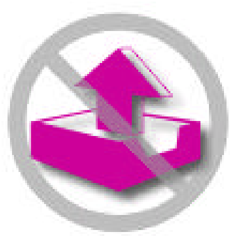
anti-up
anti-blue
-2/3

anti-up
anti-blue
-2/3

anti-up
anti-red
-2/3

anti-up
anti-red
-2/3

anti-up
anti-green
-2/3



anti-up
anti-green
-2/3

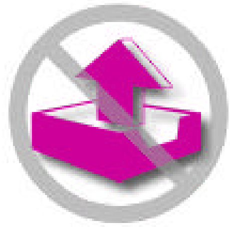
anti-up
anti-blue
-2/3

anti-up
anti-blue
-2/3

anti-up
anti-red
-2/3

-2/3
anti-red
anti-up

anti-up
anti-green
-2/3



-2/3
anti-green
anti-up

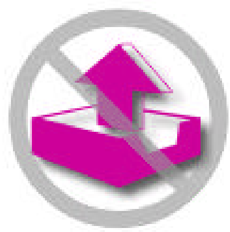
anti-up
anti-blue
-2/3

-2/3
anti-blue
anti-up

anti-up
anti-red
-2/3

-2/3
anti-red
anti-up

anti-up
anti-green
-2/3



-2/3
anti-green
anti-up

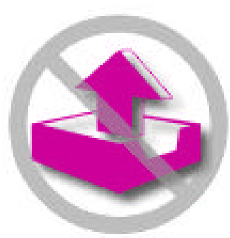
anti-up
anti-blue
-2/3

-2/3
anti-blue
anti-up

anti-up
anti-red
-2/3

-2/3
anti-red
anti-up

anti-up
anti-green
-2/3

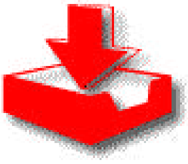


-2/3
anti-green
anti-up

anti-up
anti-blue
-2/3

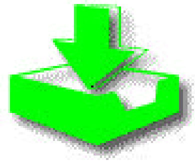
-2/3
anti-blue
anti-up

down
red
-1/3



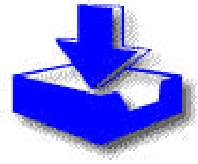
-1/3
red
down

down
green
-1/3



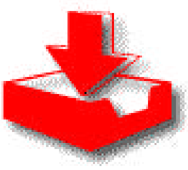
-1/3
green
down

down
blue
-1/3



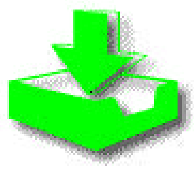
-1/3
blue
down

down
red
-1/3



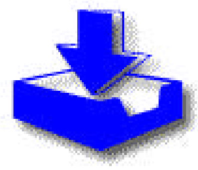
-1/3
red
down

down
green
-1/3



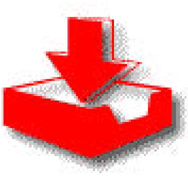
-1/3
green
down

down
blue
-1/3



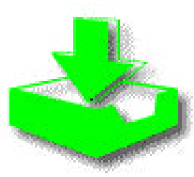
-1/3
blue
down

down
red
-1/3



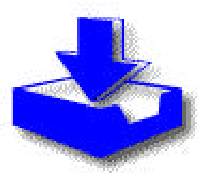
-1/3
red
down

down
green
-1/3



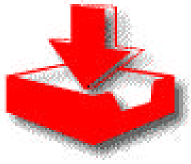
-1/3
green
down

down
blue
-1/3



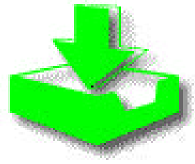
-1/3
blue
down

down
red
-1/3



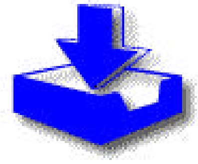
-1/3
red
down

down
green
-1/3



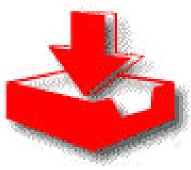
-1/3
green
down

down
blue
-1/3



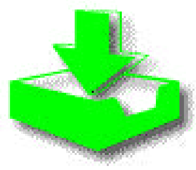
-1/3
blue
down

down
red
-1/3



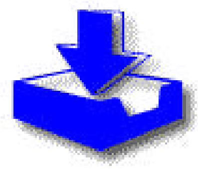
-1/3
red
down

down
green
-1/3



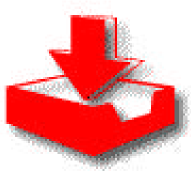
-1/3
green
down

down
blue
-1/3



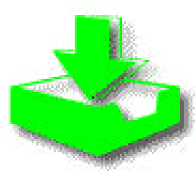
-1/3
blue
down

down
red
-1/3



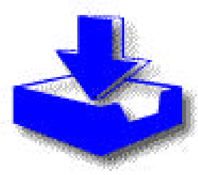
-1/3
red
down

down
green
-1/3



-1/3
green
down

down
blue
-1/3



-1/3
blue
down

electron-
neutrino
0

ν_e

electron-
neutrino
0

electron-
neutrino
0

ν_e

electron-
neutrino
0

electron-
neutrino
0

ν_e

electron-
neutrino
0

electron-
neutrino
0

ν_e

electron-
neutrino
0

anti-electron
neutrino
0

$\bar{\nu}_e$

anti-electron
neutrino
0

anti-electron
neutrino
0

$\bar{\nu}_e$

anti-electron
neutrino
0

anti-electron
neutrino
0

$\bar{\nu}_e$

anti-electron
neutrino
0

anti-electron
neutrino
0

$\bar{\nu}_e$

anti-electron
neutrino
0

photon

γ

photon

electron
-1

e^-

electron
-1

electron
-1

e^-

electron
-1

electron
-1

e^-

electron
-1

electron
-1

e^-

electron
-1

positron
+1

e^+

positron
+1

positron
+1

e^+

positron
+1

positron
+1

e^+

positron
+1

positron
+1

e^+

positron
+1

photon

γ

photon

muon
-1

$$\mu^-$$

muon
-1

anti-muon
+1

$$\mu^+$$

anti-muon
+1

anti-muon
+1

$$\mu^+$$

anti-muon
+1

anti-muon
+1

$$\mu^+$$

anti-muon
+1

muon-
neutrino
0

$$\nu_\mu$$

muon-
neutrino
0

muon-
neutrino
0

$$\nu_\mu$$

muon-
neutrino
0

anti-muon
neutrino
0

$$\bar{\nu}_\mu$$

anti-muon
neutrino
0

anti-muon
neutrino
0

$$\bar{\nu}_\mu$$

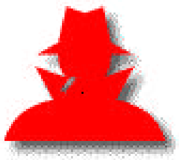
anti-muon
neutrino
0

photon

$$\gamma$$

photon

strange
red
-1/3



strange
red
-1/3

strange
green
-1/3

strange
green
-1/3

strange
blue
-1/3

strange
blue
-1/3

anti-strange
anti-red
+1/3

anti-strange
anti-red
+1/3

anti-strange
anti-green
+1/3

anti-strange
anti-green
+1/3

anti-strange
anti-blue
+1/3

anti-strange
anti-blue
+1/3

anti-tau
+1

τ^{+}

anti-tau
+1

tau
-1

τ^{-}

tau
-1

tau-
neutrino
0

ν_{τ}

tau-
neutrino
0

anti-tau
neutrino
0

$\bar{\nu}_{\tau}$

anti-tau
neutrino
0

photon

γ

photon

photon

γ

photon

photon

γ

photon

photon

γ

photon

photon

γ

photon

up
red
+2/3

up
red
+2/3

up
green
+2/3

up
green
+2/3

up
blue
+2/3

up
blue
+2/3

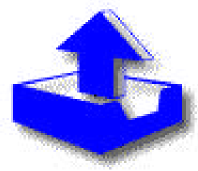
up
red
+2/3

up
red
+2/3

up
green
+2/3

up
green
+2/3

up
blue
+2/3



up
blue
+2/3

up
red
+2/3

up
red
+2/3

up
green
+2/3

up
green
+2/3

up
blue
+2/3

up
blue
+2/3

up
red
+2/3

up
red
+2/3

up
green
+2/3

up
green
+2/3

up
blue
+2/3

up
blue
+2/3

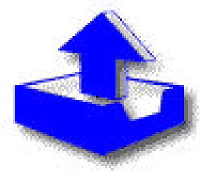
up
red
+2/3

up
red
+2/3

up
green
+2/3

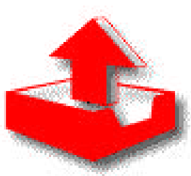
up
green
+2/3

up
blue
+2/3



up
blue
+2/3

up
red
+2/3



up
red
+2/3

up
green
+2/3

up
green
+2/3

up
blue
+2/3

up
blue
+2/3