Name: ______________________________ Date: ____________________

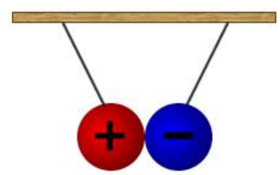
Guided Learning: The Strong Nuclear Force

Learning goals
After completing this activity, you will be able to …

- Explain how the discovery of the nucleus led to the prediction of a strong nuclear force.
- Describe how particle physics led to the discovery of the quark.
- Relate interactions between quarks to the existence of the strong nuclear force.

Vocabulary: alpha particle, antimatter, baryon, electron, force carrier particle, hadron, lepton, neutron, nucleus, particle accelerator, proton, quark, strong nuclear force

Warm-up questions
The electromagnetic force causes opposite charges to attract and like charges to repel. Within an atom, **protons** have a positive charge, **electrons** have a negative charge, and **neutrons** have no charge at all.



1. An atom consists of a **nucleus** of protons and neutrons surrounded by a cloud of electrons. Will the electrons be attracted to the nucleus or repelled from it?

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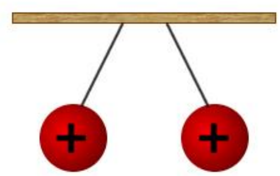

2. Are protons in the nucleus attracted to one another by the electromagnetic force or repelled from one another?

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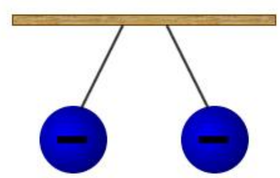

3. An atomic nucleus consists of protons and neutrons. Given your answers to the previous two questions, is there something strange about the composition of the nucleus? Explain.

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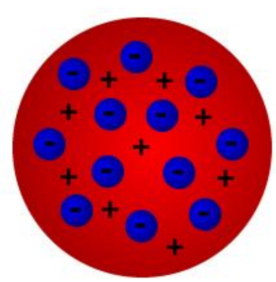
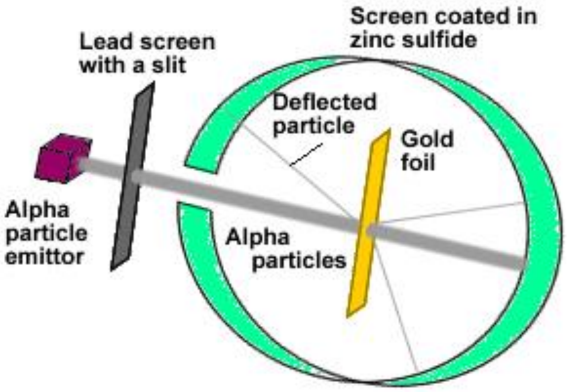
Activity A: The structure of the atom



At the end of the 19th century, the prevailing model of the atom was one proposed by J.J. Thomson. Thomson, who had recently discovered the electron, hypothesized a "plum pudding" model in which negatively charged electrons were embedded within a positively charged mass. In 1909, Ernest Rutherford, Hans Geiger, and Ernest Marsden devised an ingenious experiment to test Thomson's model.

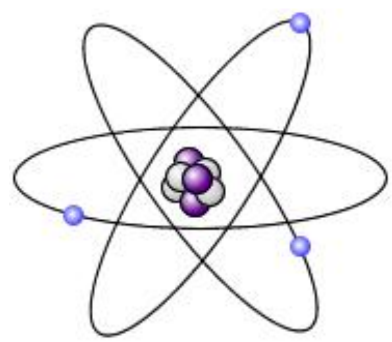


The Rutherford-Geiger-Marsden experiment

Rutherford had previously done a series of experiments on **alpha particles**, tiny particles that were emitted by certain radioactive materials. (An alpha particle is equivalent to the nucleus of a helium atom, consisting of two protons and two neutrons.) Rutherford and his colleagues set up an experiment in which a stream of alpha particles would be "shot" at a sheet of gold foil that was only a few atoms thick. A screen coated in zinc sulfide surrounded the foil. When an alpha particle hit the screen, a tiny glowing dot could be observed under a microscope.

Assuming Thomson's atom model was correct, Rutherford expected all the alpha particles to pass directly through the gold foil with little or no deflection. What they discovered was that, while the vast majority of the particles did pass directly through the foil, some particles were deflected to the side. A few others were even bounced backwards!

Rutherford concluded that most of an atom's mass was concentrated in a tiny, positively-charged nucleus. Most of the alpha particles passed through the empty space that made up most of the atom, but once in a while an alpha particle collided with the nucleus and was bounced backward or deflected to the side. Rutherford supposed that the electrons orbited the nucleus like planets around the Sun, as shown at right.



The planetary atom: Protons are purple, neutrons are white, and electrons are blue.

Rutherford went on to discover the proton in 1919. Rutherford then noticed that the mass of most nuclei was greater than the mass of the protons, leading him to predict the existence of a neutral particle in the nucleus. This was confirmed with the discovery of the neutron by James Chadwick in 1932.

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1. Why did Rutherford expect all the alpha particles to pass directly through the gold foil?

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2. What was the significance of the fact that a few alpha particles bounced off the gold foil?

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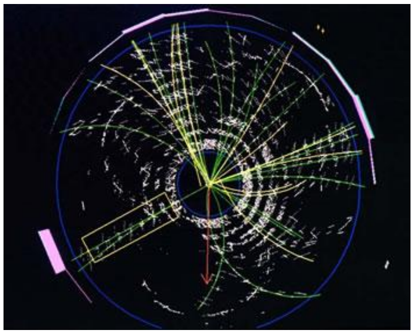
Activity B: A multitude of particles

The discovery of the nucleus was a tremendous step in the history of science, but it created a mystery that would go unsolved for nearly 60 years. Because of the electromagnetic force, each proton is repelled from other protons by a force that increases greatly as the distance between the protons is reduced. If the nucleus was composed of positively-charged protons and neutral neutrons, what kept it from flying apart?

To hold the nucleus together, scientists hypothesized that a binding force must exist between the protons and neutrons in the nucleus. This force, dubbed the **strong nuclear force**, would have to be stronger than the electromagnetic force but could only operate at extremely short distances.

Fermilab particle accelerator

The exact nature of this force was gradually revealed between 1945 and 1970. In this time period, a new branch of physics, *particle physics*, developed to discover and study the most fundamental particles in nature. To find these particles, physicists use **particle accelerators**, such as the one shown at right. These are circular or linear tubes in which tiny particles are accelerated to nearly the speed of light. These particles are then smashed together with enormous energy, often producing new particles with exotic names such as muons, bosons, and neutrinos.



Proton-antiproton collision

The table summarizes how many of these particles are classified. Underlined particles make up everyday matter.

Hadrons		Leptons
Mesons	**Baryons**	
Pion Rho meson Eta meson Kaon	<u>Proton</u> <u>Neutron</u> Lamba Sigma Delta Xi Omega	<u>Electron</u> Electron neutrino Muon Muon neutrino Tau Tau neutrino

In addition to the particles listed above, there is an **antimatter** particle for each particle: anti-protons, anti-electrons (also called *positrons*), and so forth. When a particle and its antiparticle collide, they annihilate one another in a burst of energy. An image of a proton-antiproton collision is shown above.

While the **leptons** are currently considered fundamental particles because they have no internal structure and cannot be broken down, the **hadrons** are more massive particles that are thought to be made up of still smaller particles, called **quarks**. The existence of quarks was proposed by two scientists independently in 1964: Murray Gell-Mann and George Zweig.

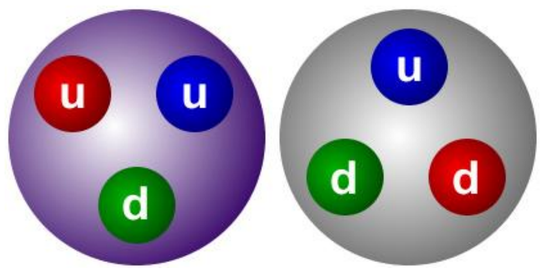
Quarks are believed to be fundamental particles with very odd properties such as “color,” “flavor,” and “spin.” (Note: These words are used as analogies and should not be taken literally.) Quarks also have a fractional charge. Six flavors of quarks have been discovered so far:

Generation	Flavor and symbol	Charge (relative to electron)
First generation	up (u)	+ ⅔
	down (d)	– ⅓
Second generation	charm (c)	+ ⅔
	strange (s)	– ⅓
Third generation	top (t)	+ ⅔
	bottom (b)	– ⅓

First generation quarks are the smallest of quarks and are the only stable quarks. Other types of quarks can only be produced in high-energy collisions and quickly decay to first generation quarks. As for other particles, there is an antiquark for each flavor of quark.

Baryons such as protons and neutrons each consist of three quarks: A proton is made of two up quarks and one down quark, while a neutron is made of one up quark and two down quarks.

Quarks are further distinguished by their “color.” (Like many aspects of particle physics, color is not a real property of quarks but an analogy that helps us to understand their properties.) Any hadron must be neutral in color. Baryons have a quark of each color (red, green, and blue), while mesons contain a quark and an antiquark with colors that cancel out, such as green and magenta. Color is not a permanent property of quarks but changes frequently.



Protons (left) and a neutrons (right) are made of quarks (colored balls).

1. How does the composition of the nucleus predict the existence of the strong force? ________

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2. Fundamental particles cannot be broken down into other particles. What two categories of particles are considered fundamental? ___________________________________

3. Add up the charges of the quarks in a proton and the quarks in a neutron.

What is the charge of a proton? _________ What is the charge of a neutron? _________

Activity C: Fundamental forces

In addition to particles, particle physicists have studied the forces between particles, which they call "interactions." Particles interact by exchanging special particles called **force carrier particles**. According to the theory, each of the four fundamental forces (gravity, electromagnetism, the strong nuclear force, and the weak nuclear force) is mediated by its own particle: gravity by *gravitons*, electromagnetism by *photons*, the strong force by *gluons* and the weak force by *bosons*. (Note: Gravitons are purely hypothetical and have not been discovered yet.) These particles, their relative strength, and their relative range are described below:

Interaction	Relative strength	Range	Force carrier particle
Gravity	1	infinite	graviton (hypothetical)
Electromagnetism	1×10^{36}	infinite	photon (discovered ~1923)
Strong force	2×10^{38}	$\approx 1 \times 10^{-15}$ m	gluon (1979)
Weak force	2×10^{33}	$\approx 1 \times 10^{-18}$ m	$W^{\pm}$ and Z bosons (1983)

The strong nuclear force arises from the forces between quarks, called "color forces." Quarks within the same baryon must represent all three colors—red, green, and blue. Every so often two quarks will exchange gluons, changing color at the same time. Unlike other forces, the color force increases in strength as the quarks move farther apart within the hadron. As a result, quarks can float quite freely within the confines of the hadron, but can never escape—no "free quark" could ever be observed. Likewise gluons are not free to leave the boundaries of the hadron and thus do not directly participate in strong nuclear interactions.

The Standard Model

The "standard model" of particle physics includes three classes of fundamental particles—force carrier particles, quarks, and leptons—and at least 16 fundamental particles. As ungainly as this model is, it has been tremendously successful in predicting the existence of new particles years before their actual discovery.

Today many physicists are looking for a *theory of everything* (TOE): a single theory that explains the existence of all of the particles and forces and unites particle physics with general relativity.

Thus, the strong nuclear force that holds baryons (protons and neutrons) together in nuclei is actually a faint residue of the color forces holding quarks together. Because both quarks and gluons are confined inside hadrons, the forces between baryons are mediated by mesons such as pions and rho mesons. A proton and a neutron must constantly exchange mesons to stick together. (Imagine the two particles playing a game of tennis, with mesons as the tennis balls.) The forces that arise from these interactions are only a fraction as great as those that occur between quarks, but are still tremendously strong. Unlike the color forces, the strength of the strong force drops off sharply with distance and is only significant within the nucleus.

1. List the four fundamental forces, or interactions, in order from strongest to weakest:

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2. How are interactions between particles like a game of tennis? ________________________

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3. How is the force between baryons (protons and neutrons) in the nucleus related to the force between quarks? ____

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4. **Think and discuss:** The “standard model” is the name given to the current system of leptons, hadrons, and force carrier particles. In spite of its success at predicting the existence of new particles, many physicists are not satisfied with the standard model. Why do you think this is the case?

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